A Stereo Machine Vision System for measuring three-dimensional crack-tip displacements when it is subjected to elastic-plastic deformation

Arash Karpour and Dr. Khosrow Zarrabi

The School of Mechanical and Manufacturing Engineering

The University of New South Wales

Sydney, Australia

Abstract

This paper describes a Stereo Machine Vision System (SMVS) for measuring three-dimensional displacements at discrete points on the surface of an object. At the University of New South Wales (UNSW), the need for such a system has been generated for measuring the crack-tip displacements of elastic-plastic cracked components that are subjected to the mix-modes I, II and III loading. Being a non-contacting optical system, the SMVS naturally lends itself to measuring in-plane and out-of-plane displacement components, simultaneously at the points of interest, when the specimen is subjected to various degrees of mixed-mode loading.

The SMVS described in this paper measures three-dimensional displacement components at the desired points on the object surface using the triangulation method. An automatic calibration method has been developed based on intrinsic and extrinsic parameters. To measure the three dimensional displacement components along the crack flank of a cracked specimen under simultaneous in and out-of-plane (i.e., mixed modes I, II and III) loading using a universal testing machine, a pair of grips have specially been designed; for which the authors have been awarded a patent. The application of the SMVS to a typical cracked specimen, made of PMMA, has shown that the in-plane and out-of-plane displacements along the crack flank can be measured with an error less than 11%.

1 Introduction

In recent years, the field of sensing and imaging has become increasingly important due to the demand for accurate and reliable instrumentation for many important industrial, biomedical, material and mechanical applications. Despite the plethora of measuring techniques available, optical techniques are often preferred in many applications due to their non-contact form of measurement. This paper focuses on a three dimensional displacement (deformation) measurement using a Stereo Machine Vision System (SMVS). Such a system has practical significance in many areas, including the crack-tip opening displacement measurement of a compact tension specimen under mixed-modes I, II and III fracture loading. In the literature, numerous aspects of object motion and displacement measurement using an optical system are analysed. In spite of this, practical and affordable machine vision systems for three-dimensional displacement measurement are scarce and those that are commercially available are usually too costly.

This paper describes a SMVS that is designed to be pragmatic and affordable. Section 2 describes the workings of the SMVS. Section 3 details the application of the system to measure crack-tip opening displacement under mixed modes I, II and III fractures. Section 4 discusses the typical results. Finally, section 5 outlines the main conclusions of the investigation.

2 Stereo Machine Vision System (SMVS)

Referring to Figure 1 and **Chyba! Nenašiel sa žiaden zdroj odkazov.**, the stereo machine vision system consists of two DMK 21AF04 cameras, two micro-positioners, two macro-positioners, four cap screws as locking systems, two identical zoom lenses and a firewire card; which is the interface between the two cameras and the personal computer. The two cameras are set up on a calibrating platform in a stereo-arrangement. The two macro-positioners are in fact two sets of linear bearings that allow the cameras and micro-positioners the ability to slide in a Y-Z plane to approximate a desired location.

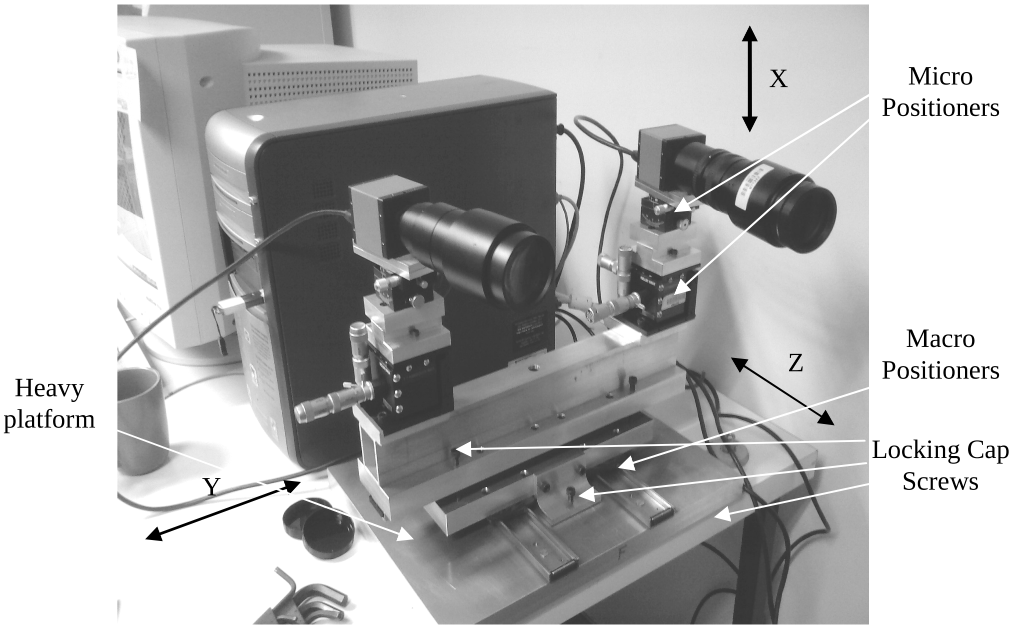

Figure 1 - Stereo Machine Vision System

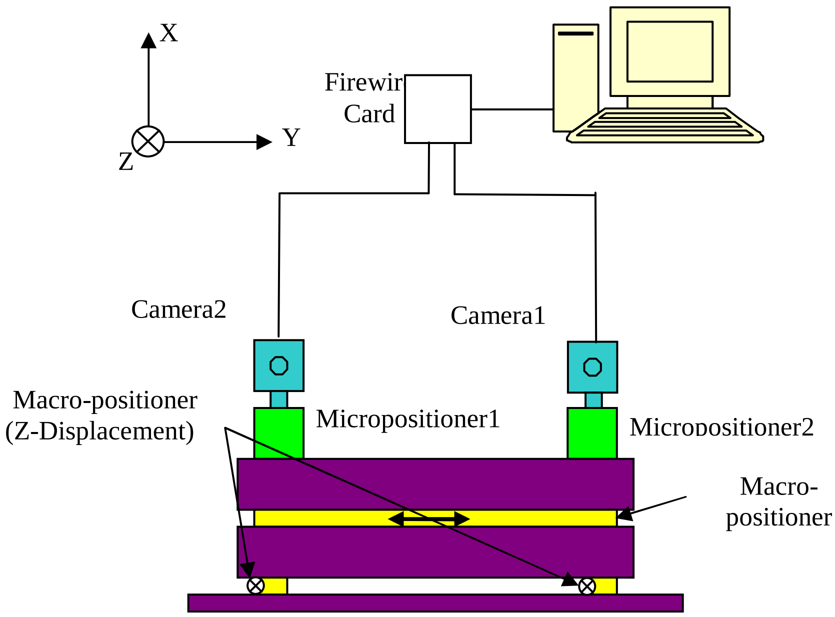

Figure 2 - Schematic Setup of Stereo Machine Vision System

The lenses that are used in the SMVS are NAVITAR Zoom 7000 lenses. These lenses offer a 6:1 zoom ratio or a 6X magnification power over a focal range of 18 mm to 108 mm.

In order to measure the anticipated displacements in various, discrete points, the surface of the aluminium subject is uniformly covered with white mat paint. Circular markers are then generated, using an Advanced Video Extensometer Marker Pen manufactured by INSTRON, at the desired locations. Typically, the diameter of a black mark is 1 mm. The SMVS software locates these black marks to use as a consistent reference point. These marks are illustrated in Figure 3. To further reduce inconsistencies, the specimen surface is uniformly illuminated to reduce shadow and extreme background contrast. Six white lights (20W) and a panel of 108 high intensity red L.E.Ds surround the specimen. This provides a homogenous illumination over the surface of interest.

When the black, circular marks were applied to the specimen, they were placed in two rows of three marks on either side of the notch. The marks on the far left side are aligned approximately with the crack tip. The marks on the far right side are placed in close proximity to the tip of the notch. To regulate the SMVS and the specimen, the first step was to calibrate the system to identify the relative positions of the two cameras to each other (extrinsic parameters), then to the specimen surface (intrinsic parameters) and finally to the position of marks on the specimen surface. The latter was formed relative to a coordinate system attached to the upper left corner of the specimen (see Section 2.1 for details). Additionally, the calibration module uses object recognition software to identify the black marks and their centres as these are taken as references for subsequent displacement measurements. Following the calibration stage, each camera captures one image of the specimen surface containing the six marks. This is performed in a stereo fashion when the specimen is loaded to a desired level. The images are stored in an allocated file on the computer hard disk for processing on later occasion. The loads applied to the specimen are then incremented by an appropriate magnitude. A second set of images of the same specimen surface are captured by the cameras and stored on the same file. After each pair of images are captured, a selected mark from the left camera image is matched to its corresponding mark on the right camera image. This process is coined a 'correspondence'. The system software uses the well-known epipolar method [1] to determine the positions of the black marks at each load level and therefore the displacements of the marks from one load level to the next.

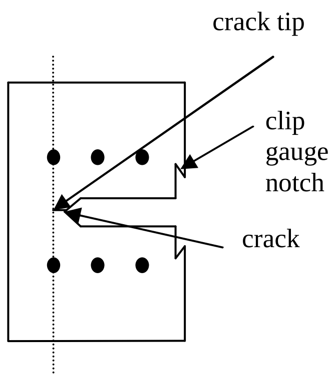

Figure 4 – Marks Positions on Specimen Surface

2.1 Calibration

Before the SMVS can be applied to the measurement of three dimensional displacements, it must be calibrated. Calibration of the system consists of the following steps. Firstly; the specimen is installed in the desired position using the grips that connect it to the INSTRON universal testing machine. The cameras and the assembled positioners are constructed and images of the specimen surface, including the marks, are captured. The cameras positions are adjusted so that the marks are approximately in the capturing frames, i.e., in the middle of the computer monitor. Secondly, the specimen is replaced by a checkerboard (Figure 4) mounted on the micro and macro-positioners. This allows 6 degrees of motion of the checkerboard relative to the cameras. The checkerboard consists of alternate black and white squares. The size of each square is 1 mm by 1 mm. To manufacture the checkerboard, the black and white pattern is laser printed on high resolution paper. This paper is then glued on a glass plate, forming the checkerboard panel. The checkerboard is mounted and rotated about the three coordinate axes to give the cameras various perspectives for the intrinsic calibration. This is then translated along the three axes. At each position two frames of the checkerboard, one by the left camera and another by the right camera, are taken. This totals 16 pairs of frames and stored on the hard disk of PC. Then these 16 pairs of frames are used to determine the intrinsic parameters of the cameras such as focal length and location of the centre of each frame, in terms of pixels, effective pixel size, radial distortion coefficient of the lenses, etc. See Section 2.1.1 below for details. Additionally, these frames are used to determine the the extrinsic parameters that describes the spatial relationship between the local or camera coordinate system (x, y) , defined for each image plane of each camera, and the global (world) or pattern coordinate system (X, Y, Z) They are a rotation matrix and translation vector [12]. In determining the extrinsic parameters additional pairs of frames of the checkerboard are taken and stored on the hard disk while the checkerboard is returned to its original position, i.e., the position where the specimen should be placed; see Section 1 for details. Finally, a successful calibration is indicated by the software when the images of the same points in a pair of frames of the same checkerboard position match. This is coined by the software as the 'correspondence'. The details of which are described in Section 2.1.1.

As explained in Section 2.1.1, the correspondence module of the software is done after extracting the intrinsic and the extrinsic parameters of the cameras. Using the obtained parameters and triangulation algorithm [4], the three-dimensional coordination of the marks, and therefore their displacements, are easily calculated.

2.1.1 Determination of Intrinsic and Extrinsic Parameters

Figure 5 shows the checkerboard mounted on the micro-positioners so that it can be rotated and translated in known amounts, accurately relative to the cameras during the calibration, where intrinsic and extrinsic parameters are determined.

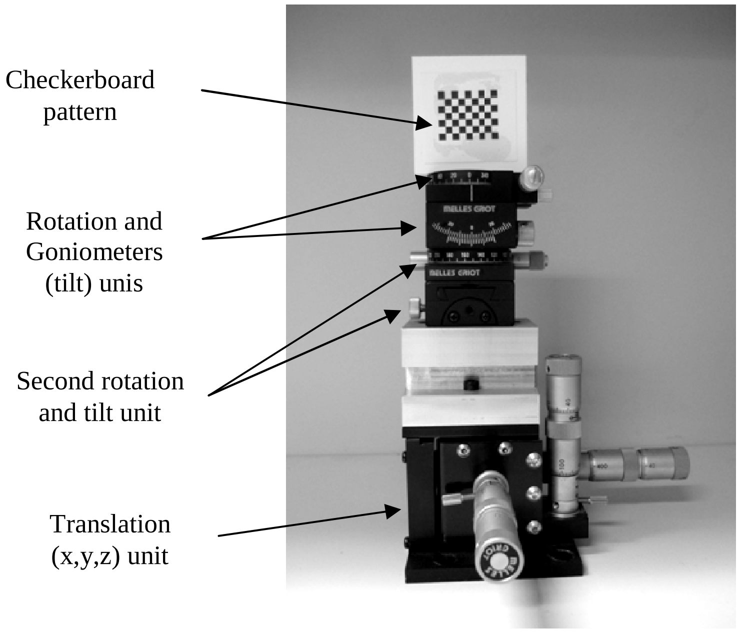

Figure 5 – Checkerboard and micro-positioners assembly

The captured 16 pairs of frames referred to in Section 2.1 use the following algorithm, described in references [4] and [5], to determine the intrinsic parameters:

Using the homography between the stored frames of the checkerboard and the checkerboard plane, one may write:

$$\{m\} = [A][R]\{t\}\{M\} \qquad (1)$$

Where $\{m\} = [x, y]^T$ represents a vector of coordinates of the corner of each square in the checkerboard in terms of the camera coordinate system, matrix [A] represents the intrinsic parameters, [R] is the rotation matrix and {t} is translation vector ([R] and {t} represent the extrinsic parameters) and $\{M\} = [X, Y, Z]^T$ represents a vector of coordinates of the corner of each square in the checkerboard in terms of the global (world) or pattern coordinate system. Noting that the number of equations is more than the number of unknowns, equation (1) is solved by minimising the pertinent mean squared error. This will determine: [A], [R], {t} and {M}.

2.1.2 Correspondence

If two images of the same point in space, taken from two different points of view, the correspondence problem is to find a set of points in one image which can be identified as the same points in the second image. In the SMVS the correspondence problem is solved automatically with only the images of the checkerboard as inputs. This is solved by executing edge detection of the checkerboard images (Figure 6), where edge detection is applied independently on images taken from the left and the right camera, thus matching the corresponding images. In order to calculate the 3-D position of objects, the cameras must capture corresponding points, which represent the same object. Without this, problems arise due to the variation in the angles with which the cameras take images of the object.

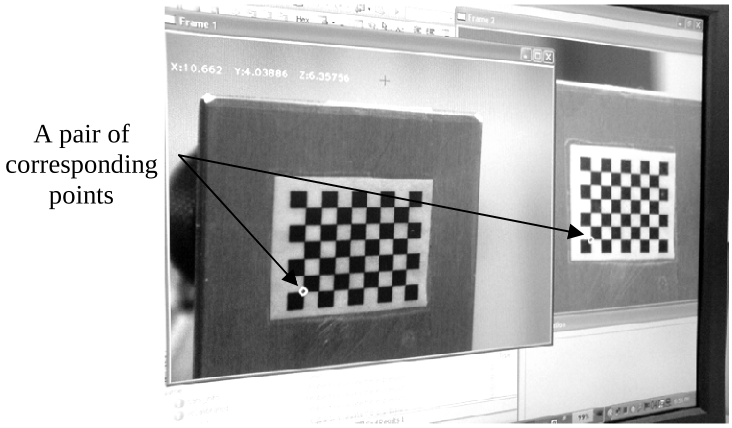

Figure 6 – Correspondence of two images of checkerboard taken by left and right cameras

3 Application

3.1 Test Rig & Test Procedure

To apply mixed-mode I/II/III loading, the authors have used an apparatus the set-up of which is depicted in Figure 7 and 8. The experimental apparatus consists of a universal testing (INSTRON Digital 8504 Servo Hydraulic) machine; two novel designed and manufactured grips, the pre-cracked specimen, a data acquisition system, a PC and SMVS. Using the upper load shaft and a nut (see Figure 8), the upper grip connects the specimen to a 10 KN load cell whose function is to measure the load applied to the specimen. The lower grip connects the specimen to the base of the INSTRON universal testing machine via the lower load shaft and a nut. The analogue output signal of the load cell (the applied load) is digitized by the data acquisition system and fed into a personal computer (PC) for analysis. Having pre-cracked the specimen by fatigue process, it is pulled to fracture and the load and three-dimensional displacements at the tip of the crack are measured and recorded incrementally using this experimental set-up. For an additional accuracy check, the mode I component of the crack-tip opening displacement (the displacement component in the x-direction) is measured by a clip gauge and mode III component of the displacement (the displacement in the z-direction) is measured by a pair of Linear Variable Displacement Transducers (LVDT). Note that the mode II component of the displacement cannot be measured easily without using the SMVS. In general, the INSTRON Digital 8504 machine is only capable of applying two co-linear forces to a specimen. In the present set-up, the innovative design of the grips allows the force to be applied to the crack-tip region in various in-plane and out-of-plane directions simultaneously, generating the desired mixed-mode I/II/III loading.

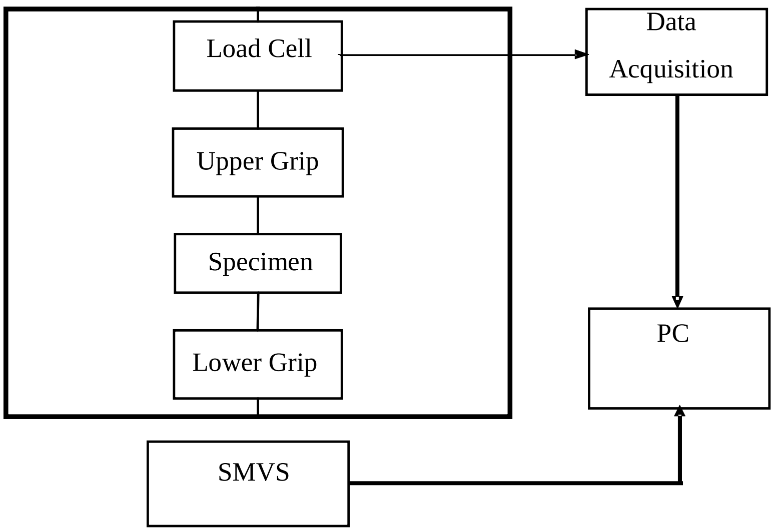

Figure 7 - Schematic set up of apparatus

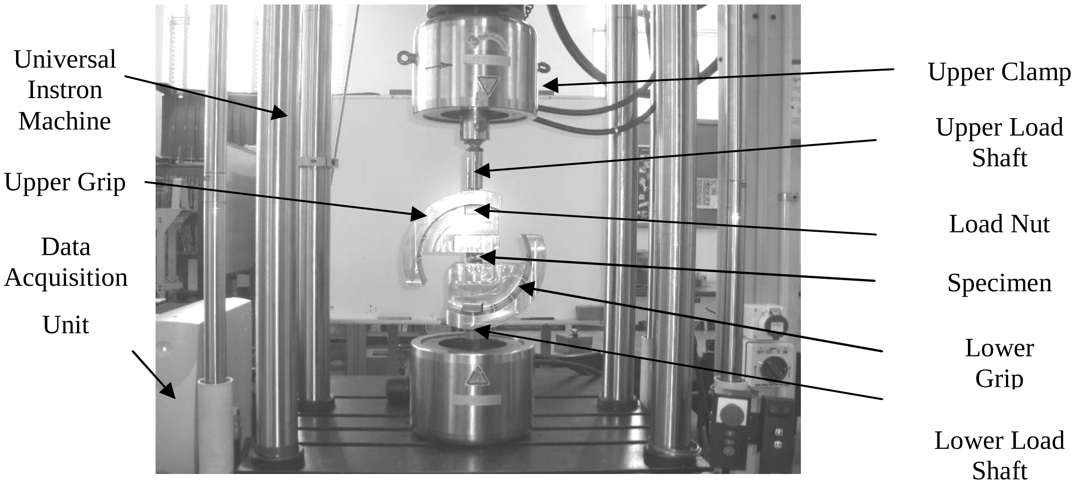

Figure 8 – Experimental set up

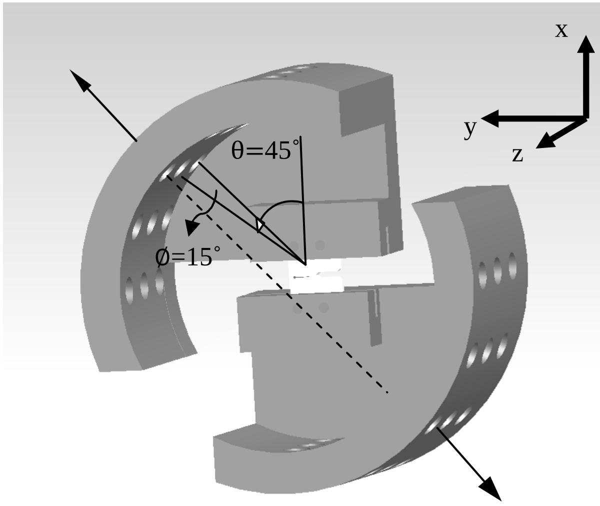

Figure 9 - Grips and specimen assembly when in-plane angle θ=45˚ and out-of-plane angle Ø=15˚ (mixed Mode I/II/III).

3.2 Results & Discussion

As mentioned above, the load applied incrementally to the pre-cracked PMMA specimens, at a step of 0.1 KN, up to the fracture point with displacements in the three-directions were measured at each load step using the SMVS. For comparison and to gauge the accuracy of the displacement measurement by SMVS, as mentioned above, the displacements in the x and z-directions were also measured by LVDTs and a clip gauge respectively. Figures 10 to 12 show the variation of the applied load with various displacement components. These figures show that the displacements measured by SMVS and mechanical sensors are close with maximum differences in the displacement in the x-direction was 10.35% (Figure 10) and in z-direction 0.1% (Figure 12).

Noting that PMMA is a brittle material, it was expected that the variation of load versus displacement to be linear. Referring to Figures 10 to 12, it seems that the data could approximately be represented by three lines. Where these lines intersect, i.e., at the load of 0.05KN (point A), the fracture was initiated but it was stable, i.e., if the load kept constant or reduced then the fracture process would not be continued and the specimen would remain as one piece. But because the load was increased at the load of 0.15KN (point B), an unstable fracture is initiated until the final fracture occurring at 0.35KN (point C) where the specimen broke into two pieces. Noting this behaviour, three critical crack-tip opening displacements may be identified, i.e., 0.0100 mm is defined at point A (0.05KN), 0.1700 mm is defined at point B (0.15KN) and 0.2400 mm is defined at point C (0.35KN) where the final fracture occurred, see, Figures 10 to 12 and Table 1.

Using the fracture toughness of PMMA for mode I ($K_{IC} = 1.05\ \text{MPa}\sqrt{\text{m}}$) and mode II ($K_{IIC} = 1.02\ \text{MPa}\sqrt{\text{m}}$)measured by Knott and Bhattacharjee [15], and equations $\delta_{IC} = \frac{\kappa+1}{\mu}\sqrt{\frac{x_c}{2\pi}}K_{IC}$ ... (2) and (3) derived by Ma et al [16], the critical elastic crack-tip opening displacements for modes I (δ_{IC}) and II (δ_{IIC}) are calculated and compared with those measured by SMVS (see point A in Figures 10 and 11) in Table 1.

$$\delta_{IC} = \frac{\kappa+1}{\mu}\sqrt{\frac{x_c}{2\pi}}K_{IC} \qquad \text{... (2)}$$

$$\delta_{IIC} = \frac{\kappa+1}{\mu}\sqrt{\frac{x_c}{2\pi}}K_{IIC} \qquad \text{... (3)}$$

where:

δ_{IC} , δ_{IIC} , δ_{IIIC} are the elastic critical crack-tip opening displacements at point A (Figures 10 to 12) for mode I (x-direction), mode II (y-direction) and mode III (z-direction);

E = 2000 MPa is the modulus of elasticity obtained from uniaxial tensile test;

$\kappa = \frac{(3-\upsilon)}{(1+\upsilon)} = 2$ for plane stress condition with υ =0.33 is the Poisson's ratio;

x_c =23.06 mm is the distance from the crack-tip to the centre of mark closest to the edge of the specimen;

$\mu = \frac{E}{2(1+\nu)}$ =939.88 MPa is the shear modulus.

Note that to the authors' knowledge there is no elastic critical crack-tip opening displacements for mode III in literature. Referring to table 1, the 56% and 61% differences between the measured elastic critical crack-tip opening displacements and those from literature are partly due to approximations in equations (2) and (3).

Table 1 –Critical elastic crack-tip opening displacements for various modes

Displacement	Measured by SMVS (mm)	Literature (mm)	Deference (%)
δ_{IC}	0.0100	0.0064	56
δ_{IIC}	0.0100	0.0062	61
δ_{IIIC}	0.1700	Not available	-

B

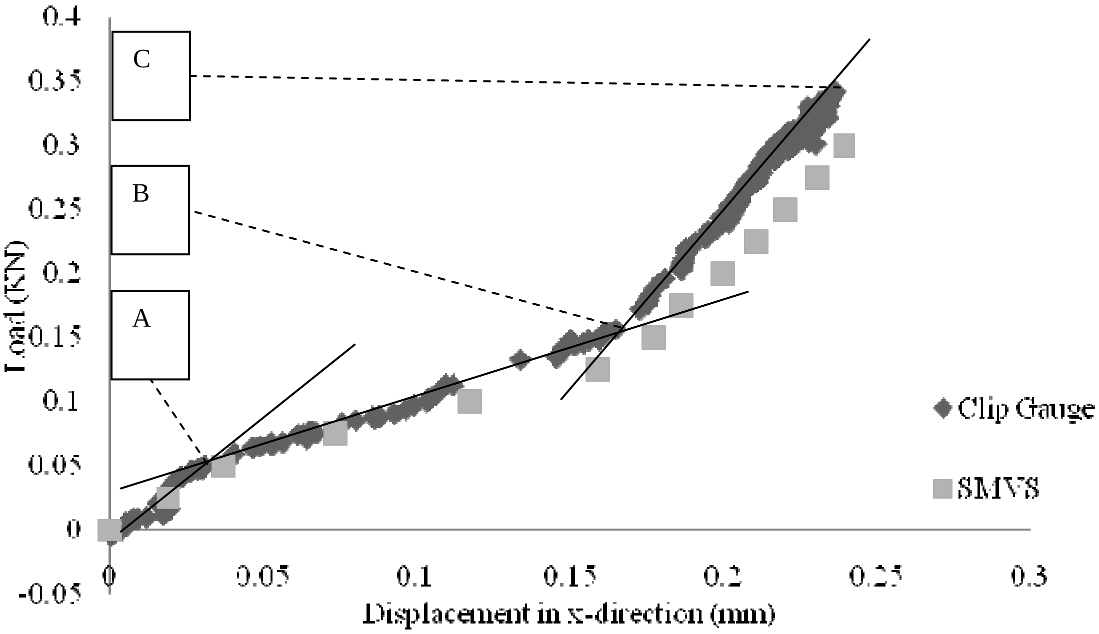

Figure 10 - Load versus displacement in x-direction for 4 mm thick PMMA specimen when the load is applied along the direction defined by θ=45˚ and $\emptyset$=15˚ -Mode I component; see also Figure 9.

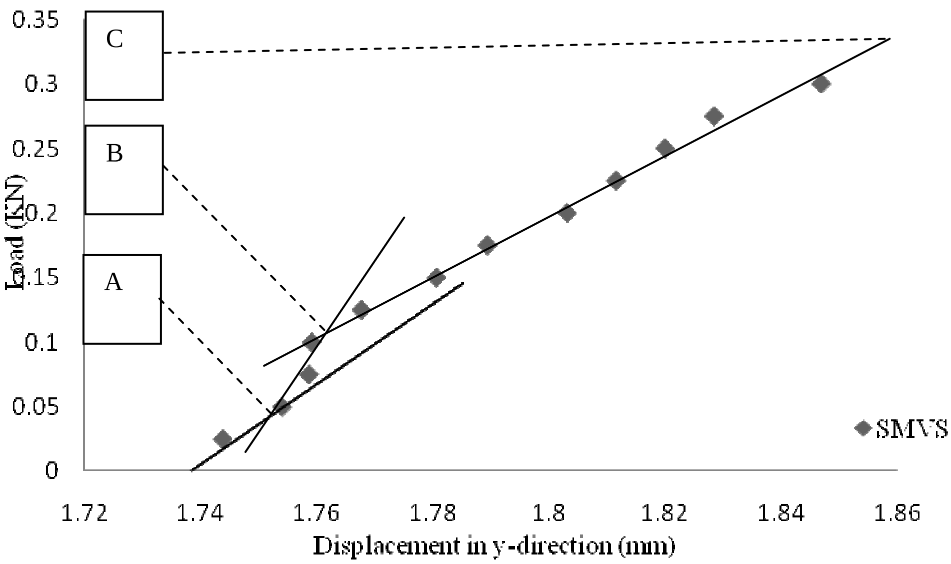

Figure 11- Load versus displacement in y-direction for 4 mm thick PMMA specimen when the load is applied along the direction with θ=45˚ and $\emptyset$=15˚ (1.74mm is taken as origin)- Mode II component; see also Figure 9.

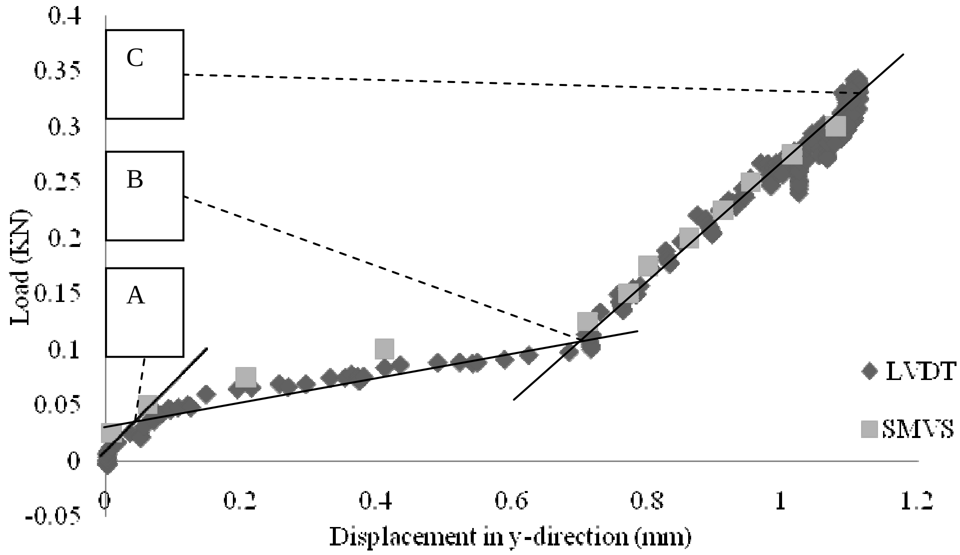

Figure 12 - Load versus displacement in z-direction for 4 mm thick PMMA specimen when the load is applied along the direction with θ=45˚ and $\emptyset$=15˚ - Mode III component; see also Figure 9.

Conclusion

A Stereo Machine Vision System (SMVS) has been described that allows three-dimensional displacement measurement in a non-contact manner. SMVS includes an automatic and pragmatic calibration algorithm and procedure that is used to determine intrinsic and extrinsic parameters of the cameras.

The developed SMVS has then been applied to study fracture of the plate specimens containing an edge crack made of PMMA under complex mixed modes I, II and III loading. In order to apply the required complex loading using an universal testing machine such as the INSTRON Digital 8504 Servo Hydraulic Machine innovating pair of grips have been designed, manufactured and used to conduct the mixed modes I/II/III fracture testing.

The results show that the critical crack-tip opening displacement at the fracture load in the in-plane and out-of-plane directions can be measured with errors in order of 11%.

References

[1] David A. Forsyth and Jean Ponce, Computer Vision: A Modern Approach, Prentice Hall, 2003.

[2] Janne Koljonen, Jarmo T. Alander. *Deformation image generation for testing a strain measurement algorithm*. Optical Engineering 47_10_, 107202 _October 2008_

University of Vaasa, Department of Electrical Engineering and Automation

[3] A. Azerbayejani, B. Horowitz and A. Pentland, ``Recursive estimation of structure from motion using relative orientation constraints'', *Proceedings of the International Conference of Computer Vision and Pattern Recognition*, IEEE Computer Society Press, pp.294-299, June 1993.

[4] Z. Zhang. Flexible Camera Calibration By Viewing a Plane From Unknown Orientations. International Conference on Computer Vision (ICCV'99), Corfu, Greece, pages 666-673, September, 1999.

[5] Z. Zhang. A Flexible New Technique for Camera Calibration. IEEE Transactions on Pattern Analysis and Machine Intelligence, 22(11):1330-1334, 2000.

[6] H. Longuet-Higgins, ``A computer algorithm for reconstructing a scene from two projections'', *Nature*, 293:133-135, 1981.

[7] R. Tsai and T. Huang, ``Uniqueness and Estimation of Three-Dimensional Motion Parameters of Rigid Objects with Curved Surfaces'', *IEEE transactions on Pattern Analysis and Machine Intelligence*, vol.6, pp.13-27, Jan. 1984.

[8] O. Faugeras and S. Maybank, ``Motion from point matches: multiplicity of solutions'', International Journal of Computer Vision, 4(3):225-246, June 1990.

[9] N. Cui, J. Weng and P. Cohen, ``Extended Structure and Motion Analysis from Monocular Image Sequences'', *Proc. International Conference on Computer Vision*, pp. 222-229, Osaka, Japan, 1990.

[10] M. Spetsakis and J. Aloimonos, ``Structure from motion using line correspondences'', *International Journal of Computer Vision*, 4(3):171-183, 1990.

[11] R. Szeliski and S. B. Kang, ``Recovering 3D shape and motion from image streams using non-linear least-squares'', Journal of Visual Communication and Image Representation, 5(1):10-28, March 1994.

[12] A. Shashua, ``Omni-Rig Sensors: What Can be Done With a Non-Rigid Vision Platform?'' Proc. of the Workshop on Applications of Computer Vision (WACV), Princeton, Oct. 1998.

[13] Open Source Computer Vision Library: http://www.intel.com/technology/computing/opencv/index.htm.

[14] Q.-T. Luong and O. Faugeras, ªSelf-Calibration of a Moving Camera from Point Correspondences and Fundamental Matrices,ª Int'l J. Computer Vision, vol. 22, no. 3, pp. 261-289, 1997.

[15] Knott, D.Bhattacharjee D.B.a.J.F., Effect of mixed-mode I and II loading on the fracture surface of polymethyl mthacrylate (PMMA).. Int. J.Fract. , (1995) **72**: p. pp 359-381

[16] Ma , F., Deng, X., Sutton, M.A. and Newman Jr, J.C.*, A CTOD based mixed mode fracture criterion. . Mixed Mode Crack Behavior,* 1998: p. pp. 86-110.