

**DIGITAL IMAGE RECTIFICATION
TOOL FOR METRIFICATION OF
GUSSET PLATE CONNECTIONS IN
STEEL TRUSS BRIDGES**

Final Report

**DIGITAL IMAGE RECTIFICATION TOOL FOR
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STEEL TRUSS BRIDGES**

Final Report

by

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Washington, DC 20590-0003

March 2009

1. Report No. FHWA-OR-RD-09-15	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Digital Image Rectification Tool for Metrification of Gusset Plate Connections in Steel Truss Bridges		5. Report Date March 2009	
		6. Performing Organization Code	
7. Author(s) Christopher Higgins, and Quang D. Nguyen Oregon State University Corvallis, OR 97331		8. Performing Organization Report No.	
9. Performing Organization Name and Address Oregon Department of Transportation Bridge Engineering Section 355 Capitol St NE, Rm. 301 Salem, OR 97301-3871		10. Work Unit No. (TRAVIS)	
		11. Contract or Grant No.	
12. Sponsoring Agency Names and Addresses Oregon Department of Transportation Bridge Engineering Section 355 Capitol St NE, Rm. 301 Salem, OR 97301-3871 Federal Highway Administration 400 Seventh Street, SW Washington, DC 20590-0003		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes			
16. Abstract A method was developed to obtain dimensional data from photographs for analyzing steel truss gusset plate connections. The method relies on a software application to correct photographic distortion and to scale the photographs for analysis. The approach enables rapid and accurate collection of dimensional measurements compared to traditional methods. Users can quickly create AutoCAD drawings by collecting dimensional information about the gusset plates from the photographs. The rectified photographs provide a record of field conditions that can be compared with subsequent field inspection results to help identify and quantify long term changes in visual characteristics. The implementation procedure is straightforward and does not require specialized knowledge of photogrammetry. It can be practically employed under field conditions using current technology and personnel, and it reduces the likelihood of data entry errors. Dimensional measurements from the method provide results that are as good conventional field measurements and are within tolerances that most engineers would find reasonable for gusset plate connection capacity evaluations.			
17. Key Words gusset, truss, bridge, steel, connection, rating, analysis, photograph, inspection, dimension, measurement		18. Distribution Statement Copies available from NTIS, and online at http://www.oregon.gov/ODOT/TD/TP_RES/	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 47	22. Price

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
<u>LENGTH</u>				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
<u>AREA</u>				
in ²	square inches	645.2	millimeters squared	mm ²
ft ²	square feet	0.093	meters squared	m ²
yd ²	square yards	0.836	meters squared	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	kilometers squared	km ²
<u>VOLUME</u>				
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	meters cubed	m ³
yd ³	cubic yards	0.765	meters cubed	m ³
NOTE: Volumes greater than 1000 L shall be shown in m ³ .				
<u>MASS</u>				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
<u>TEMPERATURE (exact)</u>				
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
<u>LENGTH</u>				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
<u>AREA</u>				
mm ²	millimeters squared	0.0016	square inches	in ²
m ²	meters squared	10.764	square feet	ft ²
m ²	meters squared	1.196	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	kilometers squared	0.386	square miles	mi ²
<u>VOLUME</u>				
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	meters cubed	35.315	cubic feet	ft ³
m ³	meters cubed	1.308	cubic yards	yd ³
<u>MASS</u>				
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
<u>TEMPERATURE (exact)</u>				
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

ACKNOWLEDGEMENTS

This research was funded by the Oregon Department of Transportation as part of a study to evaluate steel truss gusset plate connections. The research was coordinated by Mr. Steven Soltesz of the ODOT Research Unit. The authors would like to thank Mr. Jason Killian of the O.H. Hinsdale Wave Research Laboratory for an initial sample of the MATLAB rectification script.

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1.0 INTRODUCTION

Steel deck truss and gusset plate connection performance has become an important topic after the recent collapse of the I-35W Bridge in Minneapolis, Minnesota. Due to this failure, steel truss bridges will likely require additional structural evaluation of the gusset plate connections in addition to conventional member evaluations. Connection evaluations will require complete and accurate as-built drawing sets and condition reports and these will need to be maintained into the future to monitor and evaluate changes over the life of the structure.

The Federal Highway Administration lists approximately 37 steel deck truss bridges and 191 other types of truss bridges within Oregon in the National Bridge Inventory (*NTSB Recommendations 2008*). Larger numbers are found nationally and this large inventory of bridges will require significant resources to conduct connection evaluations. Tools that can aid in effective means of field data collection to provide analysis inputs will hasten the complex and time consuming task of steel truss bridge evaluation. The principal purpose of the present study are to develop methods to rectify orthographic digital photographs (orthophotos) of steel truss bridge gusset plate connections so as to extract physical dimensions that can be used for comparison with available drawing details and to provide reliable geometric information about the in-situ connections to facilitate load-rating evaluations.

2.0 BACKGROUND

Digital close-range photogrammetry has been used previously for historic architecture documentation and bridge inspections (*Heuvel 1998; Criminisi 2000*). These studies deployed setups that required at least two images to obtain structural dimensional information in three-dimensions (3D). This required a large number of control points to correlate the images. The data obtained was used to create computer models from the images. Methodologies for the use of single images have also been used to obtain both two-dimensional (2D) and 3D geometry from images when applying constraints such as straight lines and vanishing points.

Close-range digital photogrammetry has been shown to be suitable for structural surveying and laser scanning also has the potential for use (*Mills and Barber 2004*). This research demonstrated techniques for a survey of Hastings Tower, which is part of Ashby Castle, located in Birmingham, U.K. . The case study was conducted using a Leica TRCA1003 for terrestrial surveying, a Riegl LMS Z210 for laser scanning, a Kodak DCS660 digital camera for multi-station convergent photogrammetry, and a Wild P32 metric camera for stereo photogrammetry. The study showed that the digital multi-station convergent photogrammetry produced results of higher precision and accuracy than conventional stereo photogrammetry. Proper planning and location were important to obtaining accurate measurements with each of these methodologies.

Low-cost digital cameras have shown the potential for use in close-range digital photogrammetric measurements after lens calibrations are performed (*Chandler et al. 2005*). An experimental test model constructed out of medium density fiberboard, and a reference digital elevation model (DEM) of the experimental test model was generated using a Leica TC1010 total station, a Kodak DCS460 camera, and IMAGINE OrthoBase Pro imaging software. Three low-cost digital cameras were calibrated using an external calibration method and the OrthoBase Calibration software. Images taken from the low-cost digital cameras generated digital elevation models that were compared to the reference DEM. The results showed that the low-cost digital cameras generated DEMs close to the true DEM. Proper lens calibration improved the accuracy of the results.

Close-range photogrammetry techniques have been shown to provide a simple and cost effective approach to historical building documentation (*Arias et al. 2004*). A case study involved traditional agro-industrial building models taken from multi-station setup of 2 plumb lines, 24 camera positions and 27 control points. The data was input into Photomodeler Pro 4.0 and obtained a root-mean-square error of 9 mm for the model.

Jáuregui et al. (2006) evaluated the use of close-range photogrammetry to provide dimensions of two case study bridges. A multi-station setup of large grid of targets, scale bars, and camera stations was used to provide control points in 3D. The models used Photomodeler and AutoCAD. Errors between photogrammetric values and hand measurements had a maximum of 1.43%.

Metrification of flat elements on buildings has been performed by Tommaselli et al. (2005) to demonstrate the capability of taking three digital photographs and distance measurements from a mounted position of a flat element and obtaining the dimensions. This was done by finding the position of the camera relative to the flat element. Rodríguez et al. (2008) studied the use of single images to determine the dimension of a billboard using a mathematical model. The linear, horizontal and vertical lines on the billboard were used to create a rotation matrix from an indirect method by applying constraints based on geometric relationships. The point coordinates were then determined by inverse collinearity equations.

While past studies have demonstrated the technique of close-range photogrammetry for metrification of elements, this study differs from previous research because, for the present case of evaluation of truss bridges, photographs cannot easily be taken from a mounted stationary position. In the field, photographs of bridge gusset plates will likely be taken from a snooper with both the snooper and bridge in motion from wind and traffic, or by climbing on the structure, thus it will not be feasible to obtain stationary positions to correlate stereo or multi-station images. To rapidly setup and collect dimensional data of gusset plates, the present study established control points with a reusable magnetic reference target placed on the gusset plate. An image rectification and metrification methodology was developed and implemented in a software program to allow a non-specialized user to process the captured images and collect the data necessary for engineering evaluations of steel gusset connections. This technique significantly reduces the amount of time needed in the field to acquire dimensional data and the resulting fidelity is as good as or better than manually collected and recorded data. The developed software program allows output of rectified images and user selected image coordinates so that a CAD drawing can be directly created. As a result of this methodology, only the thickness of the gusset plates and a single reference dimension need to be directly measured in the field to enable gusset plate strength evaluations.

3.0 METHODOLOGY

Photographs are taken of a real world image and placed on a two-dimensional image plane. When an image is captured with a camera and lens, it generally contains perspective distortion (parallel lines converging at a finite point), as well as other distortions due to the lens characteristics (such as barrel distortion or pin-cushion). To remove perspective, the image can be rectified using a mathematical transformation which maps elements in the real world image to those in the photographic image plane. To remove barrel distortion or pin-cushion, either flat field lenses must be deployed or lens correction parameters can be used to post-process images. For the present case, barrel distortion and pin-cushion are minimized by using lenses that minimize these distortions.

When the salient features of the real world image correspond generally to a single plane, as is the present case for gusset plate connections, two-dimensional correspondences can be used to rectify the image, which simplifies the transformation. One of the most common techniques for image rectification is the direct linear transformation (DLT) algorithm. This transformation requires that certain geometrical characteristics be established between in the real world image and the image plane so that the image can be rectified. For the present case, point correspondences are used to map points between the real world image and the photographic image plane based on central projection shown in Figure 3.1. Central projection maps the common points between planes and preserves lines in both planes.

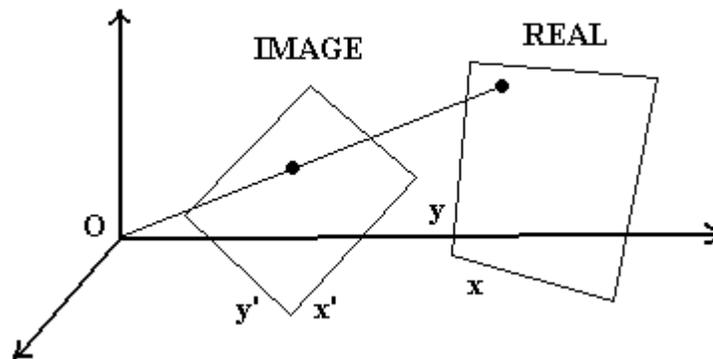


Figure 3.1: Central projection showing image and real planes.

When the geometrical features are established so as to provide a true dimensional scale, the resulting transformation will not only be rectified, it is scaled to the real world dimensions, which allows metrification from the rectified image. For implementation of the DLT algorithm, the image plane and real world planes are assumed to be homogeneous. A transformation

matrix, \mathbf{H} , is determined to satisfy the following equation (Equation 3.1) for each control point, i :

$$\mathbf{H} \begin{bmatrix} X_i' \\ Y_i' \\ 1 \end{bmatrix} = \begin{bmatrix} X_i \\ Y_i \\ 1 \end{bmatrix} \quad \text{(Equation 3.1)}$$

In the equation X' and Y' are photograph image plane control point coordinates, X and Y are real world control point coordinates, and \mathbf{H} is a 3x3 matrix. To solve for the transformation matrix \mathbf{H} , a minimum of four control points are needed (x and y coordinates each provide a degree-of-freedom (DOF) for a total of eight DOFs and one more is provided by scale, thereby providing nine DOFs to solve for the matrix). If more points are available, error estimations can be made, as described subsequently. The method generates a two-dimensional transformation based solely on the control point coordinates, thus, camera parameters are not needed. Such DLT algorithms are used in commercial photogrammetric software such as IMAGINE OrthoBase Pro.

3.1 CONTROL POINTS FOR IMAGE TRANSFORMATION

Implementation of the DLT requires that known control points be established in the real world image that can be captured in the image plane. For the present research, reference targets were developed that can be placed on a gusset plate. These targets establish 9 control points which provide more image constraints than the minimum required to solve for the transformation matrix, thereby enabling error estimation. The control points are ideally spread throughout the image. The reference target control points standoff from the surface of the gusset plate, which is necessary for clearance over bolt and rivet heads, but this standoff distance causes the reference target to appear larger in the photograph than if it were to lie explicitly on the gusset plate surface. The offset can be corrected assuming the camera is a single point and using similar triangles to calculate the apparent size increase of the reference target compared to if it were to lie on the gusset plate surface. The standoff distance for the reference targets used in this study is approximately 2 in. from the gusset plate surface.

The offset correction factor for the reference targets can be calculated, as shown Equation 3.2:

$$Offset = \frac{L}{L - L_o} \quad \text{(Equation 3.2)}$$

In the equation L is the distance from the camera to the gusset plate surface, L_o is the target standoff distance, taken as 2 in. for the present case, as illustrated in Figure 3.2. Using this offset correction factor, the actual dimensions for the gusset plate can be corrected, as shown in Equation 3.3:

$$L_{prt} = \text{Offset}(L_{rt}) \quad \text{(Equation 3.3)}$$

In the equation L_{prt} is the corrected length measurement on the gusset plate and L_{rt} is the apparent length based on image transformation using the control points that standoff from the actual gusset plate surface. Dimensions taken from the rectified image without the above correction will be smaller than the true dimensions. As seen in Figure 3.3, the correction factor becomes small as the camera location moves farther away from the gusset plate. Differences are less than 5% when the camera is more than 5 ft from the gusset plate. Thus, for large camera distances it may not be necessary to correct for the target standoff as the errors will be small and generally conservative in regard to evaluation of available gusset plate strength (except for compression where the apparent unbraced lengths will be shorter than actual without correction).

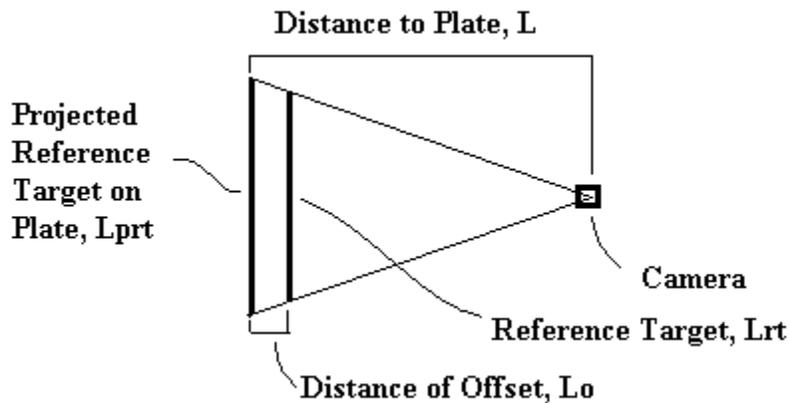


Figure 3.2: Offset correction diagram.

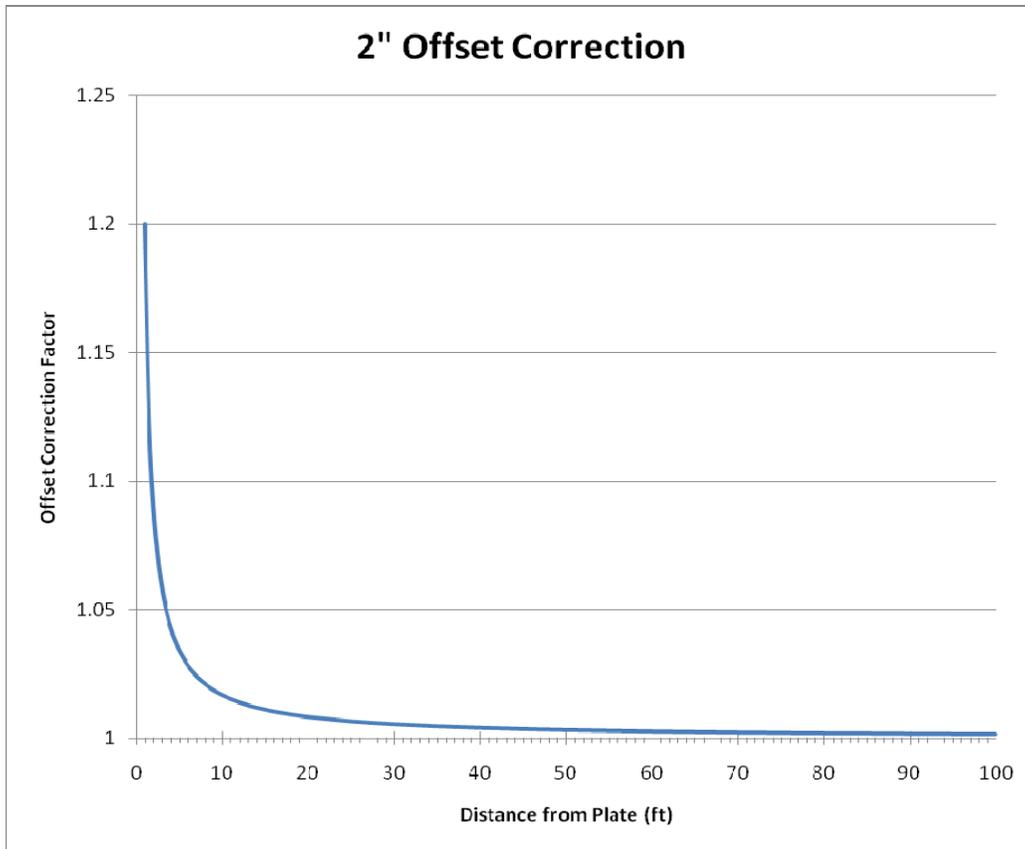


Figure 3.3: Offset correction factor as a function of the camera distance from the gusset plate for a target with 2 in. standoff distance.

To rapidly establish reliable and repeatable control points in the real world image, two reference targets were developed. One is relatively small (8 in. arms) and the other is relatively large (24 in. arms). The small reference target is used for smaller gusset plates or for splice plates between chord members and the large reference target is used for most typical large gusset plate connections. The characteristics of the targets are:

- 8 in. reference target for small gusset plates (Figure 3.4)
- Two $\frac{1}{2}$ x $\frac{1}{2}$ x 8 in. Ultra Corrosion-Resistant Pure Titanium (Grade 2) bars
- Nine 1 in. diameter, 0.2 in. thick aluminum discs that serve as the control points
- One 2-1/32 in. diameter, 5/16 in. thick aluminum encased round ceramic magnet
- One 1 in. diameter 1.5 in. thick aluminum cylinder base
- 24 in. reference target for large gusset plates (Figure 3.5)
- Two $\frac{1}{2}$ x $\frac{1}{2}$ x 24 in. Ultra Corrosion-Resistant Pure Titanium (Grade 2) bars

- Nine 1-½ in. diameter, 0.2 in. thick aluminum discs that serve as the control points
- One 2-5/8 in. diameter, 3/8 in. thick aluminum encased round ceramic magnet
- One 1-½ in. diameter, 1.5 in. thick aluminum cylinder base

The titanium bars are placed in a “+” shape. The nine aluminum discs are equally spaced along the titanium bars. The aluminum cylinder base is bolted along with the ceramic magnet to the center of the “+”. Titanium is used for the arms of the reference target due to the corrosion-resistant properties, high strength-to-weight ratio, and low coefficient of thermal expansion for the material. Aluminum was selected for its lightweight and corrosion resistant properties. The magnetic base allows the reference target to be held securely on the gusset plate surface, even with many layers of paint, to be easily reused, and to leave the gusset plate undamaged.

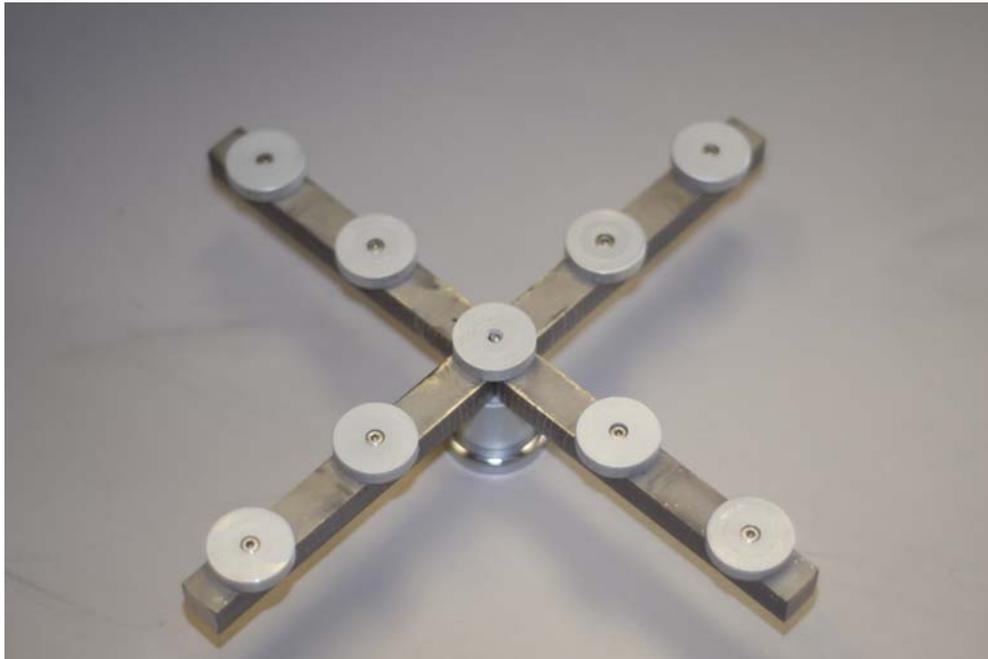


Figure 3.4: 8 in. Reference target

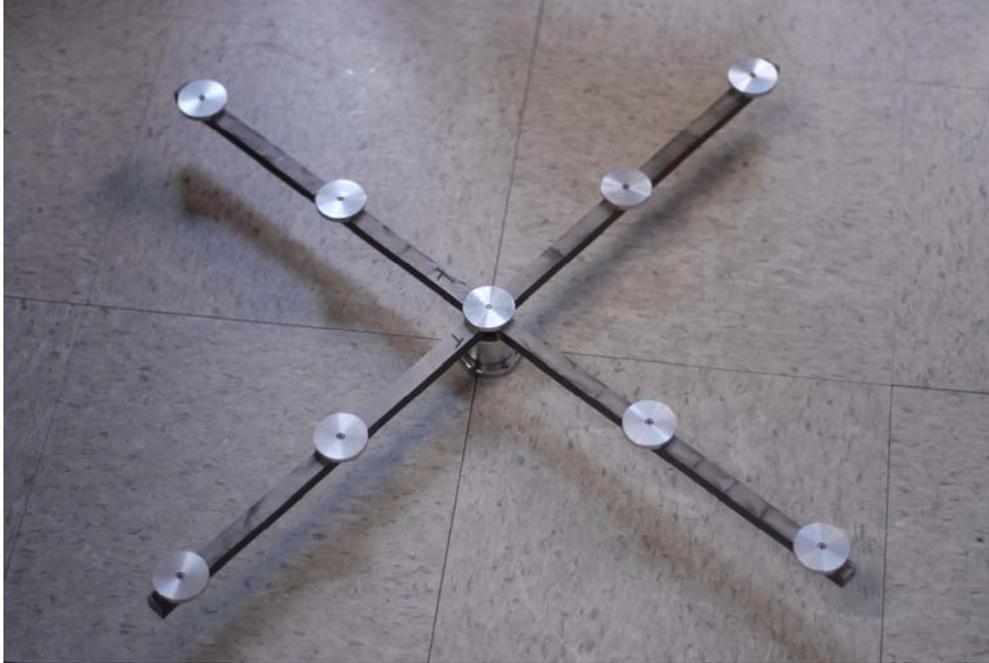


Figure 3.5: 24 in. Reference target

3.2 ERROR ESTIMATION

Errors are introduced in the rectification process by camera and reference target imperfections, movement as the photograph is taken, and during control point selection. The nine control points on the reference targets are used to determine the measurement error in the rectified image and as the sample size for the error calculations. The root-mean-square error (RMSE) and standard deviation error (σ) are obtained from the differences in the predicted coordinate locations calculated from the H-matrix and their true coordinate locations known from accurate physical measurements of the target points a priori, as shown in Equation 3.4 and Equation 3.5.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (\theta_i' - \theta_i)^2} \quad \text{(Equation 3.4)}$$

In the Equation 3.4 θ_i' is the predicted value and θ_i is the true value of the i^{th} control point, and n is the number of control points.

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (e_i - \bar{e})^2} \quad \text{(Equation 3.5)}$$

In Equation 3.5 e_i is the location error of the i^{th} point, \bar{e} is the average location error, and n is the number of control points. These are determined from the nine known control points established using the reference target in the image.

The errors were assumed to be normally distributed and a 99.7% confidence interval for an acceptable uncertainty threshold was selected, which corresponds to three standard deviations. The pixel scale depends on the number of pixels per inch (real scale) on the original digital photograph and calculated based on the smallest number of pixels across the known length between the outermost points on the two target arms. The predicted location uncertainty with 99.7% confidence for a single point in the rectified orthographic image is estimated to be within the sum of the RMSE, three standard deviations, and one pixel size. For measurement of a line length within the bounds of the reference target, the measurement error would be double that from the point location uncertainty and computed as shown in Equation 3.6.

$$E_{\text{measurement}} = 2 \times (RMSE + 3\sigma + \text{pixel}) \quad \text{(Equation 3.6)}$$

3.3 IMPLEMENTATION

The image rectification program is coded in MATLAB and utilizes the Image Processing Toolbox for MATLAB. The gusset plate digital photographs are loaded into the program. The image pixels of the reference targets are manually selected by the user and then automatically correlated to the known real world target coordinates (with the origin being taken as the center of the “+”) using the DLT algorithm. As the cross product of two vectors oriented in the same direction is zero, Equation 3.1 can be expressed as shown in Equation 3.7.

$$\begin{bmatrix} X_i \\ Y_i \\ 1 \end{bmatrix} \times \mathbf{H} \begin{bmatrix} X_i' \\ Y_i' \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad \text{(Equation 3.7)}$$

After expanding Equation 3.7, collecting all the \mathbf{H} terms into a nine element column vector, h , and gathering the coefficients in a 3×9 matrix, \mathbf{A} , the equation is reduced for each i^{th} control point and is expressed in Equation 3.8.

$$\mathbf{A}h = 0 \quad \text{(Equation 3.8)}$$

Only the first two rows of \mathbf{A} are linearly independent. The nine control points cause Equation 3.8 to be over-determined. To solve this equation for the least-squares solution of h with all nine control points, constrain $\|h\| = 1$ then $\|\mathbf{A}h\|$ becomes a minimization problem. Taking the singular value decomposition (SVD) of \mathbf{A} , three matrices (\mathbf{U} , \mathbf{D} , and \mathbf{V}) are obtained such that $\mathbf{A} = \mathbf{U}\mathbf{D}\mathbf{V}^T$. The last row of \mathbf{V} corresponds to the eigenvector of $\mathbf{A}^T\mathbf{A}$ with the least eigenvalue,

thus it is the solution to h . Transformation matrix \mathbf{H} is obtained by rearranging the first three elements of vector h as the first row, the middle three elements as the second row, and the last three elements as the third row of \mathbf{H} , respectively.

The program then uses the H-matrix to remove the perspective distortion in an image. A rectified image is output as a JPEG file with a pixel scale corresponding to that of the real world image. The program then allows the user to take measurements from the rectified and scaled image. Available measurements in the current implementation include length, perimeter, angle, and bolt locations, which can be manually selected in the program. The data can be output to a Microsoft Excel readable file which can then be used to create a LSP file that can be imported into AutoCAD to create a scaled gusset plate drawing. Scripts have been written to create such LSP files using the selected pixel coordinate data in the rectified and scaled images. The resulting drawings that represent the field dimensions can be compared with existing drawings to verify design drawings. They can further be used to aid subsequent structural calculations.

Software used to perform the rectification, metrification, and drawing processes are:

- MATLAB 7.6.0 (R2008a) with Image Processing Toolbox
- Microsoft Office Excel 2007
- Autodesk AutoCAD 2008

Actual step-by-step implementation of the process is shown in Appendix A.

4.0 EXAMPLE IMPLEMENTATION

A mock gusset plate was developed to demonstrate the rectification and metrification techniques. The gusset plate was modeled after the U3 connection of the Booth Ranch Bridge at Milepost 113 on southbound I-5 near Myrtle Creek, Oregon. Booth Ranch Bridge is a 275 ft steel deck truss bridge and the drawing set is from March 1967. The truss member connection type is similar to that of the recently collapsed I-35W Bridge in Minnesota. Connection U3 was selected for the present study due to the nonsymmetrical design and is shown in Figure 4.1. The edge dimensions of the gusset plate are shown in Table 4.1. The mock gusset plate was made of $\frac{3}{4}$ in. thick plywood, 109 1 in. diameter A325 structural hex-head bolts, and two 4x4x0.12 in. steel plates. The steel plates were used to enable attachment of the magnetic reference targets to the mock gusset plate as shown in Figure 4.2. The mock gusset plate was painted grey and the bolts installed as shown in Figure 4.3.

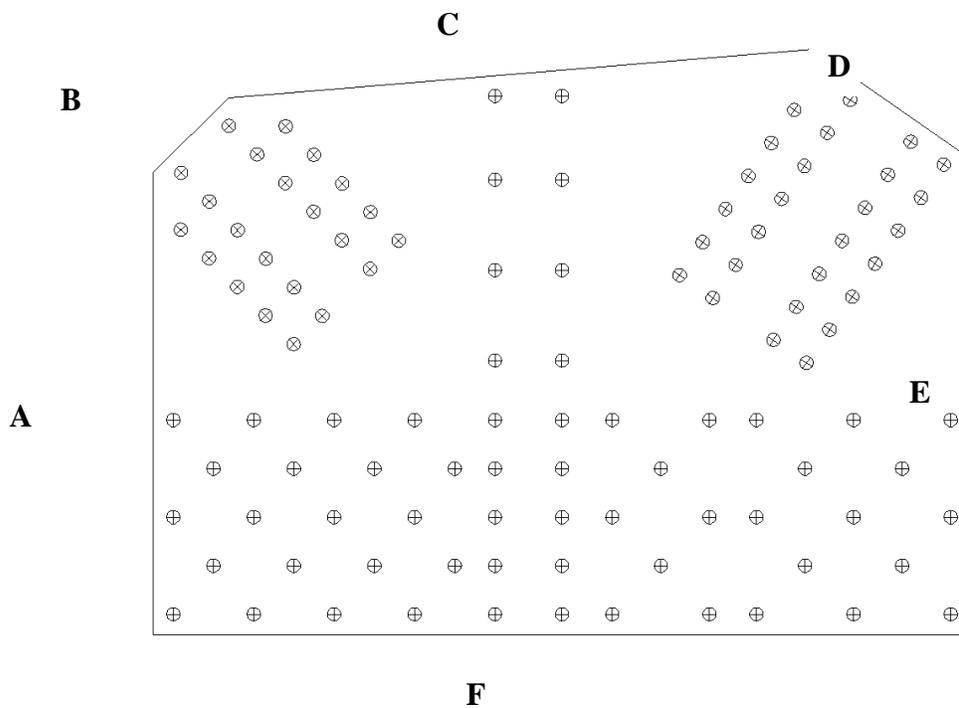


Figure 4.1: CAD drawing of mock gusset plate from connection U3 in Booth Ranch Bridge



Figure 4.2: Mock gusset plate with steel plates to permit magnetic target attachment.

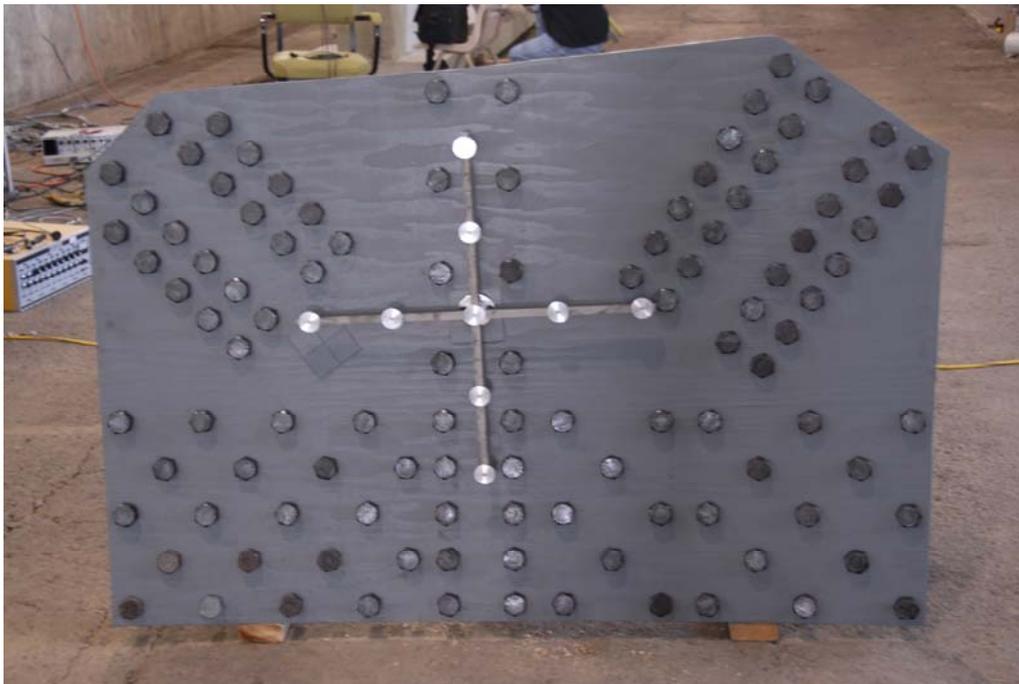


Figure 4.3: Painted pock gusset plate with 24 in. reference target

Table 4.1: Mock gusset plate dimensions

	Actual
	Length (in)
Side A	34.50
Side B	7.90
Side C	43.75
Side D	14.33
Side E	35.50
Side F	61.00

Several digital cameras and lenses were used to capture images of the mock gusset plate. The cameras ranged from professional-grade digital single-lens reflex (SLR) cameras with different lens combinations, to a mid-range consumer-grade digital camera with a built-in zoom lens. The following digital cameras and lens combinations were used:

- Camera 1: Nikon D200 single-lens reflex (SLR) digital camera (Fig. 8)
 - Resolution: 10.9 Megapixel (3872x2592)
 - Lens 1: Nikon AF-S DX VR Zoom NIKKOR 18-200mm f/3.5-5.6G IF-ED
 - Lens 2: Nikon AF NIKKOR 50mm f/1.8D
- Camera 2: Nikon D300 single-lens reflex (SLR) digital camera (Fig. 9)
 - Resolution: 12.2 Megapixel (4288x2848)
 - Nikon AF VR Zoom NIKKOR 80-400mm f/4.5-5.6D ED
- Camera 3: Olympus C-3040 Zoom Digital Camera (Fig. 10)
 - Resolution: 3.3 Megapixel (2048x1536)
 - Built-in 3x optical zoom lens f/1.8-f/2.6

These non-metric digital cameras were not calibrated. Field inspectors will likely be using a variety of available digital cameras with various lenses and zoom capability and these cameras will likely not be mounted on a tripod or stationary platform while photographs are taken. Controlled calibration may not be feasible or transferable to field applications and thus, cameras and the techniques deployed must be compatible with hand-held operation under realistic field conditions.

To simulate such conditions, several different images of the mock gusset plate were taken with the different cameras and using different settings. Distances from the camera to the gusset plate were measured with a Leica Disto™ Pro⁴ laser distance meter. The perspective angle of the camera view from the plane of the gusset plate was measured, and the different camera and lens settings were recorded. Results are described in the subsequent section.



Figure 4.4: Nikon D200 SLR Digital Camera



Figure 4.5: Nikon D300 SLR Digital Camera (Nikon USA 2008)



Figure 4.6: Olympus C-3040 Zoom Digital Camera (Olympus Imaging America Inc. 2008)

5.0 RESULTS

A series of 10 images were used to demonstrate the rectification and metrification methodology developed and to compare resulting measurements of gusset plate geometry from the orthophotos. Figures 5.1a to 5.10a show the original image and Figures 5.1b to 5.10b show the corresponding rectified images using the methodology described in the previous sections. Using the rectified images, the offset corrections (Equation 3.2) were applied based on the camera location relative to the gusset plate and measurements of the outer dimensions on the gusset plate were taken and compared with the known dimensions in Table 5.1. For each of the images, the results are shown in Tables 5.2 to 5.4. Measurement error were determined and the largest percent error were found in sides B and D because they are the smallest measurements and the largest absolute error values were found in side F because it is the largest measurement. The average absolute errors for the plate measurements in each of the 10 cases were below the expected error based on Equation 3.6, except for the cases with significant camera skew relative to the plate plane. The largest percent error measured was -3.35% for the Camera 1 with Lens 1 at 20 ft at 70° off-center, which represents almost a worst case imaging situation. With Camera 1 at 0° off-center, the largest absolute error value was -0.33 in. for side F. Overall, images taken with greater skew angles had larger errors values than those that were closer to orthogonal with the mock gusset plate. The largest percentage errors were found in Camera 3 than for Camera 1 due to Camera 3's built-in lens having more inherent radial distortion. Cases where the gusset plate filled the largest percentage of the image space, the camera had higher resolution, and the image was in good sharp focus, produced better results. Of particular interest are results from Case 7, which is taken hand-held with a long zoom lens from a distance of 250 ft from the mock gusset plate. The resulting measurements were on par with the other images taken at closer range. This indicates that if good quality photographic equipment is used and where a snooper cannot be used to access the bridge to capture images, it may be possible to collect images from a position on the bank or in a boat with another person climbing the structure measuring plate thickness, taking validation length measurements, and placing reference targets. Figure 5.11 shows the *.lsp file generated CAD drawing and Figure 5.12 compares it to the original CAD drawing.

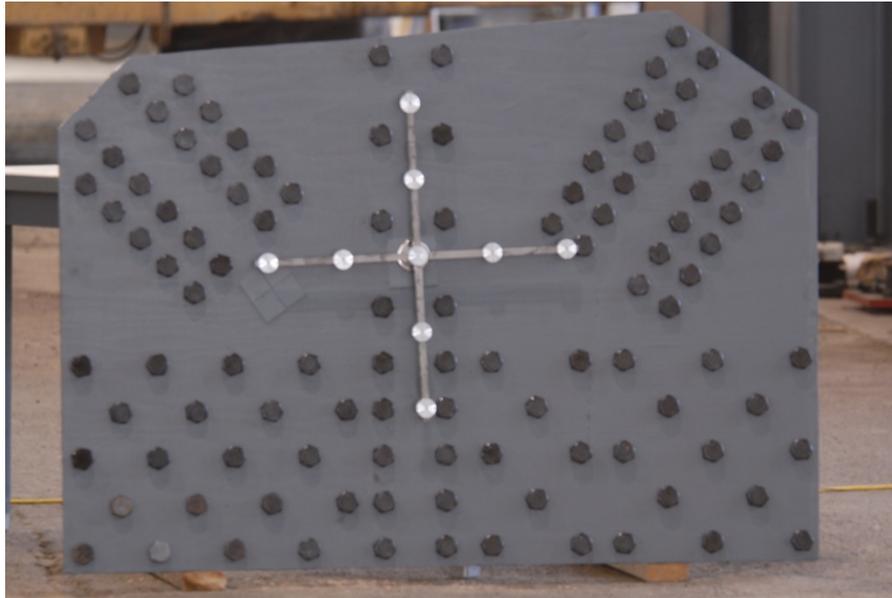


Figure 5.1a: Camera 1 Lens 1 Original – 50ft @ 0° Off-center

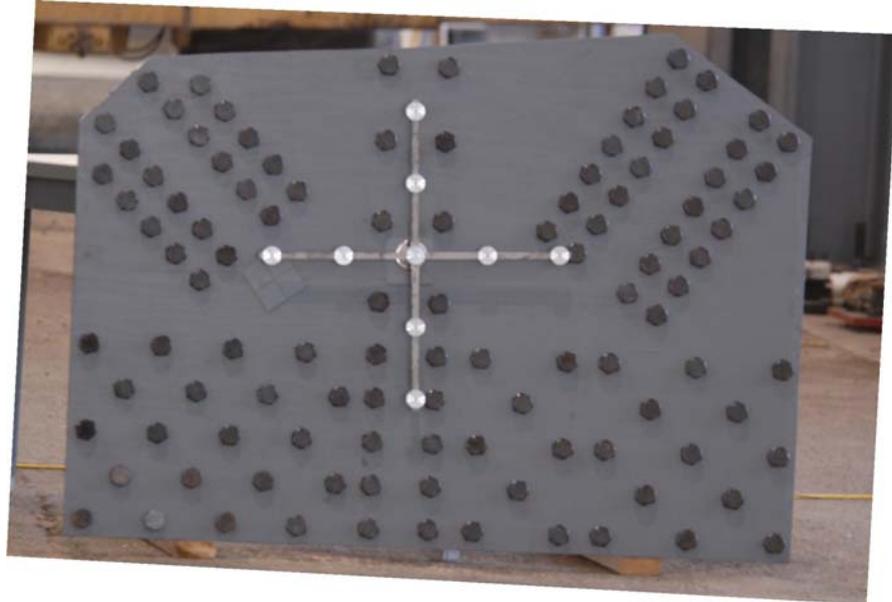


Figure 5.1b: Camera 1 Lens 1 Rectified – 50ft @ 0° Off-center



Figure 5.2a: Camera 1 Lens 1 Original – 15ft @ 0° Off-center

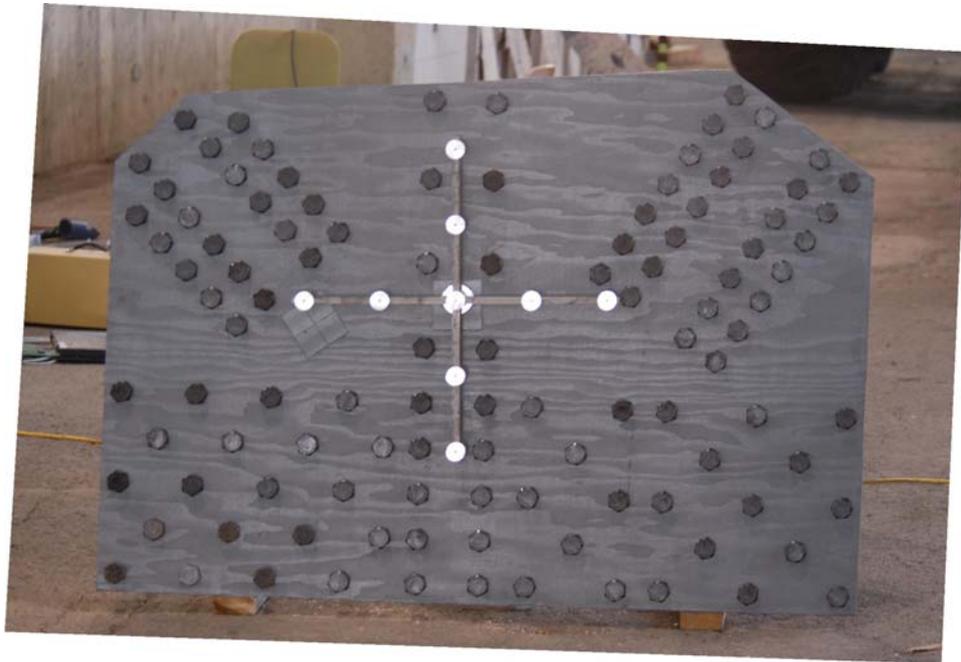


Figure 5.2b: Camera 1 Lens 1 Rectified – 15ft @ 0° Off-center

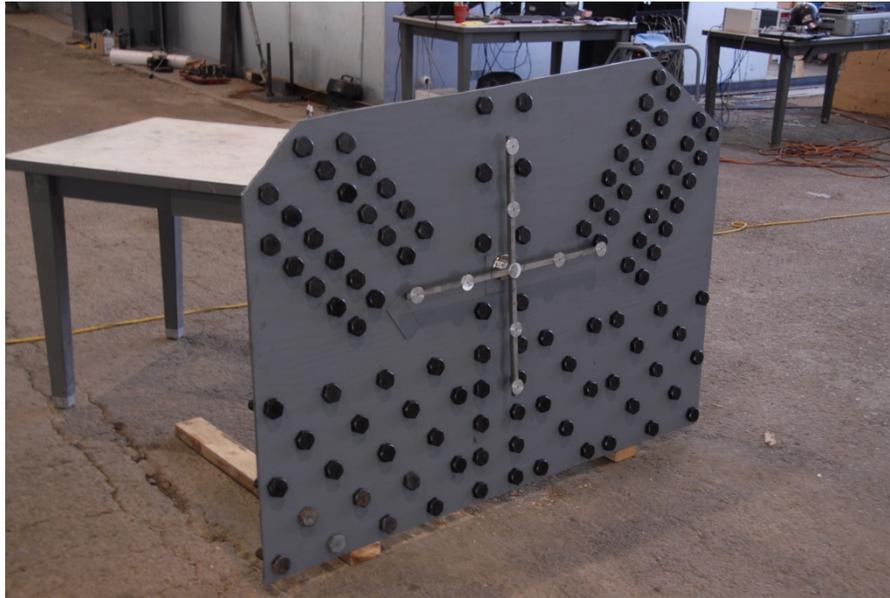


Figure 5.3a: Camera 1 Lens 1 Original – 10ft @ 45° Off-center

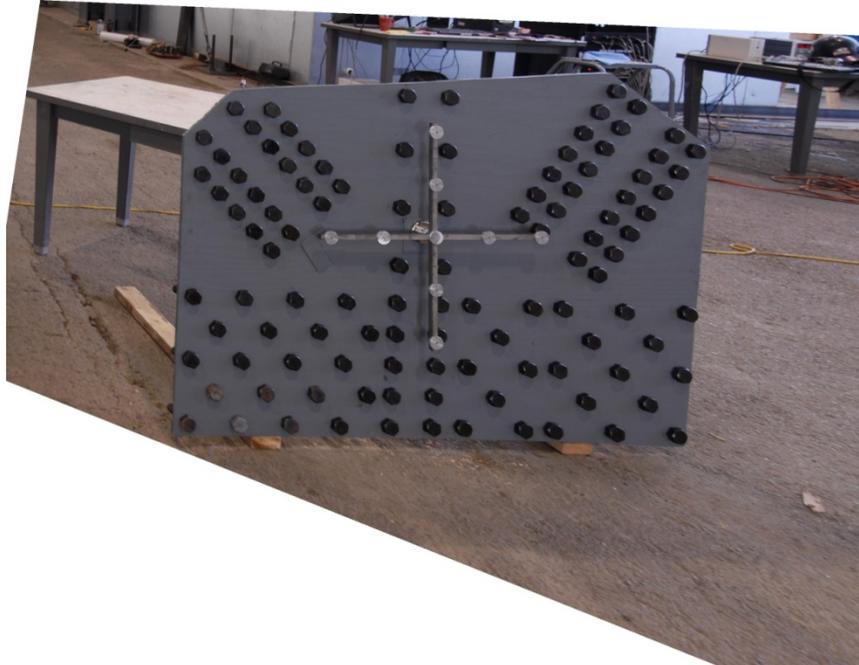


Figure 5.3b: Camera 1 Lens 1 Rectified – 10ft @ 45° Off-center

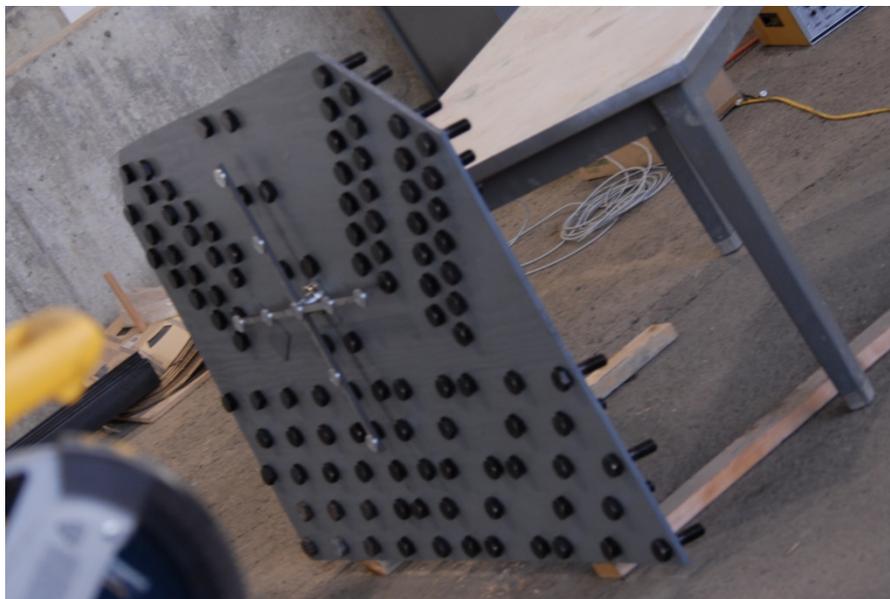


Figure 5.4a: Camera 1 Lens 1 Original – 20ft @ 70° Off-center

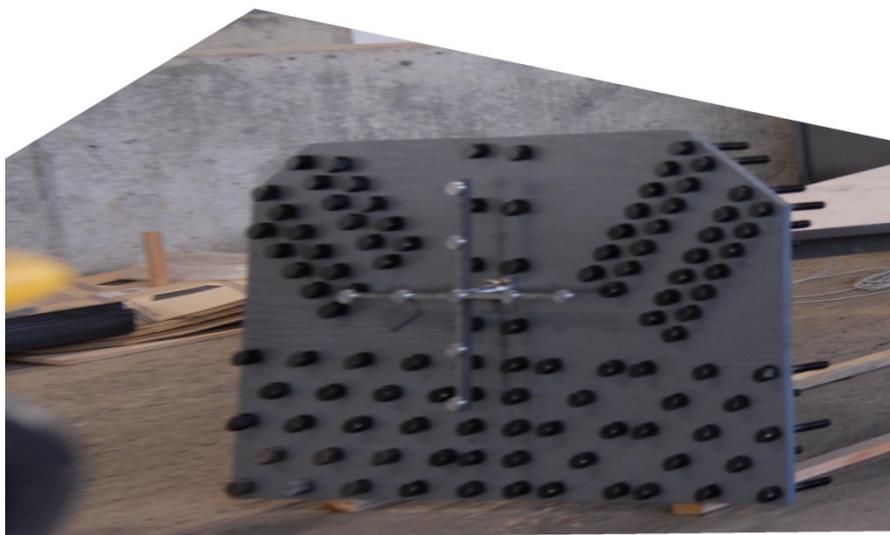


Figure 5.4b: Camera 1 Lens 1 Rectified – 20ft @ 70° Off-center

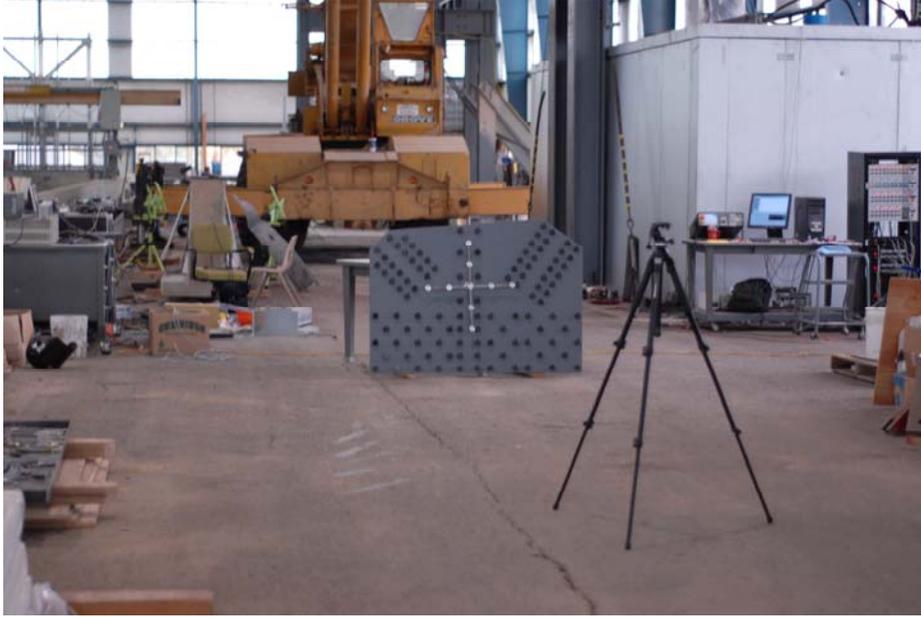


Figure 5.5a: Camera 1 Lens 2 Original – 50ft @ 0° Off-center

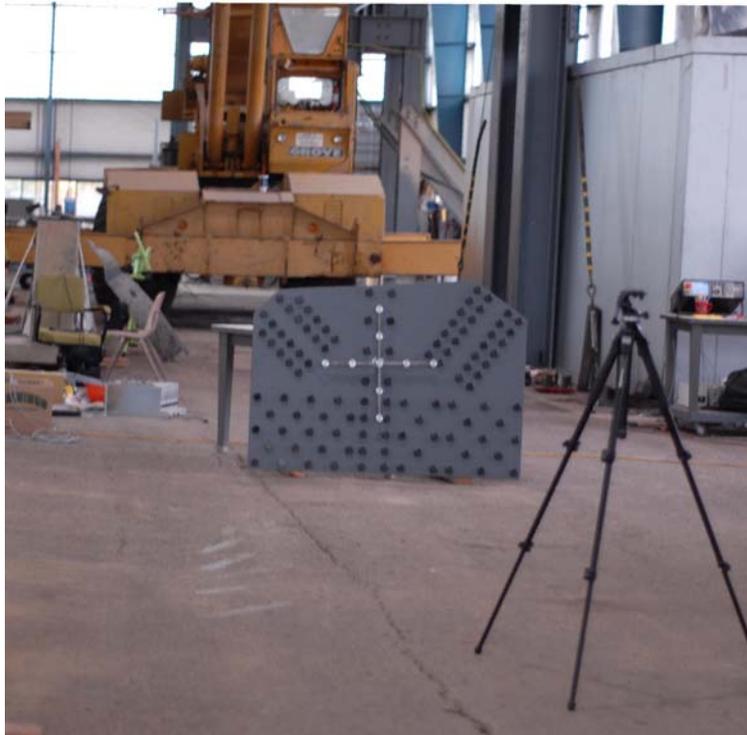


Figure 5.5b: Camera 1 Lens 2 Rectified – 250ft @ 0° Off-center



Figure 5.6a: Camera 1 Lens 2 Original – 35ft @ 30° Off-center

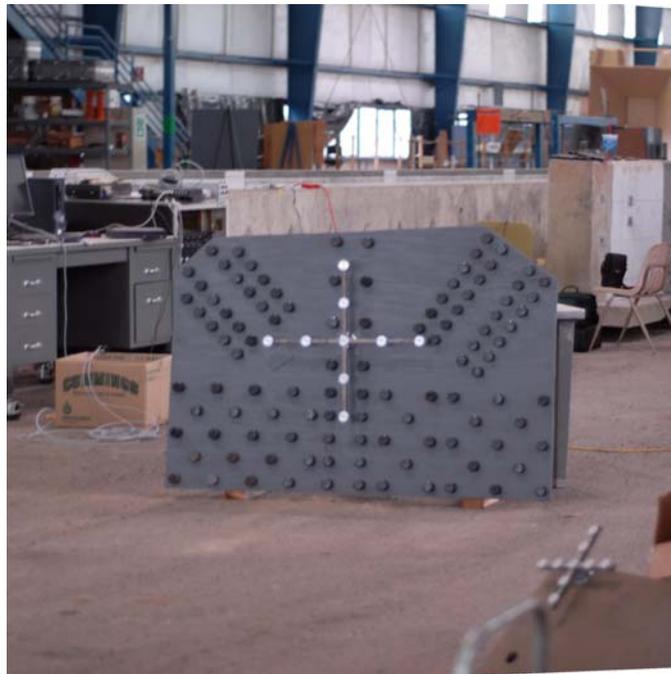


Figure 5.6b: Camera 2 Lens 2 Rectified – 35ft @ 30° Off-center



Figure 5.7a: Camera 2 Original – 250ft @ 0° Off-center

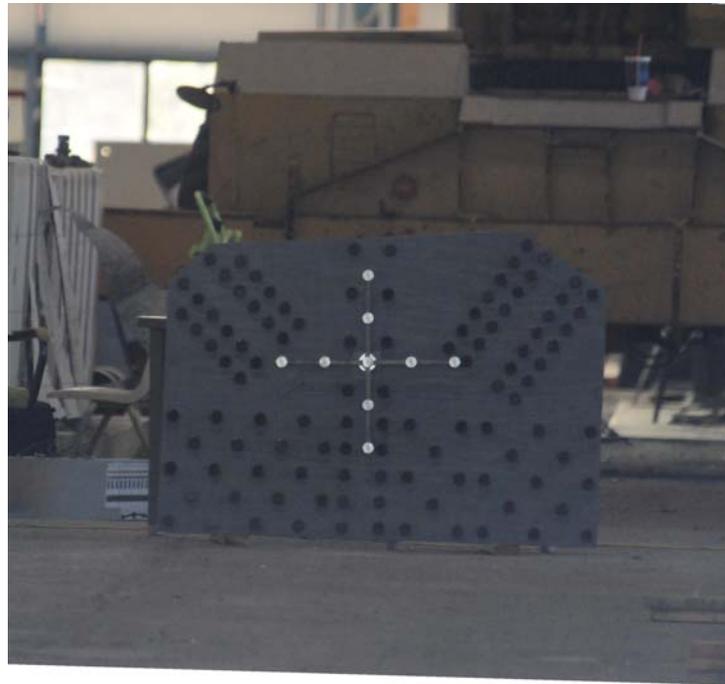


Figure 5.7b: Camera 2 Rectified – 250ft @ 0° Off-center

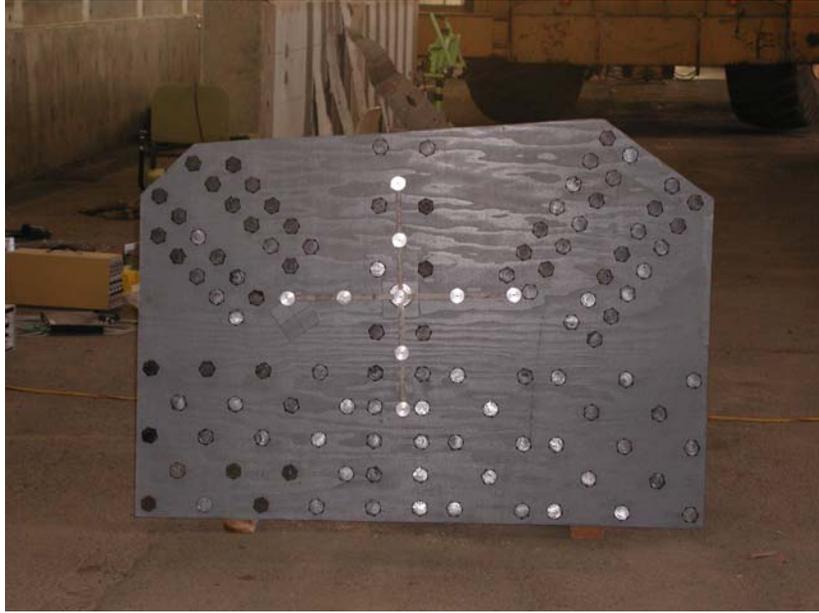


Figure 5.8a: Camera 3 Original – 15ft @ 0° Off-center



Figure 5.8b: Camera 3 Rectified – 15ft @ 0° Off-center

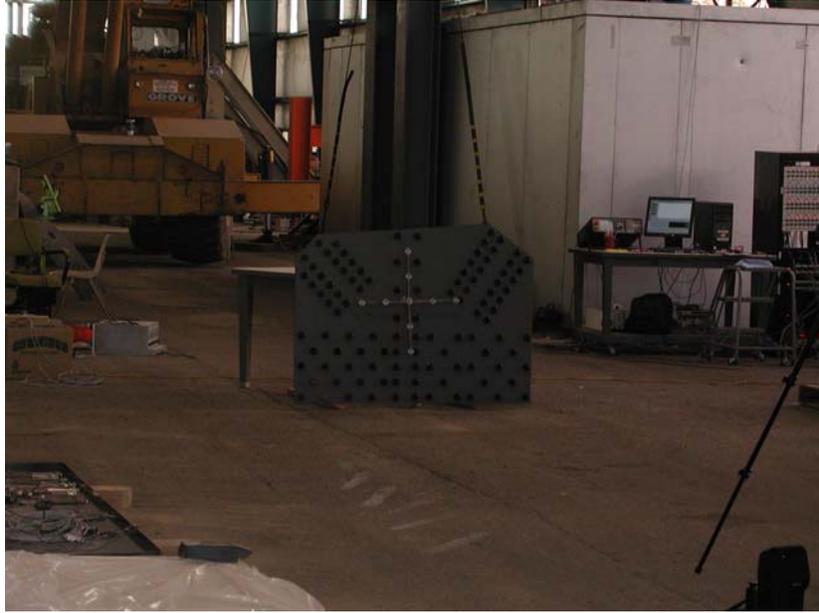


Figure 5.9a: Camera 3 Original – 50ft @ 0° Off-center

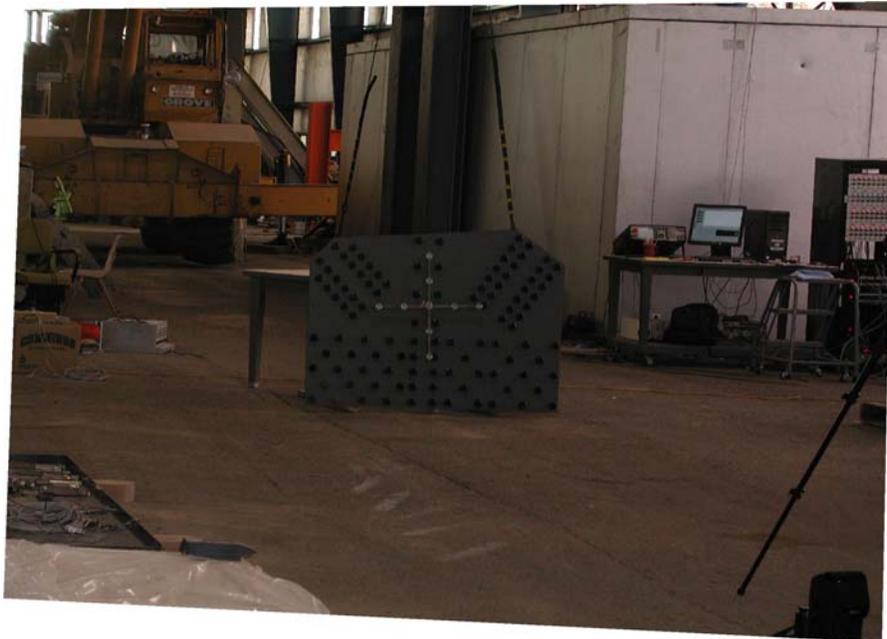


Figure 5.9b : Camera 3 Rectified – 50ft @ 0° Off-center



Figure 5.10a: Camera 3 Original – 15ft @ 45° Off-center



Figure 5.10b: Camera 3 Rectified – 15ft @ 45° Off-center

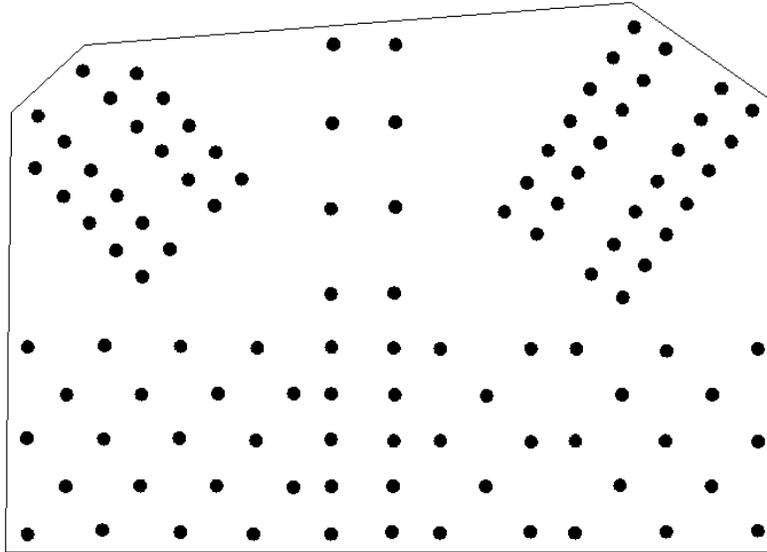


Figure 5.11: AutoCAD line drawing of the mock gusset plate generated from LSP file created in Excel for Camera 2
– 250ft @ 0° off-center

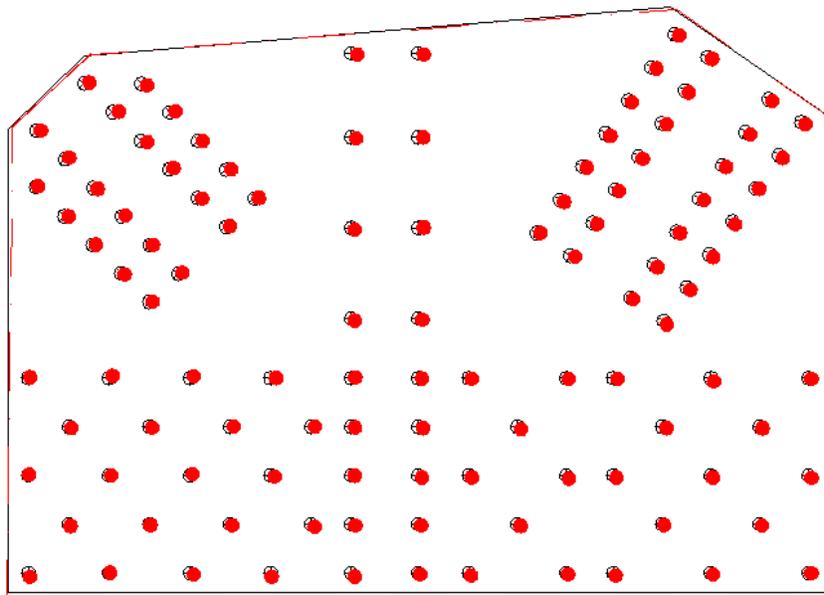


Figure 5.12: AutoCAD line drawing of the mock gusset plate generated from LSP file shown in red compared to the original AutoCAD drawing shown in black

Table 5.1: Example demonstration cases: Camera type, lens, distance from mock gusset plate, and skew angle to plane of mock gusset plate.

Case 1	Camera 1 Lens 1 – 50ft @ 0° Off-center
Case 2	Camera 1 Lens 1 – 15ft @ 0° Off-center
Case 3	Camera 1 Lens 1 – 10ft @ 45° Off-center
Case 4	Camera 1 Lens 1 – 20ft @ 70° Off-center
Case 5	Camera 1 Lens 2 – 50ft @ 0° Off-center
Case 6	Camera 1 Lens 2 – 35ft @ 30° Off-center
Case 7	Camera 2 – 250ft @ 0° Off-center
Case 8	Camera 3 – 15ft @ 0° Off-center
Case 9	Camera 3 – 50ft @ 0° Off-center
Case 10	Camera 3 – 15ft @ 45° Off-center

Table 5.2: Measured length values

	Sde A (in)	Sde B (in)	Sde C (in)	Sde D (in)	Sde E (in)	Sde F (in)
Actual	34.50	7.90	43.75	14.33	35.50	61.00
Case 1	34.61	8.04	43.84	14.44	35.49	60.92
Case 2	34.58	8.00	43.71	14.34	35.27	60.84
Case 3	34.72	7.81	43.88	14.22	34.96	59.75
Case 4	34.47	8.15	42.67	13.99	34.31	61.92
Case 5	34.41	8.05	43.93	14.19	35.44	60.67
Case 6	34.48	7.97	43.77	14.17	35.23	61.35
Case 7	34.56	7.89	43.72	14.19	35.51	61.34
Case 8	34.94	8.07	43.93	14.39	35.18	61.35
Case 9	34.53	8.01	43.70	14.08	35.17	60.64
Case 10	34.31	7.55	43.97	14.22	35.32	58.37

Table 5.3: Absolute error in length measurements

Case	Sde A Error (in)	Sde B Error (in)	Sde C Error (in)	Sde D Error (in)	Sde E Error (in)	Sde F Error (in)	Average Error (in)	St. Dev. Error (in)	Abs. Expected Error by Eq. 6 (in)
1	0.11	0.14	0.09	0.11	-0.01	-0.08	0.06	0.09	0.15
2	0.08	0.10	-0.04	0.01	-0.23	-0.16	-0.04	0.13	0.15
3	0.22	-0.09	0.13	-0.11	-0.54	-1.25	-0.27	0.55	0.17
4	-0.03	0.25	-1.08	-0.34	-1.19	0.92	-0.24	0.81	0.31
5	-0.09	0.15	0.18	-0.14	-0.06	-0.33	-0.05	0.19	0.25
6	-0.02	0.07	0.02	-0.16	-0.27	0.35	0.00	0.21	0.16
7	0.06	-0.01	-0.03	-0.14	0.01	0.34	0.04	0.16	0.14
8	0.44	0.17	0.18	0.06	-0.32	0.35	0.15	0.27	0.15
9	0.03	0.11	-0.05	-0.25	-0.33	-0.36	-0.14	0.20	0.31
10	-0.19	-0.35	0.22	-0.11	-0.18	-2.63	-0.54	1.04	0.33
Abs Avg	0.13	0.14	0.20	0.14	0.31	0.68	0.27	0.21	0.21

Table 5.4: Percentage error in length measurements

Case	Sde A %Error	Sde B %Error	Sde C %Error	Sde D %Error	Sde E %Error	Sde F %Error	Average %Error
1	0.32%	1.77%	0.21%	0.77%	-0.03%	-0.13%	0.48%
2	0.23%	1.27%	-0.09%	0.07%	-0.65%	-0.26%	0.09%
3	0.64%	-1.14%	0.30%	-0.77%	-1.52%	-2.05%	-0.76%
4	-0.09%	3.16%	-2.47%	-2.37%	-3.35%	1.51%	-0.60%
5	-0.26%	1.90%	0.41%	-0.98%	-0.17%	-0.54%	0.06%
6	-0.06%	0.89%	0.05%	-1.12%	-0.76%	0.57%	-0.07%
7	0.17%	-0.13%	-0.07%	-0.98%	0.03%	0.56%	-0.07%
8	1.28%	2.15%	0.41%	0.42%	-0.90%	0.57%	0.65%
9	0.09%	1.39%	-0.11%	-1.74%	-0.93%	-0.59%	-0.32%
10	-0.55%	-4.43%	0.50%	-0.77%	-0.51%	-4.31%	-1.68%
%Avg	0.18%	0.68%	-0.09%	-0.75%	-0.88%	-0.47%	-0.22%

6.0 CONCLUSIONS

A methodology was developed to permit rectification and metrification of digital images of steel truss gusset plate connections. The approach will enable rapid and accurate collection of field measurements, as compared to traditional methods to enable structural evaluations of gusset plate connections. The program enables the operator to quickly create AutoCAD drawings by collecting dimensional information about the gusset plate and connectors from the scaled orthographic photograph (orthophoto), thereby limiting data entry errors and redundant efforts. The availability of scaled orthophotos provides a useful record of field conditions and can be compared with subsequent field inspection results to help identify and quantify long term changes in visual characteristics. Further, the availability of scaled orthophotos enables comparison between available drawing sets and as-built details for gusset plates. The implementation procedure is straightforward and does not require specialized knowledge of photogrammetry. It can be practicably employed under field conditions using current technology and personnel. Dimensional measurements from the scaled orthophotos provide results that are as good conventional field measurements and are within tolerances that most engineers would find reasonable for gusset plate connection capacity evaluations.

To effectively implement the technique for metrification of steel truss bridge gusset plate connections the following recommendations are made:

- Deploy a high resolution SLR camera with high-quality lens if possible. The available metadata recorded with these cameras can also be helpful in documenting the data collection effort.
- Fill the image frame with the gusset plate as much as possible.
- Take a sharp well focused image. This may require good available light, higher ISO settings, smaller apertures, or combinations of these settings.
- Take the best available image with the camera as orthogonal to the gusset plate surface as possible (to minimize inherent perspective).
- Deploy flat-field lenses that have reduced radial distortion or use lenses with well defined optical properties that can be corrected a posteriori.
- Take at least one physical length measurement on the gusset plate (and mark on the plate so it is visible in the image) to enable validation of the dimensions collected from the orthophotos produced.
- Take a measurement of the plate thickness, as this cannot be determined directly by the present method

7.0 FUTURE WORK

Future research that can build upon this study include:

- Incorporate automated control point selection and edge detection into the program.
- Automate image comparison between existing drawings and the dimensions and properties obtained from the present software.
- Automate finite element model generation and analysis from the image data.
- Additional program customization and optimization.
- Use lens manufacturer software to correct inherent distortions from fisheye and other types of lenses and test the accuracy of the corrected images

8.0 REFERENCES

- Arias, P., C. Ordóñez, H. Lorenzo, J. Herraéz, and J. Armesto. Low-cost documentation of traditional agro-industrial buildings by close-range photogrammetry. *Building and Environment*, Vol. 42, 2007, pp. 1817-1827.
- Criminisi, A., I. Reid, and A. Zisserman. Single View Metrology. *International Journal of Computer Vision*, No. 40, pp. 123-148.
- Hartley, R. I. and A. Zisserman. *Multiple View Geometry in Computer Vision*, Second Edition, Cambridge University Press, 2004.
- Heuvel, F. 3D reconstruction from a single image using geometric constraints. *ISPRS Journal of Photogrammetry and Remote Sensing*, No. 53, 1998, pp. 354-368.
- Jauregui, D, Y. Tian, and R. Jiang. Photogrammetry Applications in Routine Bridge Inspection and Historic Bridge Documentation. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1958, TRB, National Research Council, Washington D.C., 2006, pp. 24-32
- Mills, J. and D. Barber. Geomatics Techniques for Structural Surveying. *Journal of Surveying Engineering*. 2004, Vol. 130, No.2, pp. 56-64.
- National Transportation Safety Board (NTSB), “Data Report State-by-State Bridge Counts”, March 12, 2008
- Nikon USA. D300 from Nikon, Nikon Cameras, 2008,
www.nikonusa.com/Find-Your-Nikon/ProductDetail.page?pid=25432
- Olympus Imaging America Inc., “C-3040 Zoom”, Olympus Imaging America Inc., 2008,
www.olympusamerica.com/cpg_section/cpg_product.asp?huge_picture_lobby=1&p=&bc=&product=661
- Rodríguez, J., M.T. Martín, P. Arias, C. Ordóñez, and J. Herraéz. Flat elements on buildings using close-range photogrammetry and laser distance measurement. *Optics and Lasers in Engineering*, No. 46, 2008, pp. 541-545.
- Tommaselli, A. and M. Reiss. A Photogrammetric Method for Single Image Orientation and Measurement. *Photogrammetric Engineering and Remote Sensing*, Vol. 71, No. 6, 2005, pp. 727-732.

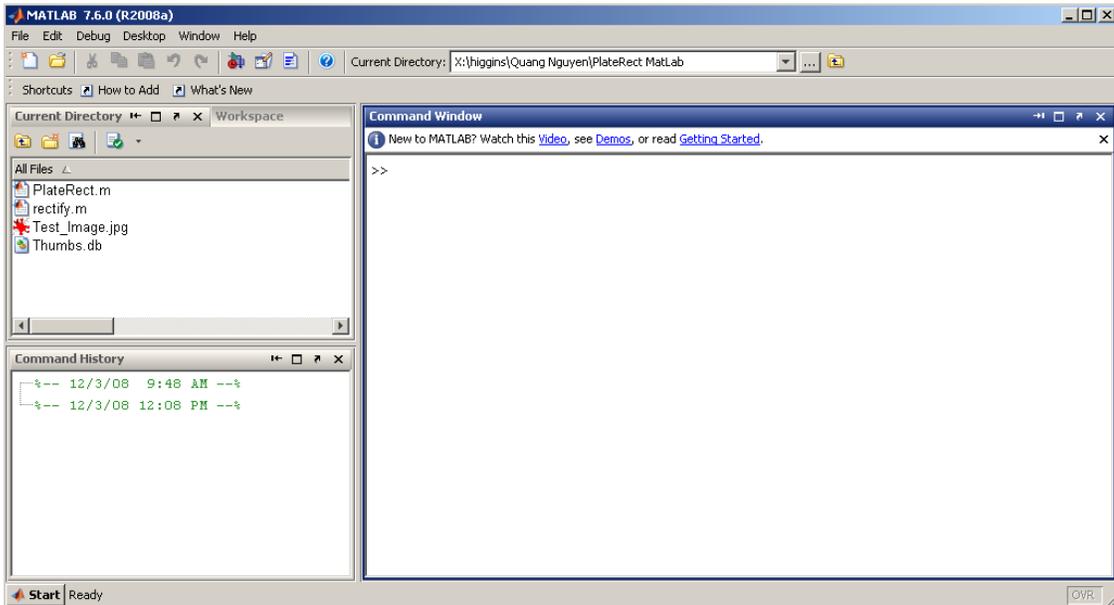
APPENDIX A: USER'S MANUAL

OUT IN THE FIELD

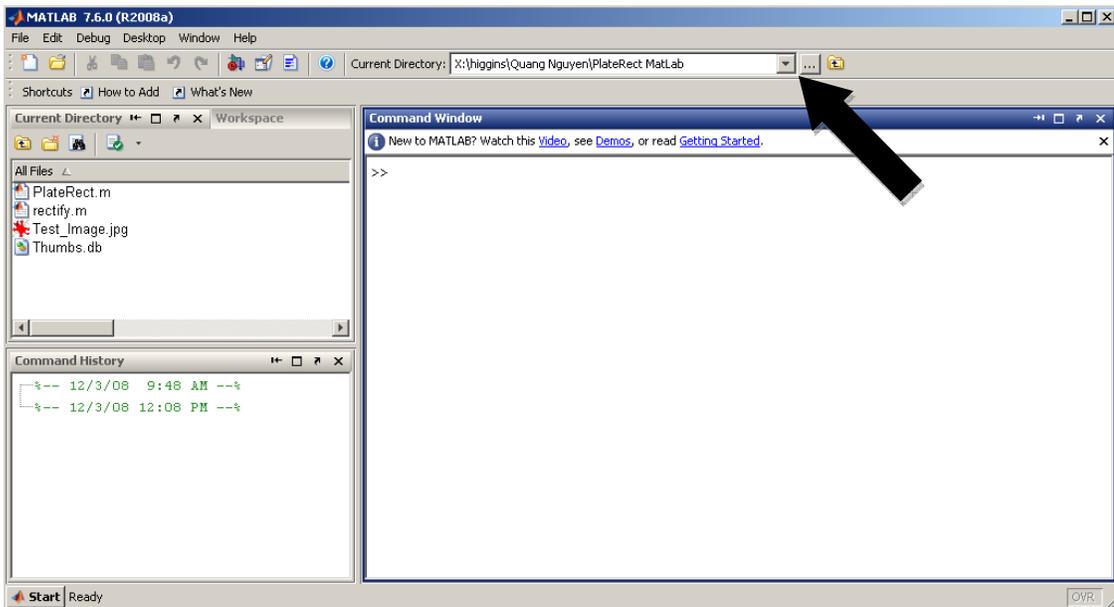
1. Record general information
 - a. Bridge Name
 - b. Location
 - c. Date & Time
 - d. Gusset Plate name/identifier
 - e. Plate thickness
 - f. Any distortion, sway, or buckling
2. Record reference target information
 - a. Size
 - b. Approximate distance from reference target with laser distance measurer
3. Place reference target near the center of the plate. The plate needs to be within approximately 50 inches of the center of the reference target (**see Special Notes).
4. Take a digital photograph of the gusset plate using the maximum resolution available with the gusset plate filling the image as much as possible.
5. Record digital photograph information
 - a. Camera used
 - b. Camera settings
 - c. File name
6. Repeat steps 1 – 5 for additional gusset plates

IN THE OFFICE

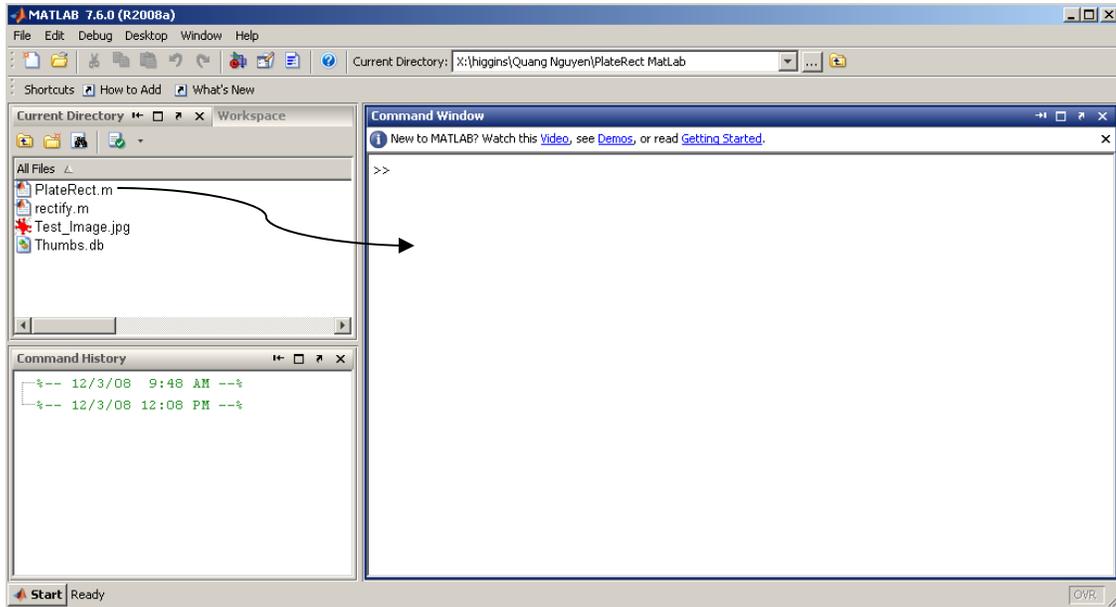
1. Download digital photographs from the camera into folder with the PlateRect.m and rectify.m files
2. Open MATLAB Program.



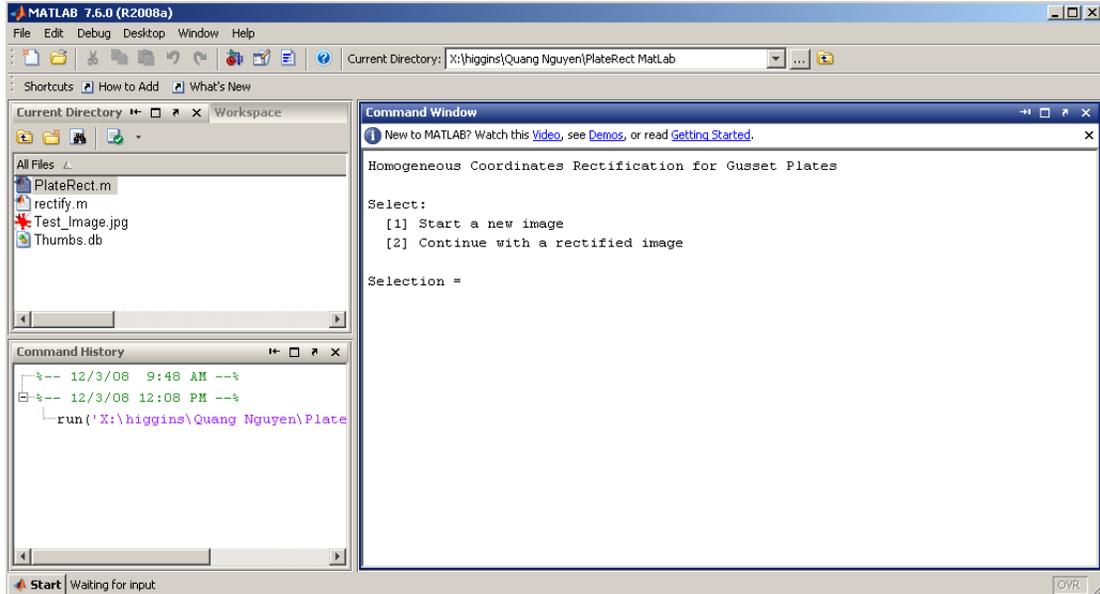
3. Open the directory with PlateRect.m, rectify.m and digital photographs in MATLAB.



4. Type “PlateRect” in the Command Window to start the Plate Rectification Program or drag the PlateRect.m file from the Current Directory window into the Command Window.

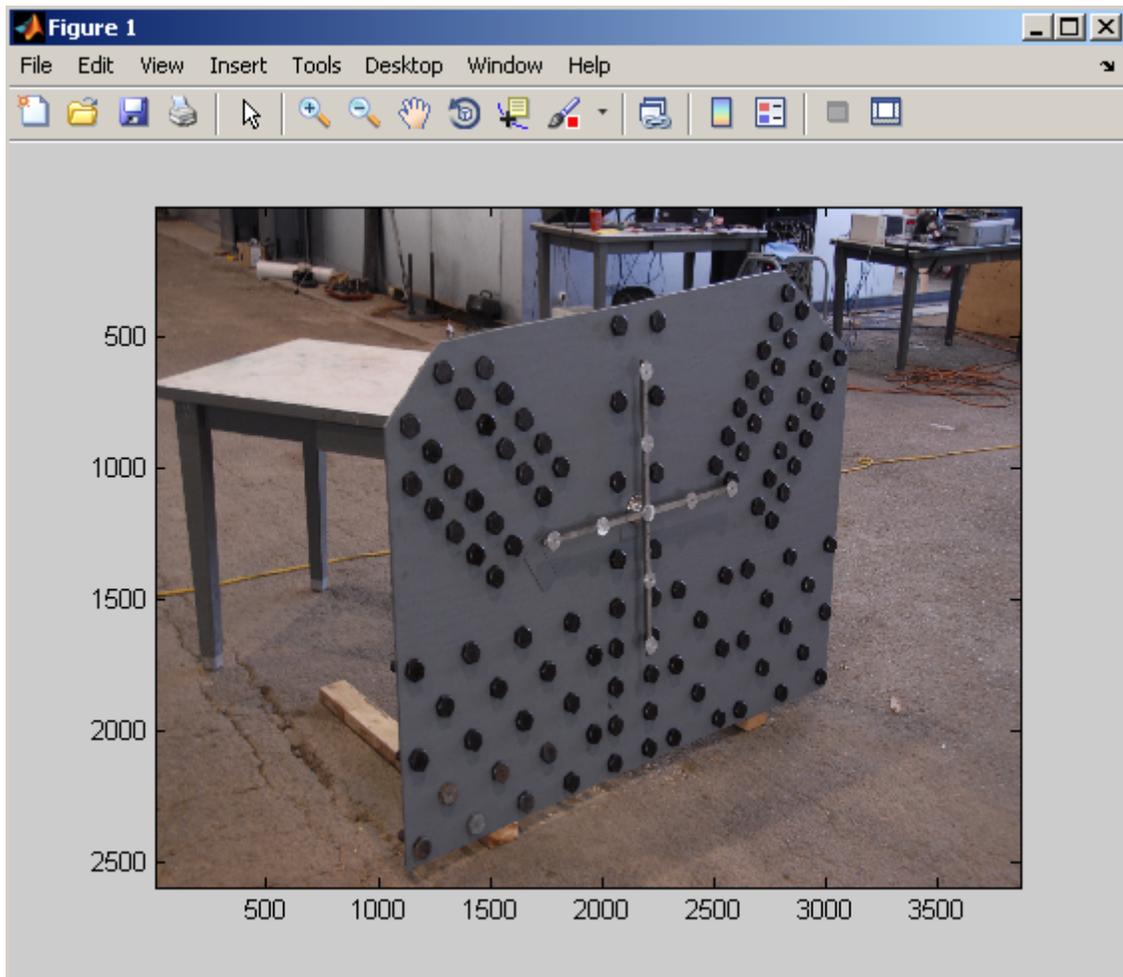


5. Select [1] for a new image or [2] to continue from an older image.



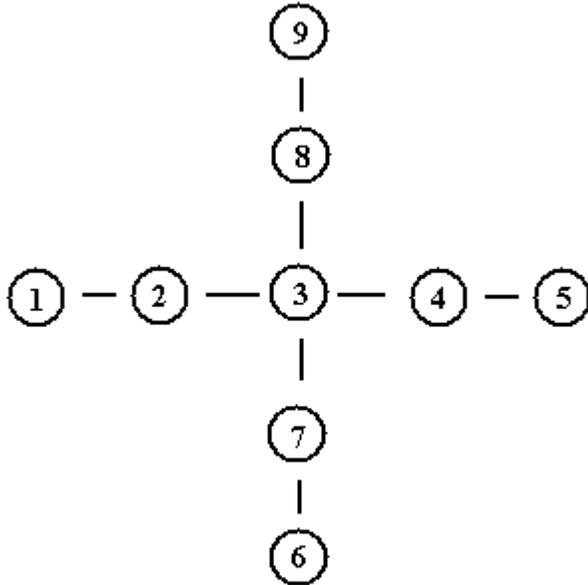
- a. [1] Start a new image
 - i. Continue on to Step 6.
- b. [2] Continue with a rectified image

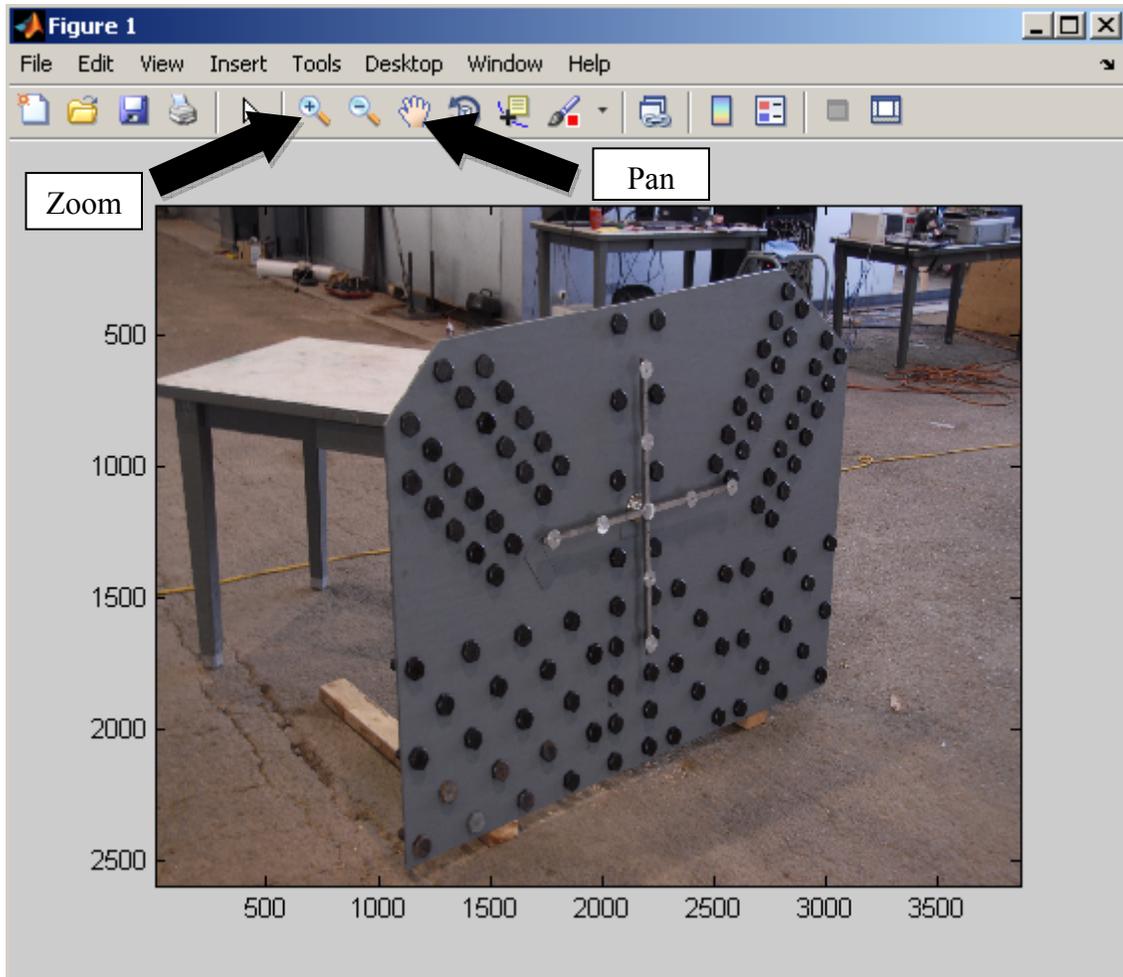
- i. The rectified image and excel file generated from a previous session needs to be in the same folder with the PlateRect.m and rectify.m files.
 - ii. The files should have the same name with the image file having “filename_r.jpeg” and the excel file having “filename.xls”.
 - iii. The program will then skip to Step 13.
6. Enter the name of the first photograph to be rectified or copy and paste the file name from the Current Directory window into the Command Window. A separate window will open displaying the image.



7. Select the size of the reference target from the choices provided.
8. Enter the approximate distance from the reference target in feet.

9. Select the 9 Controls Points on the reference target.
- When selecting a control point, you can zoom in, zoom out, and pan until “Enter” is pressed, then you click on the desired point. Repeat this process for each control point.
 - Control Points 1 – 5 go from **left to right** across the reference target
 - Control Points 6 – 9 go from **bottom to top** across the reference target **skipping the center point**.

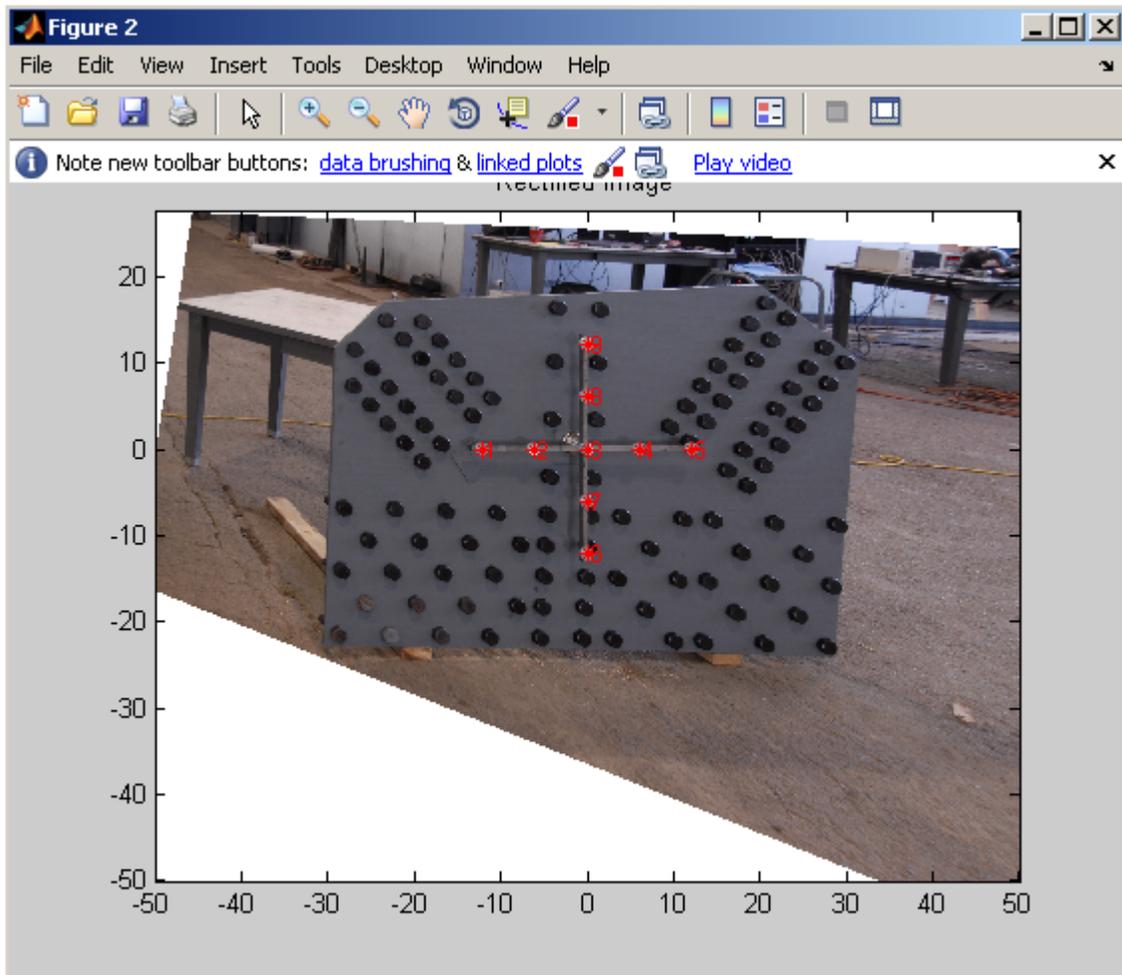




Use the Zoom and Pan features to improve the selection of the control points. The figure window can be resized/maximized as well.

10. The program will calculate an H-matrix and output the predicted measurement error. You can choose to reselect the 9 Control Points if you want to have a new H-matrix and measurement error calculated.
11. The program will save the input and output information calculated in an excel spreadsheet called “<imagefilename>_YYYY-MM-DD_HH.MM.SS.xls” (**NOTE:** When this file is opened in excel, it will have a prompt that saying that the file was not made using excel).

12. A separate window will open displaying the rectified image. The program will save the rectified image as “<imagefilename>_YYYY-MM-DD_HH.MM.SS_r.jpeg”.



13. Select from the 4 available options. Each option will open a new window. Instructions for each step will be displayed in the command window.

a. [1] Measurements

- i. [1] Distance – You will select 2 points on the image and the program will calculate the distance between the 2 points.
- ii. [2] Angle – You will select 3 points on the image (end-middle-end) and the program will calculate the lengths of the sides and the angle between the 3 points.
- iii. [3] Clear Points – This will clear the previously selected points.
- iv. [4] Back to menu – This will return to the previous menu selection.

b. [2] Perimeter

- i. Select Perimeter - You will select the corners of the gusset plate. Left click selects the points, right click lets you zoom and pan until “Enter” is pressed, and middle click lets you undo the last point or end selecting the perimeter. All the data will be saved to the excel file.
- ii. If a perimeter has been selected previously:
 1. Reselect perimeter
 2. Back to menu

c. [3] Bolt locations

- i. Select bolt locations – You will select the bolts of the gusset plate. Left click selects the points, right click lets you zoom and pan until “Enter” is pressed, and middle click lets you undo the last point or end selecting bolts. All the data will be saved to the excel file.
- ii. If bolt locations have been selected previously:
 1. Reselect bolt locations
 2. Continue selecting bolt locations
 3. Back to menu

d. [4] Quit Program

14. Open the excel spreadsheet with the image information. The spreadsheet will have tabs that contain all of the input and output data in addition to the 3 standard excel tabs.

15. Open the excel spreadsheet “CAD.xls” that creates AutoCAD *.lsp files and enable macros.

16. Copy/Paste XY coordinates from the image information spreadsheet into the AutoCAD *.lsp spreadsheet (**NOTE:** Ignore any 9999 values). Fill out any additional information in the excel spreadsheet.

17. Click the button to make the *.lsp file.
18. Open AutoCAD Program.
19. Run *.lsp file to create the Gusset Plate in AutoCAD under the menu Tool>AutoLISP>load application...
20. Save AutoCAD file.

SPECIAL NOTES

1. The rectified image is limited to 2500x2500 pixels and the minimum pixel size is 0.04 inches per pixel. This sets the image grid to be -1250 pixels to 1250 pixels or -50 inches to 50 inches (100 inches across) in both the X and Y axes at minimum pixel size and maximum image size. Changing these values will increase the processing time and memory required. A larger pixel size allows increases the distance allowed across the image. Minimum pixel size can be changed in line 173 and image size limits can be changed in lines 242 to 245 in the MATLAB script.
2. Reference target size can be altered in the section starting at line 52 in the MATLAB script.
3. Reference target standoff can be altered in the section starting at line 71 in the MATLAB scrip

APPENDIX B: MATLAB SCRIPT


```
% Homogeneous Coordinates Rectification for Gusset Plates
%
% This program is designed to take a digital image of a gusset plate and
% rectify the image. The rectified image can be saved. The output image
% is saved as a jpeg.
%
% Information about the image and outputs are saved to an excel file.
%
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% Last Update 12/3/2008

clear all
close all
clc

% Select new or old image
flag = 1;
NewImage = 0;
while flag
    clc
    fprintf('Homogeneous Coordinates Rectification for Gusset Plates\n\n');
    rs = input('Select:\n [1] Start a new image\n [2] Continue with a rectified
image\n\nSelection = ','s');
    if (rs == '1')
        NewImage = 1;
        flag = 0;
    end
    if (rs == '2')
        % Load the image and display it
        RectImgName = input('Enter name of the image: ','s');
        imgxls = [RectImgName(1:end-7),'.xls'];
        AxAll = xlsread(imgxls,'AxAll');
        figure
        IAll = imread(RectImgName);
        imagesc([AxAll(1) AxAll(2)],[AxAll(3) AxAll(4)],IAll);
        title('Rectified Image')
        hold on
        flag = 0;
    end
end

if (NewImage == 1)
    % Load the image and display it
    ImgName = input('Enter name of the image: ','s');
    figure
    I = imread(ImgName);
    imagesc(I)
    hold on
```

```
% Input reference target size
flag = 1;
while flag
    rs = input('\nSelect size of the reference target in inches:\n [1] 8-inch\n[2] 24-inch\n\nSelection = ','s');
    if (rs == '1')
        reftime = 8;
        flag = 0;
    end
    if (rs == '2')
        reftime = 24;
        flag = 0;
    end
end

% Input reference target
reftime = input('Enter approximate distance from reference target in feet: ');

% Correction of reference marks being offset the surface of the target.
% Values based on the physical height of the reference marks
% from the plate surface.
% 8" reference marker height is 2.02 inches.
% 24" reference marker height is 2.13 inches.
% 0.12" thick steel plate on mock gusset plate
% This is based on perspective and similar triangles.
if (reftime == 8)
    offset = 2.02 + 0.12;
    offsetcorrect = (reftime*12)/(reftime*12-offset);
end

if (reftime == 24)
    offset = 2.13 + 0.12;
    offsetcorrect = (reftime*12)/(reftime*12-offset);
end

% Input control points to calculate the H-matrix
controlpoints = 9;
GoodControl = 1;
while GoodControl
    % Select reference marks
    % 1 - 5 Left to Right
    % 6 - 9 Bottom to Top
    U = zeros(1,controlpoints);
    V = zeros(1,controlpoints);
    refnames = '123456789';
    for j = 1:controlpoints
        clc
        fprintf('Homogeneous Coordinates Rectification for Gusset Plates\n\n');
```

```

fprintf('Select the 9 control points.\n');
fprintf('Control points 1 - 5 Left to Right.\n');
fprintf('Control points 6 - 9 Bottom to Top.\n');
fprintf('Do not select the center control point twice.\n\n');
display(sprintf('Control Point %d', j))
zi = input('Zoom in on control point then press ''Enter''.','s');
display(sprintf('Click on the control point %d', j))
[U(j) V(j)] = ginput(1);
plot(U(j),V(j),'y*')
h = text(U(j)+25,V(j),refnames(j));
set(h,'color','y','fontsize',9)
end
clc
fprintf('Homogeneous Coordinates Rectification for Gusset Plates\n');

% Set nine real world coordinates of the reference target in inches
X = offsetcorrect*[-refsize/2 -refsize/4 0 refsize/4 refsize/2 0 0 0 0];
Y = offsetcorrect*[0 0 0 0 0 -refsize/2 -refsize/4 refsize/4 refsize/2];

% Plot image with controls points
imagesc(I)
hold on
for j = 1:controlpoints
    plot(U(j),V(j),'y*')
    h = text(U(j)+25,V(j),refnames(j));
    set(h,'color','y','fontsize',9)
end
title('Original Image')

% OVER-DETERMINED SOLUTION
u = U;
v = V;
w = repmat(1,size(u));
x = X;
y = Y;
s = repmat(1,size(x));

for i = 1:length(u);
    A(i*2-1,1:controlpoints) = [ 0 0 0 -w(i)*x(i) -w(i)*y(i) -w(i)*s(i) v(i)*x(i)
(i) v(i)*y(i) v(i)*s(i)];
    A(i*2,1:controlpoints) = [ w(i)*x(i) w(i)*y(i) w(i)*s(i) 0 0 0 -u(i)*x(i) -u
u(i)*y(i) -u(i)*s(i)];
end

[svdU, svdD, svdV] = svd(A);
H = svdV(:,end);
h = reshape(H,3,3);
h = h';
H_AllPts = h/h(3,3)

```

```

% Root mean square error calculations
XYtrans = [];
diff = zeros(1,controlpoints);
xdiff = zeros(1,controlpoints);
ydiff = zeros(1,controlpoints);
dev = zeros(1,controlpoints);
for j = 1:controlpoints
    XYtrans = H_AllPts \ [U(j); V(j); 1];
    xdiff(j) = (X(j)-XYtrans(1,1)/XYtrans(3,1));
    ydiff(j) = (Y(j)-XYtrans(2,1)/XYtrans(3,1));
    diff(j) = sqrt(xdiff(j)^2+(ydiff(j)^2));
end

sqtotaldiff = 0;
sqttotaldev = 0;
for j = 1:controlpoints
    dev(j) = diff(j) - (sum(diff,2)/controlpoints);
    sqtotaldiff = sqtotaldiff + diff(j)^2;
    sqttotaldev = sqttotaldev + dev(j)^2;
end

% Minimum pixel scale = 0.04 inches / pixel
pixel = max([(refsize*offsetcorrect)/max(sqrt(((U(5)-U(1))^2)+(V(5)-V(1))^2)),
sqrt(((U(9)-U(6))^2+(V(9)-V(6))^2))],0.04)];

rmse = sqrt(sqtotaldiff/controlpoints)

sigma_e = sqrt(sqttotaldev/controlpoints)

measurement_error = 2*(rmse+3*sigma_e)+2*pixel
fprintf('Measurement error in inches within the reference target.\n\n');

percent_error = measurement_error*100/(refsize*offsetcorrect)
fprintf('Percent error in percentage.\n\n');

flag = 1;
while flag
    ErrorOK = input('\nDo you want to redo selecting 9 control points\n to get a
new measurement error and H-matrix?\n [1] Yes\n [2] No\n\nSelection = ','s');
    if ErrorOK == '1'
        flag2 = 1;
        while flag2
            VerifyRedo = input('Redo control points?\n [1] Yes\n [2]
No\n\nSelection = ','s');
            if VerifyRedo == '1'
                flag2 = 0;
                flag = 0;
                imagesc(I)
                hold on

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        end
        if VerifyRedo == '2'
            flag2 = 0;
        end
    end
end
end
if ErrorOK == '2'
    flag = 0;
    GoodControl = 0;
end
end
end

% Save information about image
clc
fprintf('Homogeneous Coordinates Rectification for Gusset Plates\n\n');
fprintf('Saving image information to file.\nThis may take a few seconds...\n');
imgfilename = [ImgName, '_', datestr(now, 'yyyy-mm-dd_HH.MM.SSAM')];
imgxls = [imgfilename, '.xls'];
xlswrite(imgxls, ImgName, 'Image Name', 'A1');
xlswrite(imgxls, refsize, 'RefSize', 'A1');
xlswrite(imgxls, 'in', 'RefSize', 'B1');
xlswrite(imgxls, refdist, 'RefDist', 'A1');
xlswrite(imgxls, 'ft', 'RefDist', 'B1');
xlswrite(imgxls, rmse, 'RMSE', 'A1');
xlswrite(imgxls, 'in', 'RMSE', 'B1');
xlswrite(imgxls, sigma_e, 'Sigma e', 'A1');
xlswrite(imgxls, 'in', 'Sigma e', 'B1');
xlswrite(imgxls, measurement_error, 'Error', 'A1');
xlswrite(imgxls, 'in', 'Error', 'B1');
xlswrite(imgxls, H_AllPts, 'H', 'A1');

clc
fprintf('Homogeneous Coordinates Rectification for Gusset Plates\n\n');
imginfotxt = ['Image info saved to ', imgxls, '\n\n'];
fprintf(imginfotxt);

% Corners of the rectified image
% maximum rectified image pixel size 2500x2500
XYc1 = H_AllPts \ [0; 0; 1];
XYc2 = H_AllPts \ [0; size(I,1); 1];
XYc3 = H_AllPts \ [ size(I,2); 0; 1];
XYc4 = H_AllPts \ [size(I,2); size(I,1); 1];

xmax = min([max([XYc1(1,1)/XYc1(3,1), XYc2(1,1)/XYc2(3,1), XYc3(1,1)/XYc3(3,1), XYc4(1,1)/XYc4(3,1)]), 1250*pixel]);
xmin = max([min([XYc1(1,1)/XYc1(3,1), XYc2(1,1)/XYc2(3,1), XYc3(1,1)/XYc3(3,1), XYc4(1,1)/XYc4(3,1)]), -1250*pixel]);
ymax = min([max([XYc1(2,1)/XYc1(3,1), XYc2(2,1)/XYc2(3,1), XYc3(2,1)/XYc3(3,1), XYc4(2,1)/XYc4(3,1)]), 1250*pixel]);
ymin = max([min([XYc1(2,1)/XYc1(3,1), XYc2(2,1)/XYc2(3,1), XYc3(2,1)/XYc3(3,1), XYc4(2,1)/XYc4(3,1)]), -1250*pixel]);

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(2,1)/XYc4(3,1)],-1250*pixel]);

% Plot retified image
% Plate needs to be within 50 inches from the center of the target at
% minimum pixel redraw size
fprintf('Calculating image transformation.\nThis may take a few minutes...\n');
[IAll,AxAll] = rectify(ImgName,H_AllPts,[xmin xmax ymin ymax pixel pixel]);
xlswrite(imgxls,AxAll,'AxAll','A1');
figure
imagesc([AxAll(1) AxAll(2)],[AxAll(3) AxAll(4)],IAll);
axis image
axis xy
hold on
for j = 1:length(u)
    plot(X(j),Y(j),'r*')
    h = text(X(j)+.25,Y(j),refnames(j));
    set(h,'color','r','fontsize',9)
end
title('Rectified Image')

imgrect = [imgfilename,'_r.jpeg'];
imwrite(IAll(end:-1:1,:,:),imgrect,'jpeg');
imgsavetxt = ['\nImage saved to ',imgrect,'\n\n'];
fprintf(imgsavetxt);
zi = input('Press ''Enter'' to contintue. ');
end

PX = [];
PY = [];
BX = [];
BY = [];
os = 1;
while os
    clc
    fprintf('Homogeneous Coordinates Rectification for Gusset Plates\n\n');
    OptionSelect = input('Select an option:\n [1] Take measurements on the image\n [2]
Select the plate perimeter\n [3] Select bolt locations\n [4] Quit Program\n\nSelection
= ','s');

% Selection of measurement types
if OptionSelect == '1'
    Calc = 1;
    figure
    imagesc([AxAll(1) AxAll(2)],[AxAll(3) AxAll(4)],IAll);
    if (NewImage == 1)
        axis image
        axis xy
    end
    hold on

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```

title('Measurements')
while Calc
    clc
    fprintf('Homogeneous Coordinates Rectification for Gusset Plates\n\n');
    MeasureType = input('Measurement Type:\n [1] Distance\n [2] Angle\n [3]
Clear Points\n [4] Back\n\nSelection = ','s');

    % Measure the distance between two selected points
    if MeasureType == '1'
        DistMeasure = 1;
        while DistMeasure
            clc
            fprintf('Homogeneous Coordinates Rectification for Gusset
Plates\n\n');

            fprintf('Distance between two points:\n');
            zi = input('Zoom in on first point, press ''Enter'', then click on
the control point. ');
            [x1 y1] = ginput(1);
            plot(x1,y1,'c*')
            zi = input('Zoom in on second point, press ''Enter'', then click on
the control point. ');
            [x2 y2] = ginput(1);
            plot(x2,y2,'c*')
            plot([x1 x2],[y1 y2])
            dist = sqrt((x2-x1)^2+(y2-y1)^2)
            flag = 1;
            while flag
                RepeatMeasure = input('Another distance measurement?\n [1]
Yes\n [2] No\n\nSelection = ','s');
                if RepeatMeasure == '1'
                    flag = 0;
                end
                if RepeatMeasure == '2'
                    flag = 0;
                    DistMeasure = 0;
                end
            end
        end
    end

    % Measure the angle between three selected points
    if MeasureType == '2'
        AngMeasure = 1;
        while AngMeasure
            clc
            fprintf('Homogeneous Coordinates Rectification for Gusset
Plates\n\n');

            fprintf('Angle between three points:\n');
            zi = input('Zoom in on first point, press ''Enter'', then click on
the control point. ');
            [x1 y1] = ginput(1);

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        plot(x1,y1,'c*')
        zi = input('Zoom in on second point, press ''Enter'', then click on↵
the control point. ');
        [x2 y2] = ginput(1);
        plot(x2,y2,'c*')
        zi = input('Zoom in on third point, press ''Enter'', then click on↵
the control point. ');
        [x3 y3] = ginput(1);
        plot(x3,y3,'c*')
        plot([x1 x2],[y1 y2])
        plot([x2 x3],[y2 y3])
        dist1to2 = sqrt((x2-x1)^2+(y2-y1)^2)
        dist2to3 = sqrt((x3-x2)^2+(y3-y2)^2)
        L1 = [x1-x2 y1-y2];
        L2 = [x3-x2 y3-y2];
        angle = acos(dot(L1,L2)/(dist1to2*dist2to3))*180/pi
        flag = 1;
        while flag
            RepeatMeasure = input('Another angle measurement?\n [1] Yes↵
[2] No↵\nSelection = ','s');
            if RepeatMeasure == '1'
                flag = 0;
            end
            if RepeatMeasure == '2'
                flag = 0;
                AngMeasure = 0;
            end
        end
    end
end

% Clear points on rectified image
if MeasureType == '3'
    imagesc([AxAll(1) AxAll(2)],[AxAll(3) AxAll(4)],IAAll);
    axis image
    axis xy
    hold on
end

% Quit taking measurements
if MeasureType == '4'
    Calc = 0;
end

end

end

% Select Perimeter of the gusset plate
% Output coordinates of the corners to an excel file
if OptionSelect == '2'
    figure

```

```

imagesc([AxAll(1) AxAll(2)],[AxAll(3) AxAll(4)],IA11);
if (NewImage == 1)
    axis image
    axis xy
end
hold on
title('Perimeter')
flag = 1;
redocheck = 1;
clc
fprintf('Homogeneous Coordinates Rectification for Gusset Plates\n\n');
if length(PX) > 1
    for j = 1:length(PX)
        plot(PX(j),PY(j),'m*')
        if j > 1
            plot([PX(j-1) PX(j)],[PY(j-1) PY(j)])
        end
    end
    plot([PX(1) PX(end)],[PY(1) PY(end)])
    flag2 = 1;
    while flag2
        Poption = input('Select an option:\n [1] Redo Perimeter\n [2]
End\n\nSelection = ','s');
        if Poption == '1'
            for j = 1:length(PX)
                PX(j) = 9999;
                PY(j) = 9999;
            end
            fprintf('Overwriting perimeter values with 9999.\nThis may take a
few seconds...\n');
            PXY = [PX' PY'];
            xlswrite(imgxls,PXY,'Plate','A2');
            PX = [];
            PY = [];
            flag2 = 0;
            imagesc([AxAll(1) AxAll(2)],[AxAll(3) AxAll(4)],IA11);
        end
        if Poption == '2'
            flag = 0;
            flag2 = 0;
            redocheck = 0;
        end
    end
end

while flag
    clc
    fprintf('Homogeneous Coordinates Rectification for Gusset Plates\n\n');
    fprintf('Left-Click selects a corner.\n');
    fprintf('Right-Click to zoom in/out until ''Enter'' is pressed.\n');
    fprintf('Middle-Click to undo the last corner or end selecting corners.\n');

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```

[MX MY Mclick] = ginput(1);
if Mclick == 1
    PX(end+1) = MX;
    PY(end+1) = MY;
    plot(PX(end),PY(end),'m*')
    if length(PX) > 1
        plot([PX(end-1) PX(end)],[PY(end-1) PY(end)])
    end
end
if Mclick == 2
    flag2 = 1;
    while flag2
        UEC = input('Select an option:\n [1] Undo\n [2] End\n [3]
Cancel\n\nSelection = ','s');
        if UEC == '1'
            imagesc([AxAll(1) AxAll(2)],[AxAll(3) AxAll(4)],IA11);
            axis image
            axis xy
            hold on
            for j = 1:(length(PX)-1)
                plot(PX(j),PY(j),'m*')
                if j > 1
                    plot([PX(j-1) PX(j)],[PY(j-1) PY(j)])
                end
            end
            end
            zi = input('Zoom in on the last corner, press ''Enter'', then
click on the corner. ');
            [MX MY Mclick] = ginput(1);
            if Mclick == 1
                if isempty(PX) == 0
                    PX(end) = MX;
                    PY(end) = MY;
                end
                if isempty(PX) == 1
                    PX(end+1) = MX;
                    PY(end+1) = MY;
                end
                end
                plot(PX(end),PY(end),'m*')
                if length(PX) > 1
                    plot([PX(end-1) PX(end)],[PY(end-1) PY(end)])
                end
                end
                flag2 = 0;
            end
        end
    end
    if UEC == '2'
        flag = 0;
        flag2 = 0;
        if length(PX) > 1
            plot([PX(1) PX(end)],[PY(1) PY(end)])
        end
    end
end

```

```

        if UEC == '3'
            flag2 = 0;
        end
    end
end
if Mclick == 3
    zi = input('Zoom in on a corner, press 'Enter'', then click on the
corner. ');
    end
end
clc
fprintf('Homogeneous Coordinates Rectification for Gusset Plates\n\n');
if redocheck == 1
    PXY = [PX' PY'];
    fprintf('Saving perimeter information to file.\nThis may take a few
seconds...\n');
    xlswrite(imgxls,'X','Plate','A1');
    xlswrite(imgxls,'Y','Plate','B1');
    if isempty(PX) == 0
        xlswrite(imgxls,PXY,'Plate','A2');
    end
end
end
end

% Select locations of the bolts of the gusset plate
% Output coordinates of the bolt to an excel file
if OptionSelect == '3'
    figure
    imagesc([AxAll(1) AxAll(2)],[AxAll(3) AxAll(4)],IA11);
    if (NewImage == 1)
        axis image
        axis xy
    end
    hold on
    title('Bolt locations')
    flag = 1;
    redocheck = 1;
    clc
    fprintf('Homogeneous Coordinates Rectification for Gusset Plates\n\n');
    if length(BX) > 1
        for j = 1:length(BX)
            plot(BX(j),BY(j),'c*')
        end
        flag2 = 1;
        while flag2
            Boption = input('Select an option:\n [1] Redo Bolt Locations\n [2]
Continue Bolt Locations\n [3] End\n\nSelection = ','s');
            if Boption == '1'
                for j = 1:length(BX)
                    BX(j) = 9999;
                    BY(j) = 9999;
                end
            end
        end
    end
end

```

```

        end
        fprintf('Overwriting bolt location values with 9999.\nThis may take
a few seconds...\n');
        BXY = [BX' BY'];
        xlswrite(imgxls,BXY,'Bolts','A2');
        BX = [];
        BY = [];
        flag2 = 0;
        imagesc([AxAll(1) AxAll(2)],[AxAll(3) AxAll(4)],IAll);
    end
    if Boption == '2'
        flag2 = 0;
    end
    if Boption == '3'
        flag = 0;
        flag2 = 0;
        redocheck = 0;
    end
end
end

while flag
    clc
    fprintf('Homogeneous Coordinates Rectification for Gusset Plates\n\n');
    fprintf('Left-Click selects a bolt location.\n');
    fprintf('Right-Click to zoom in/out until ''Enter'' is pressed.\n');
    fprintf('Middle-Click to undo the last bolt location or end selecting bolt
locations.\n');
    [MX MY Mclick] = ginput(1);
    if Mclick == 1
        BX(end+1) = MX;
        BY(end+1) = MY;
        plot(BX(end),BY(end),'c*')
    end
    if Mclick == 2
        flag2 = 1;
        while flag2
            UEC = input('Select an option:\n [1] Undo\n [2] End\n [3]
Cancel\n\nSelection = ','s');
            if UEC == '1'
                imagesc([AxAll(1) AxAll(2)],[AxAll(3) AxAll(4)],IAll);
                axis image
                axis xy
                hold on
                if length(BX) > 1
                    for j = 1:(length(BX)-1)
                        plot(BX(j),BY(j),'c*')
                    end
                end
                end
                zi = input('Zoom in on last bolt location, press ''Enter'', then
click on the bolt. ');

```

```

        [MX MY Mclick] = ginput(1);
        if Mclick == 1
            if isempty(BX) == 0
                BX(end) = MX;
                BY(end) = MY;
            end
            if isempty(BX) == 1
                BX(end+1) = MX;
                BY(end+1) = MY;
            end
            plot(BX(end),BY(end),'c*')
            flag2 = 0;
        end
    end
    if UEC == '2'
        flag = 0;
        flag2 = 0;
    end
    if UEC == '3'
        flag2 = 0;
    end
end
end
if Mclick == 3
    zi = input('Zoom in on a bolt location, press ''Enter'', then click on
the corner. ');
end
end
clc
fprintf('Homogeneous Coordinates Rectification for Gusset Plates\n\n');
if redocheck == 1;
    BXY = [BX' BY'];
    fprintf('Saving bolt location information to file.\nThis may take a few
seconds...\n');
    xlswrite(imgxls,'X','Bolts','A1');
    xlswrite(imgxls,'Y','Bolts','B1');
    if isempty(BX) == 0
        xlswrite(imgxls,BXY,'Bolts','A2');
    end
end
end
end

% Quit Program
if OptionSelect == '4'
    flag = 1;
    while flag
        clc
        fprintf('Homogeneous Coordinates Rectification for Gusset Plates\n\n');
        VerifyQuit = input('Quit program?\n [1] Yes\n [2] No\n\nSelection =
','s');
    end
end

```

```
        if VerifyQuit == '1'
            flag = 0;
            os = 0;
        end
        if VerifyQuit == '2'
            flag = 0;
        end
    end
end
end
end
clc
```

```
function [RI, Raxes] = rectify(Iname,T,R);
%
% FUNCTION RI = rectify(Iname,T,R);
%
% OUTPUTS:
%   RI:    Rectified Image
%   Raxes: Rectified Coordinates for Axes [Xmin Xmax Ymin Ymax]
%
% INPUTS:
%   Iname: image filename (JPEG)
%   T:     transformation matrix coefficients
%   R:     rectification parameters with format:
%           [Real World Xmin (in)
%            Real World Xmax (in)
%            Real World Ymin (in)
%            Real World Ymax (in)
%            X scale for orthorectified image (inches per pixel)
%            Y scale for orthorectified image (inches per pixel)]
%
% Modified by Jason Killian
% Modified by Quang Nguyen

% Read in image file
I = imread(Iname);
IsizeX = size(I,2);
IsizeY = size(I,1);

% Create grid of Real World coordinates
[Gridx,Gridy] = meshgrid(R(1):R(5):R(2),R(3):R(6):R(4));

% Determine the rank of the homography
Hrank = size(T,2);

switch Hrank
case 3
    % make vector of grid [x,y,z,1]
    Gvec(1,:) = reshape(Gridx,1,prod(size(Gridx)));
    Gvec(2,:) = reshape(Gridy,1,prod(size(Gridy)));
    Gvec(3,:) = ones(1,prod(size(Gridx)));
    Gsize = size(Gridx);
case 4
    % make vector of grid [x,y,z,1]
    Gvec(:,1) = reshape(Gridx,prod(size(Gridx)),1);
    Gvec(:,2) = reshape(Gridy,prod(size(Gridy)),1);
    Gvec(:,3) = ones(size(prod(size(Gridx)),1)).*R(7);
    Gvec(:,4) = ones(size(prod(size(Gridx)),1));
    Gsize = size(Gridx);
otherwise
    error('Tmatrix must be rank 3 or 4');
    return
end
```

```
clear Gridx Gridy

% Transform Real World coords to screen coords
tScreen = T*Gvec;
% calculate [u,v] pixel coords for each grid point (x,y)
Screen(1,:) = round(tScreen(1,:)./tScreen(3,:));
Screen(2,:) = round(tScreen(2,:)./tScreen(3,:));
Screen = Screen';

% blank out pixel indexes that fall outside original image
z = find(Screen(:,1)<1 | Screen(:,1)>Isizex);
Screen(z,1) = 1;
Screen(z,2) = 1;
z = find(Screen(:,2)<1 | Screen(:,2)>Isizey);
Screen(z,1) = 1;
Screen(z,2) = 1;

% convert [u,v] to linear pixel count
zScreen = (Screen(:,1)-1).*Isizex + Screen(:,2);

% Reshape original image to vector form
I(1,1,1) = 255;
I(1,1,2) = 255;
I(1,1,3) = 255;

red = reshape(I(:,:,1),Isizex*Isizey,1);
green = reshape(I(:,:,2),Isizex*Isizey,1);
blue = reshape(I(:,:,3),Isizex*Isizey,1);

% Map image colors onto Grid
Mred = red(zScreen);
Mgreen = green(zScreen);
Mblue = blue(zScreen);

% Reshape mapped image
try
    RI(:,:,1) = reshape(Mred,Gsize);
    RI(:,:,2) = reshape(Mgreen,Gsize);
    RI(:,:,3) = reshape(Mblue,Gsize);
catch
    keyboard
end
Raxes = [R(1) R(2) R(3) R(4)];
```