Feasibility Study of a Motion Capture Based, Moveable Three-Dimensional Digital Image Correlation System

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This paper discusses the development of a cost-effective and portable three-dimensional Digital Image Correlation (3D DIC) system optimized for larger specimen deformation and analysis. Traditional 3D DIC systems face limitations in scalability due to calibration constraints and sensitivity and can be expensive. A novel dual-camera mount was designed, manufactured and tested to address these issues, allowing for simplified calibration and enhanced data accuracy by allowing for increased control over the angle between the cameras and their position relative to the specimen using motion capture technology. Initial results using a MATLAB-based DIC analysis framework demonstrated improved accuracy in image mapping, despite challenges with initial designs of the camera mount which followed more traditional designs where camera angles are set for each individual camera, leading to increased chances of poor calibration. Results are compared against the pre-calibrated VIC 3-D software developed by Correlated Solutions for comparison and validation, aiming to achieve accuracy within acceptable error margins for industrial applications. This paper will also show the improvements made to the system throughout testing, including upgrades to the camera mount to improve stability and optimizations to the software to improve data analysis. The system outlined within this paper has the potential to allow users to move and scan around a larger specimen due to the camera mount that was designed and experimentation that determined optimum distances and angles for data collection. This potential to move the 3D DIC system without needing to calibrate the system after each movement sets it apart from the VIC 3-D software that while more accurate after an initial calibration becomes virtually unusable after even the slightest adjustment is made to the camera position. The future potential of an easily moveable 3D DIC system will also be discussed within this paper.

I. Nomenclature

3D DIC	=	Three-Dimensional Digital Image Correlation
DCM	=	Dual Camera Mount
MATLAB	=	Matrix Laboratory software
ROI	=	Region of Interest
VIC 3-D	=	Three-Dimensional Digital Image Correlation software

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II. Introduction

Three-dimensional Digital Image Correlation (3D DIC) systems utilize two cameras to gather deformation data from different points of view and construct a three-dimensional model of the deformation. 3D DIC systems are powerful tools in structural analysis, but they are time consuming to accurately calibrate before data can be collected and require recalibration if the cameras or the specimen move. The limitations of currently available systems make it difficult to use them to analyze larger specimens, which is what the system being presented in this paper aims to target.

There have been many studies conducted to try to address the limitations of the 3D DIC systems available. Several of these were looked at as this system was being developed. One study utilized innovative methods to conduct an experiment using a 3D DIC system to analyze the displacement and strain of damaged areas on a large composite turbine blade [1]. This study used a 9-meter-long specimen which, with the 3D DIC system being used, was too large to capture the entire surface at once. Instead, the research team mobilized their cameras along an overhead gantry that was able to move along the length of the specimen and collect images of the loaded and unloaded state at sixteen locations along the blade. Each of these images was analyzed individually and then stitched together digitally. While this approach yielded positive results for the deformation data of a very large specimen it required a highly specialized setup and extensive calibration and post-processing. This method is costly, time consuming and likely unfeasible for most projects. A second study from the Civil Engineering Laboratory of Southeast University (China) shows where 3D DIC was used to analyze deformations caused by a simulated earthquake on a model high-rise building [2]. The model was 7-meters tall and to capture the entire structure the cameras were placed to capture the top and bottom with some overlap in the middle. The cameras used were also high-speed to be able to capture as many images as possible as the structure was being shaken. To account for the overlap and improve the accuracy of the data, similar to the previously mentioned study, extensive post-processing was done to ensure accurate results from the complex set-up.

To combat the issues with using 3D DIC for large-scale structural analysis of complex experimental set-ups and extensive post-processing to get around the limitations of currently available 3D DIC systems, a new approach is proposed. The novel system developed in this paper proposes a Dual Camera Mount (DCM) that makes the cameras move dependently to each other about a fixed rotation point instead of moving independently of each other which is a cause of calibration error in current systems and allows for the system to be more easily moved around a specimen without the need for recalibration each time. This approach provides a low-cost, easy-to-use system that does not require complex or expensive machinery as it uses 3D printed parts and easy to acquire store-bought digital cameras. This system is easy to replicate and scale to the structure that needs to be analyzed. For this study, a smaller specimen was used for testing. The system runs off of script written in MATLAB and as such does not require highly specialized software like VIC 3-D made by Correlated Solutions which was used to compare and validate the data acquired by the system

III. Methods

A. Equipment

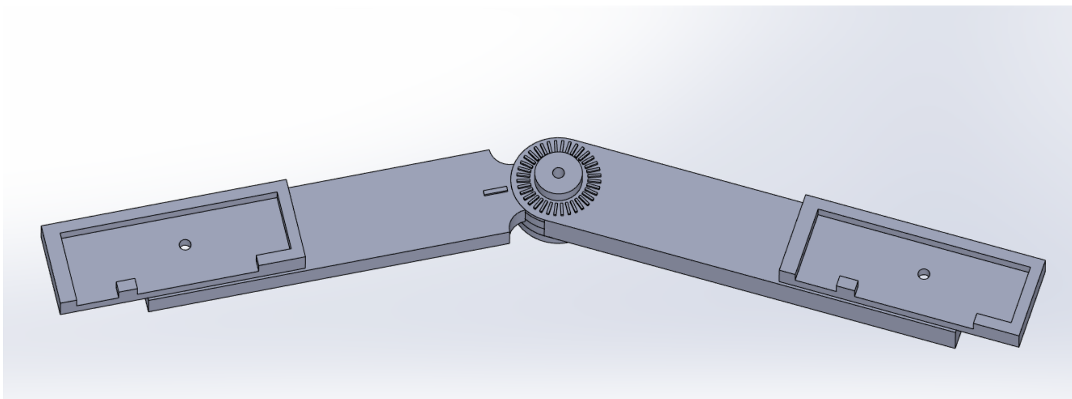
The equipment utilized for experimental procedures and data collection for the testing of the dual camera mount 3D DIC system includes the following:

1. 12 camera Optitrack motion capture system and bay provided by Autonomous System Research Laboratory (ASRL) within the Raspet Flight Research Laboratory at Mississippi State University
2. 2 Canon EOS M6 Mark II Cameras
3. Carbon fiber test specimens
4. Test specimen deformation frame
5. Camera tripod
6. Dual Camera Mounting (DCM) system
7. Calibration board

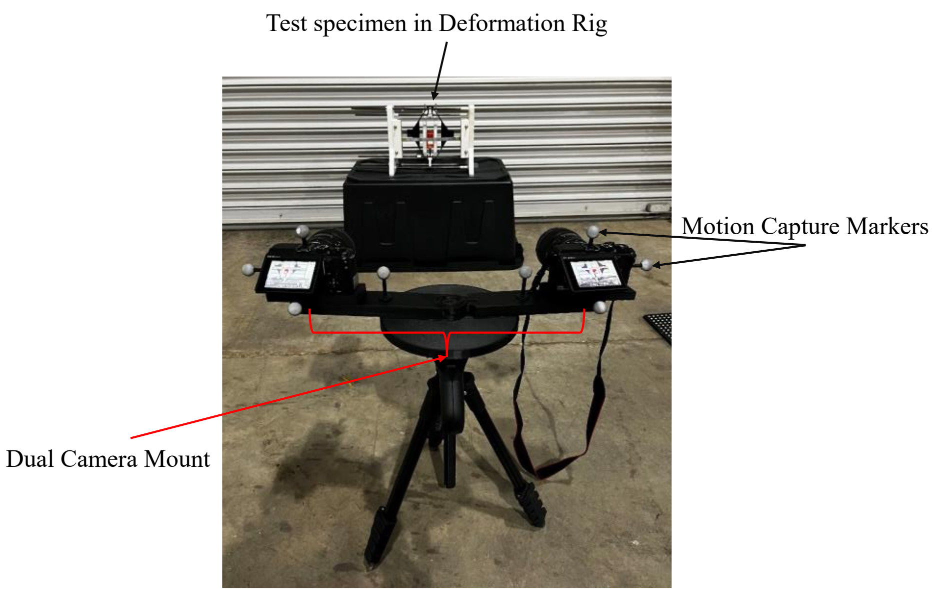
The choice of our camera equipment was vital to the quality of the data being collected. The Canon EOS M6 Mark II cameras being used have a 32.5 MP APS-C CMOS sensor and DIGIC 8 processor, providing high-resolution images. These sensors on the cameras allow for the images to have high pixel counts which reduces the information loss due to digital magnification, allowing specimen photos to be acquired from a further distance and the post-processing code to extract more data from each image, increasing the accuracy of the results. Another essential piece of equipment for the DIC system itself was a strong camera tripod to increase camera stability and support to prevent drift and blurriness of images caused by natural vibrations.

B. Set-up Overview

Before data collection could begin the motion capture cameras had to be calibrated by going through a process of providing sample calibration points and a reference ground plane. The motion capture bay was used to generate position data for the cameras, which had been tagged with reflective motion capture markers, initially while the camera mounting system was being developed. The position data was then used to ensure the cameras were pointed at the specimen and the angle between them could be found. The setup can be seen in Fig. 1 below.



(a)



(b)

Figure 1. Camera Mounting Set-up (a) 3D CAD model. (b) Physical testing set-up

Before the specimen could be deformed, a series of calibration images were taken using a flat panel with a grid of points in various positions as the target. Both cameras were triggered simultaneously to ensure consistency in data collection. The calibration panel used can be seen in Fig. 2. These calibration images were taken to be used with VIC 3-D as it cannot perform post-processing without calibration images. VIC 3-D uses these calibration images to determine the properties of the cameras such as: distance between cameras, angle between cameras, field of view, angle to specimen and focal length.

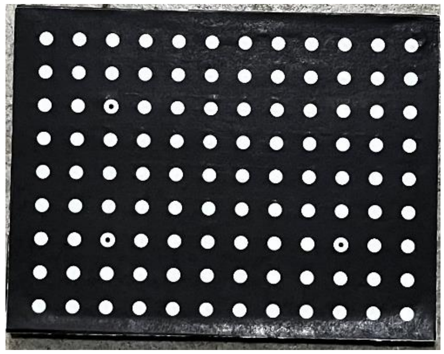


Figure 2. Calibration Panel for VIC 3-D

Once the calibration images for VIC 3-D have been taken, deformation images can be taken. In the same way the calibration images were captured, both cameras were triggered simultaneously remotely of the specimen within the test frame as seen in Fig. 1. Testing starts with the specimen undeformed and with each subsequent set of images captured, the deformation is increased steadily until noticeable deformation occurs at which point the last set of pictures is taken and the specimen is unloaded and allowed to return to its original form. Once testing has concluded, the photos are taken from the camera and uploaded to a computer for post-processing which will be discussed in the results section of this paper.

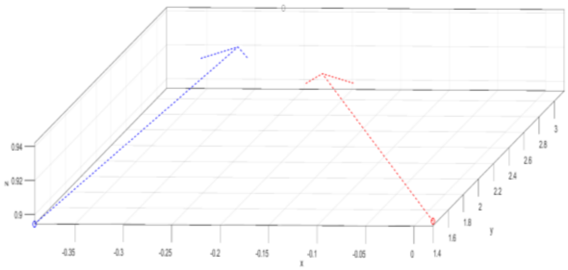
C. Evolution of Set-up

The aforementioned method coincides with the original set-up of the system; however, through experimentation, the set-up has evolved into what was just described. Originally, the two cameras were mounted on separate tripods and angled toward the specimen. This was when the motion capture system was heavily involved, ensuring that the cameras were aligned and pointing at the specimen at calculated angles. This mimicked the calibration panel images used for VIC 3-D. Over time, it was decided to improve the accuracy of the system and minimize errors caused by positioning, the cameras should be mounted onto a single tripod. This became the Dual Camera Mount (DCM) seen in Fig. 1 mounted on the tripod. The DCM allows for control over the angle and distance between the two cameras as well as ensures camera stability during data collection. The control over the angle the DCM provides allows for the creation of a fixed focal point between the two cameras that is easily determined at a fixed distance. This allows for the DCM to be moved as a whole at this fixed distance around a specimen and gather images without the need for retaking calibration images or recalibrating position using the motion capture system. The DCM allows for the post-processing code that has been written to accurately map deformation within an acceptable margin of error when compared to an industry-standard system like VIC 3-D without the need for constant calibration with any minor change in the testing environment.

IV. Results

A. MATLAB Post-Processing

As mentioned during the set-up overview, the motion capture camera system was used to generate position data that can be used to test the camera alignment which was necessary during testing prior to the implementation of the DCM. The position data and camera alignment analysis was done in MATLAB and was the first step optimizing using MATLAB to perform 3D DIC calculations and analysis. The direction vectors that show camera alignment between each other and to the target point of the specimen can be seen below in Fig. 3.



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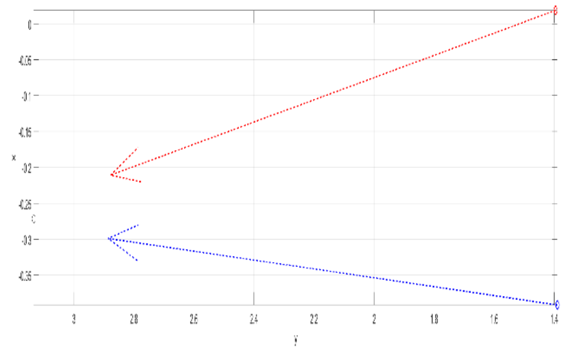

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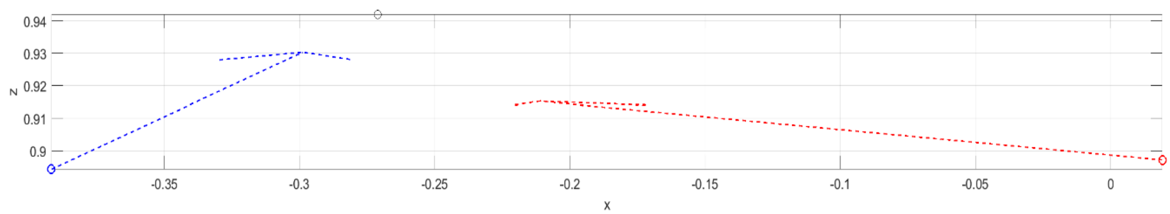


(c)

Figure 3. Camera direction from motion capture data (a) 3D positioning vectors. (b) XY positioning data. (c) XZ positioning data

MATLAB was then used to process all of the images taken during deformation. The right and left images corresponding to their respective camera were uploaded to MATLAB. Utilizing the image processing toolboxes, a region of interest (ROI) was then selected on the first left image, Fig. 4, and then the DIC took place. Data points within the ROI were overlayed on each left and right image across the increasingly deformed specimen. A 3D scatterplot was then generated using these points to show the specimen before compression and at the maximum compression tested, which can be seen in Fig. 5.

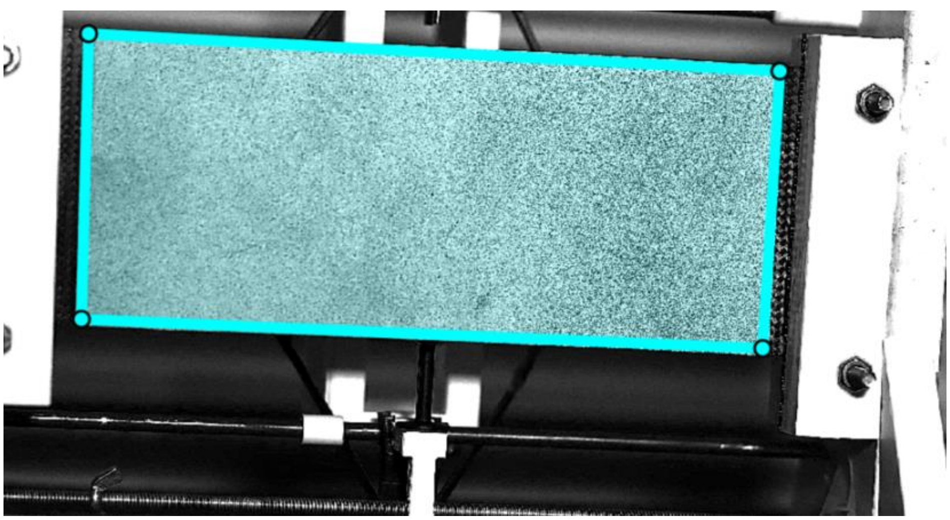


Figure 4. Selected region to use for DIC

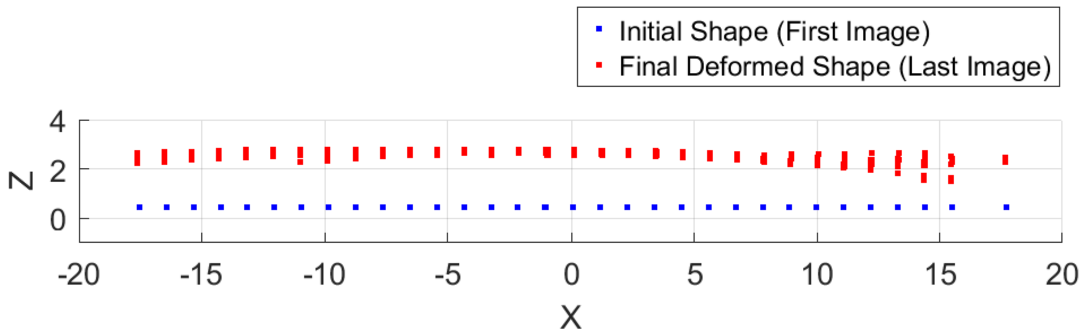
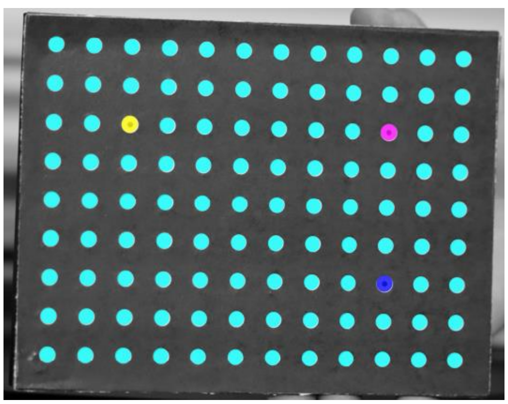


Figure 5. Initial and deformed specimen from MATLAB

B. VIC 3-D Post-Processing

In order to validate the post-processing being done using MATLAB, a known and widely used industry and research software was also used to post-process the data collected during experimentation. This software was VIC 3-D by Correlated Solutions. VIC 3-D as mentioned earlier requires calibration images to calculate camera properties and orientation. This calibration takes time to ensure accurate calculations by the software. As shown in Fig. 6a and 6b, this is what VIC 3-D sees when fed good calibration points, all the dots highlighted in color and what the calibration data looks like when VIC 3-D overlays it onto the test images.



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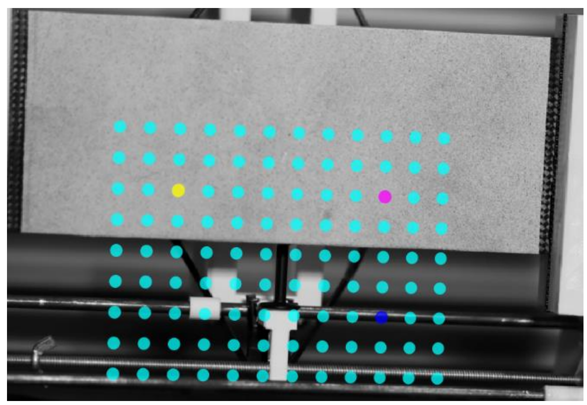
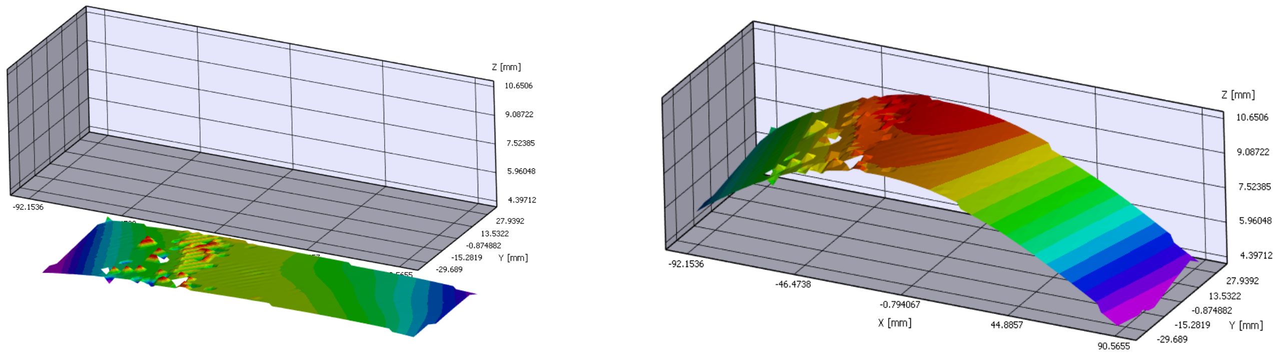


(b)

Figure 6. Calibration process. (a) Highlighted calibration panel. (b) Calibration data on specimen

Once calibration has been completed, VIC 3-D then analyzes the test images that were also given to MATLAB. The result of this post-processing is an extremely accurate 3D model that shows the deformation between each image. The images that MATLAB used to create Fig 5 were used by VIC 3-D to create Fig. 7a and 7b which show the initial and deformed states of the test specimen.



(a) (b)

Figure 7. VIC 3-D deformation data. (a) Initial specimen. (b) Deformed specimen

As can be seen in Fig. 7a and 7b, VIC 3-D had some issues with the initial state of the specimen. Some of these issues were likely a result of poor specimen speckling which VIC 3-D uses to create the points that it tracks across the images. These are the non-smooth sections of the models created. That being said, VIC 3-D shows the full range of the deformation of the specimen clearly in three-dimensions. Aside from the visual non-smoothness of the model in the above figures, the biggest shortcoming of VIC 3-D is that if anything changes in the camera or specimen positioning, recalibration has to reoccur, or data generated will have significant errors within it. Another issue with VIC 3-D is its extreme dependency on quality speckling, or the painting of a random pattern of black dots on a white background, as mentioned earlier. It leads not only to distortions in the surface of the model but also to errors in the selection of the analysis area. The same ROI was selected in VIC as was selected in MATLAB; however, as can be seen in Fig. 8, VIC 3-D only performed analysis on a smaller region as that was where it had the highest quality points to look at and it disregarded the rest of the specimen.

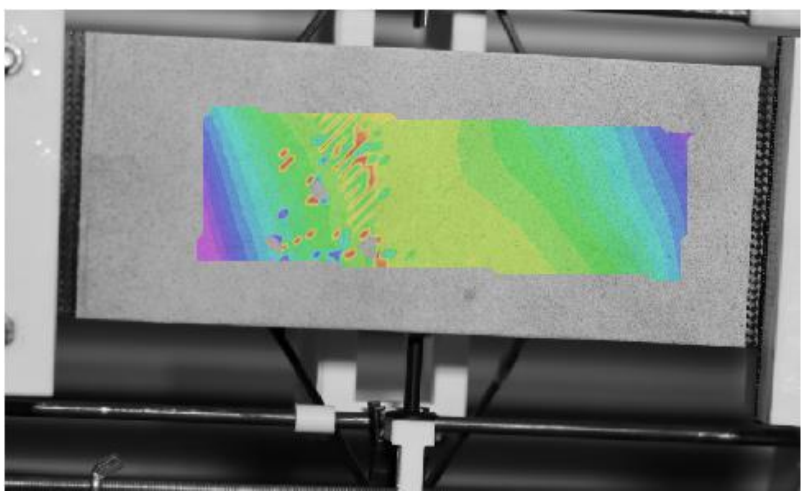
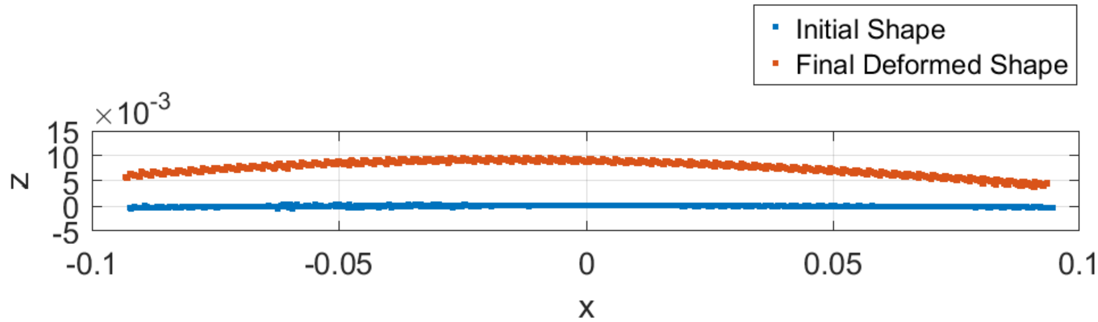


Figure 8. VIC 3-D analysis area error

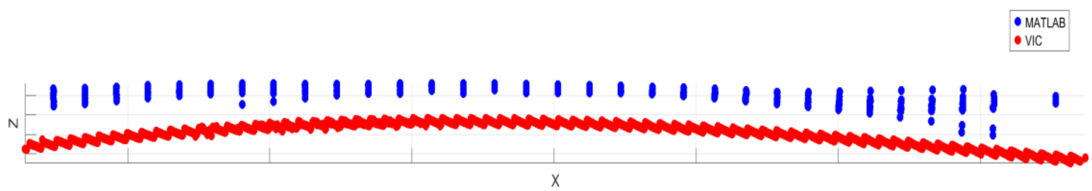
C. Comparison and Validation of MATLAB Model

MATLAB handled the data well throughout the experiments. The time required to process the data mainly depended on the size of the ROI and the amount of data points selected to be within the ROI. The VIC 3-D software was much faster when processing the images and returning results, but the prep work required to use VIC 3-D took a lot of time. Calibration images have to be taken to use VIC 3-D, and the results obtained from the software depend on the calibration score. There are many variables that can affect the calibration like the lighting, position of the calibration board in frame, the focus of the cameras on the board, and the type and size of the calibration board used. MATLAB does not require a calibration of any kind to run the DIC code. This saves a lot of time and reduces the potential for error within the results. This is not to mention the cost difference between a license for MATLAB that includes the necessary toolboxes and a license to obtain and utilize VIC 3-D with the former being drastically most purchasable.

To obtain accurate results using MATLAB, a lot of data points need to be chosen, and this can take a long time to run even with a fair amount of computing power allocated to the task. With less data points, the runtime is less, but MATLAB needs enough points to clearly define the ROI. This can lead to potential noise in the data where the data points are randomly scattered out of the ROI. With enough data points, however, the results obtained with MATLAB are comparable to VIC 3-D. The results from VIC 3-D were exported and run through the same code that the data points generated using MATLAB to compare the validity of the DIC MATLAB code. These results can be seen in Fig. 9.



(a)



(b)

Figure 9. Deformation shapes. (a) Initial and Deformed specimen using data points from VIC 3-D. (b) Comparison of data points from MATLAB DIC and VIC 3-D

When compared to the results in Fig. 9a, the results obtained using the MATLAB DIC code that are shown in Fig. 5 show the same deformation shape albeit with few data points due to computing limitations. This comparison can be seen in Fig. 9b and as can be seen in the figure, the MATLAB DIC captures an extremely similar deformation pattern as VIC 3-D. Given a powerful enough computer, the MATLAB script performing DIC is capable of generating more data points to even closer match the data points VIC 3-D generates when it post-processes images for DIC. The error between the system run on MATLAB is within an acceptable margin at this stage in this project.

V. Conclusion

The system developed as a result of the research outlined in this paper has shown that a moveable 3D DIC system is possible to create, and it does not have to be even more expensive than current available 3D systems and custom made. One can be designed that has the potential as it is refined as this project continues to be able to reduce the error gap between it and industry standard software like VIC 3-D. Going forward, this project aims to reduce the error gap in the near term while in the long term, further improvements are being looked into for the DCM to allow for attachment to a more mobile platform for larger scale specimens to be examined. To help to reduce the gap between the MATLAB DIC and software like VIC 3-D, improved computing is being examined as a possible solution to be able to handle more data points and be able to handle larger and more complex specimens. In the near- and long-term future, this project has several paths that will/can be explored to further improve the system and expand the capabilities of 3D DIC systems everywhere.

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