

Evaluation of Dynamic Roof Deformation in Rollover Crash Tests

2011-01-1093

Published
04/12/2011

Stuart W. Harvin, Bridget M. O'Brien-Mitchell, Andrew R. Dwoinen, Carol Ann Nassoiy, Daniel F. Motowski, Anthony G. Melocchi, Huizhen Lu and Manuel V. Peace
General Motors Company

Copyright © 2011 SAE International

doi:10.4271/2011-01-1093

ABSTRACT

Although the measured amount of roof deformation associated with a given rollover crash test is often the residual or post test deformation, rollover crash test researchers are aware that roof deformation occurs dynamically throughout the rollover event with varying magnitude. The challenge to quantifying dynamic roof deformation has been the lack of a reliable method to measure and record the dynamic roof deformation during the rollover test. Researchers have explored various methods to measure dynamic roof deformation including the use of film analysis of external targets, accelerometers, string potentiometers, and 3D photogrammetry.

This paper discusses a series of simulated curb trip rollover tests conducted to study and compare different methodologies to measure and record dynamic roof deformation. The tests involved midsize crossover utility vehicles instrumented with accelerometers on the roof rails at the A and B pillars and string potentiometer arrays at roof locations above the front driver and passenger seating locations. High speed digital motion cameras were rigidly mounted inside the vehicles to monitor the movement of the interior roof targets as the roof deformed during the rollover event. This paper discusses and compares the dynamic roof deformation data as measured by the roof string potentiometers and 3D photogrammetry as compared to post-test residual deformation measurements.

INTRODUCTION

Typically, the measured amount of roof deformation associated with a given rollover crash test is the residual or post test deformation. The NHTSA NASS-CDS Coding and Editing Manual [1] described method of measuring vehicle

“occupant area intrusion”, is the technique researchers have typically used to measure post test roof deformation. Essentially, the researcher selects a non-affected (undeformed) area of the vehicle to use as a reference axis on which to base the measurement. The measurement is then made vertically (z direction) from the reference axis to the point of deformation on the roof. Often, it is only the area of maximum deformation that is of interest by the researcher. This measurement is then compared to that of an exemplar vehicle, taken at the same location and related back to the same reference axis to determine the amount of deformation. The residual deformation measurements can be taken with a broad range of measurement devices from a simple tape measure while investigating an accident in the field to coordinate measurement machines (CMM) or laser scanners in a crash laboratory setting.

Rollover crash researchers are aware that roof deformation occurs dynamically, or time-dependently, throughout the rollover event with varying magnitude, which often differs from the post test measurement of the residual deformation. The term “dynamic” is sometimes associated with only the difference between the total roof crush experienced during a rollover and the residual (static) roof crush measured after the rollover.[2] However, in this study dynamic roof deformation is defined as the roof deformation or movement in any direction, as it occurs in time during the associated rollover event. This includes longitudinal or lateral shifting of the roof structure. It also involves tenting (positive z deformation) of the roof panel as well as roof panel intrusion (negative z deformation). The challenge to quantifying dynamic roof deformation has been the lack of a reliable method to measure and record the dynamic roof deformation during the rollover test. Researchers have explored various methods to measure dynamic roof deformation including the use of film

analysis of external targets, accelerometers, string potentiometers, and 3D photogrammetry. One researcher developed a system of telescoping rods on gimbals to determine the maximum amount of dynamic deformation (specifically intrusion) [3] that the vehicle experienced during a rollover crash.

A fact which is well known among safety and crash researchers is that accelerometer measurement is influenced by local sheet metal deformation and rotation experienced in the impact zone. Accelerometer measurement can even be affected by the ringing (at the natural frequency) of a structural component excited during an impact even if there is no deformation. The high frequency vibration of the vehicle structure caused by the impact can induce errors or “noise” into the accelerometer measurement. These errors are then magnified with mathematical manipulation of the data. Research has shown that even when substituted into theoretically correct dynamic rollover equations, the accelerometer data can lead to erroneous results [4]. Upon simple numerical integration, the effect of the noise in the accelerometer data was apparent to the authors. It was decided for this reason that an attempt to assess the dynamic roof displacement using the accelerometer measured data should be avoided. The focus for this paper was placed on evaluating those roof deformation measurement methods that would measure displacement directly and would be less likely to be influenced by the roof to ground impact or other vehicle kinematics during the rollover; specifically string potentiometer and 3D photogrammetric measurement.

String potentiometers have been used in different types of vehicle development tests from the measurement of vehicle displacements during suspension response testing [5] to the measurement of structural deformations during vehicle side impact [6, 7] as well as vehicle roof strength tests [8]. String potentiometers are standard instrumentation devices that can be found in most safety and crash test laboratories and are easy and straight forward to use.

3D photogrammetric measurement on the other hand, requires specialized photographic equipment and software set up to ensure that measurement error is minimized. 3D photogrammetric techniques have been used in accident reconstruction to determine static vehicle structural deformation [9] and for estimating equivalent barrier speed [10] using digital still photography. Advances in digital video camera and computer imaging technology have made it possible to use 3D photogrammetry to measure structural deformations as well as occupant kinematics dynamically [11,12].

This paper discusses a series of simulated curb trip rollover tests conducted to study and compare two different methodologies to measure and record dynamic roof deformation. The tests involved midsize crossover utility

vehicles instrumented with string potentiometer arrays at roof locations above the front driver and passenger seating locations. High speed digital motion cameras were rigidly mounted inside the vehicles to monitor interior roof targets as the roof deformed during the rollover event. The vehicles were also instrumented with accelerometers on the roof rails at the A and B pillars. The accelerometer data was used mainly to determine the timing of vehicle to ground impacts in order to better synchronize the crash test data to the recorded videos during the data analysis. This paper discusses and compares the dynamic roof deformation data as measured by the roof string potentiometers and 3D photogrammetry. The measured dynamic roof deformation is then compared to post-test residual deformation measurements.

TEST SERIES DESCRIPTION

Five simulated curb trip rollover tests were conducted on midsize crossover utility vehicles (CUVs). The simulated curb trip methodology used was that developed by O'Brien-Mitchell et. al [13] with a targeted 4g lateral deceleration pulse. Using this method, each vehicle was placed atop a flying floor with a low friction surface. Under each tire a patch of Ultra High Molecular Weight Polyethylene (UHMW/PE) plastic was placed to reduce the friction between the vehicle and the flying floor. A guided curb fixture was used as a reaction surface for the initial trip of the vehicles. Plascore honeycomb decelerator material was used to provide energy absorption to the vehicles wheels and suspension components for each test in the study. The decelerator for each wheel had the same crush property; however the decelerator dimensions were based on the respective axle mass. Figure 1 shows the decelerator and guided curb fixture in test position.



Figure 1. Honeycomb Decelerator and Guided Curb Fixture

The flying floor and vehicle were decelerated using six pneumatic brake units sliding on an above ground rail system. The flying floor deceleration pulses for all of the tests were consistent throughout the test series and are shown in [Figure 2](#).

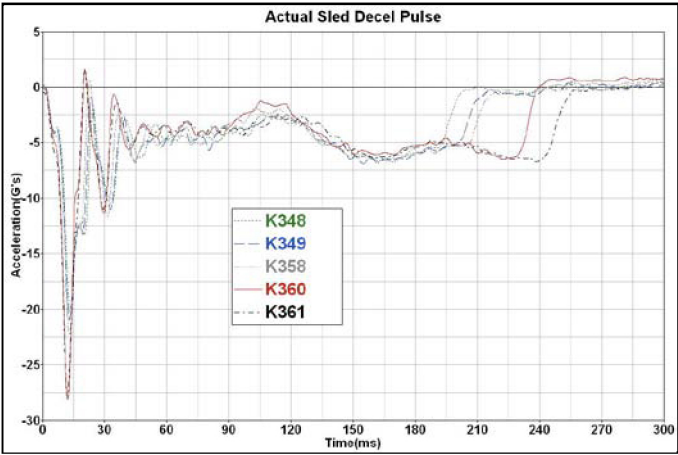


Figure 2. Sled Deceleration Pulse

The test speed was varied for each test to try to generate a variety of vehicle to ground impact angles. One test condition was repeated during the test series. The tests conducted are shown in [Table 1](#).

Table 1. Test Matrix

Test Number	Speed [km/h]	Angle at Roof to Ground Impact [deg]	Comments
K348	35.7	123	Vehicle landed on curbs, then rolled to roof. Removed anti-rebound feature on remaining tests.
K349	38.1	143	Vehicle landed on roof.
K358	40.0	164	Vehicle landed on roof.
K360	45.3	207	Vehicle contacted roof and landed on wheels.
K361	45.6	200	Vehicle contacted roof and landed on wheels.

The first test of the study (K348) used an anti-rebound device typically used to limit the amount the flying floor can rebound into a rolling vehicle. The anti-rebound device caused the test vehicle to partially land on the flying floor during impact. The remaining tests in the study were executed without the anti-rebound devices allowing the flying floor to rebound away from the rolling vehicle. [Figure 3](#) shows a photo sequence with and without the anti-rebound devices highlighted with the dotted line.

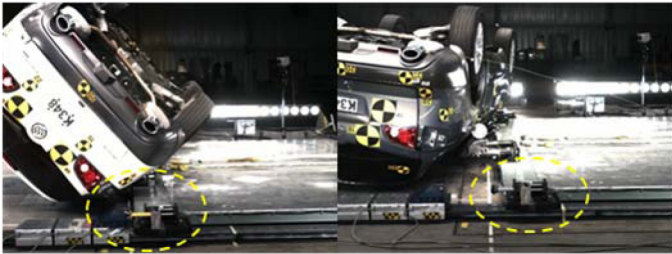


Figure 3. Anti-rebound Device Interference

VEHICLE INSTRUMENTATION

Tri-axial accelerometers (Endevco Model 7264C) were placed at the following locations on the test vehicles:

- Under the left and right front seats
- At the left and right B-pillar at the rocker
- At the left and right C-pillar at the rocker
- On and near the sensing and diagnostic module (the main airbag control unit)
- On the left and right B-pillar at the vehicle center of gravity height
- On the left and right roof rail at the B-pillar
- On the left and right front header at the A-pillar
- On the roof at the center header



Figure 4. Overall View of String Potentiometers, Right Side Similar

Rate gyroscopes (DTS ARS-1500) were placed on and near the sensing and diagnostic module as well as on the left front floorpan at the driver's seat location. String potentiometers (Spaceage Control Model 161-2145) were mounted to the roof above the geometric center of the left and right seats. Three string potentiometers were attached at each roof

location with string potentiometer wire and were mounted to the seat frames on the floor of the vehicle, as shown in [Figure 4](#) and [Figure 5](#). All electronic data was sampled at 10 kHz. All vehicle electronic data was captured with DTS TDAS Pro hardware and software.



Figure 5. String Potentiometer Mounting, Right Side
Similar

HIGH SPEED DIGITAL MOTION CAMERAS

In order to measure the roof deformation with 3D photogrammetry, three onboard high speed digital motion cameras (RedLake MotionXtra HG-TH), each with a resolution of 752×564 pixels using a frame rate of 500 frames per second (fps), were rigidly mounted in the rear of the vehicle, as shown in the schematic in [Figure 6](#).

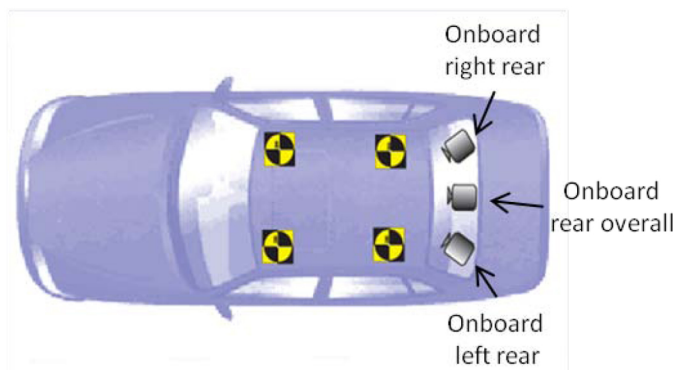


Figure 6. Onboard Camera Schematic

Three cameras were utilized for the analysis. They were plugged into the same camera controller in order for the video frames to be synchronized, which is necessary for 3D photogrammetry. The placement and lenses of the cameras were chosen in order to provide a field of view which consisted of always having at least two cameras viewing the kinematics targets to be analyzed at the same time. The center camera had a 4.8 mm lens and a field of view of the entire front of the vehicle interior and was utilized during each of the analysis. The two other cameras had 5.9 mm lenses and a field of view of the left or right side of the vehicle interior and were used for the tracking. The angle between the cameras was maximized without compromising the field of view of the targets. The calculated angles between the cameras were between 25 and 30 degrees depending on which two cameras were used for the analysis (center camera and one or the other outboard cameras). The size of the kinematics targets to be tracked was chosen to be at least 75 mm diameter in order to provide a resolution greater than 10 pixels across the target. This was required for the TrackEye software due to the angle of the target and the distance from the target to the cameras. Additional kinematics targets were placed on the vehicle interior to provide the TrackEye software with a reference coordinate system, which is defined at time zero. The targets used for reference can also be tracked, so for this analysis all the kinematics targets were used for reference. Due to the depth of view in the vehicle, the reference kinematics targets were a mix of 50 mm, 75 mm and 100 mm diameter in order to provide an appropriate resolution for the software (greater than 10 pixels across the target). [Figure 7](#), [Figure 8](#) and [Figure 9](#) show the field of view provided by the onboard cameras.



Figure 7. Onboard Rear Overall Camera View



Figure 8. Onboard Right Rear Camera View



Figure 9. Onboard Left Rear Camera View

A schematic of the offboard high speed digital motion cameras (RedLake MotionXtra HG-100K) are shown in [Figure 10](#). All offboard cameras had a frame rate of 500 fps and a resolution of 1504×1128 pixels. There were four off-board cameras that were positioned in the four corners of the test area and synchronized for film analysis of vehicle motion with 3D photogrammetry. These four cameras are shown in grey in the figure. The other cameras provided off-board front and rear overall views of the vehicle, as well as an off-board close up of the curb trip fixture, and an off-board downstream view of the rollover.

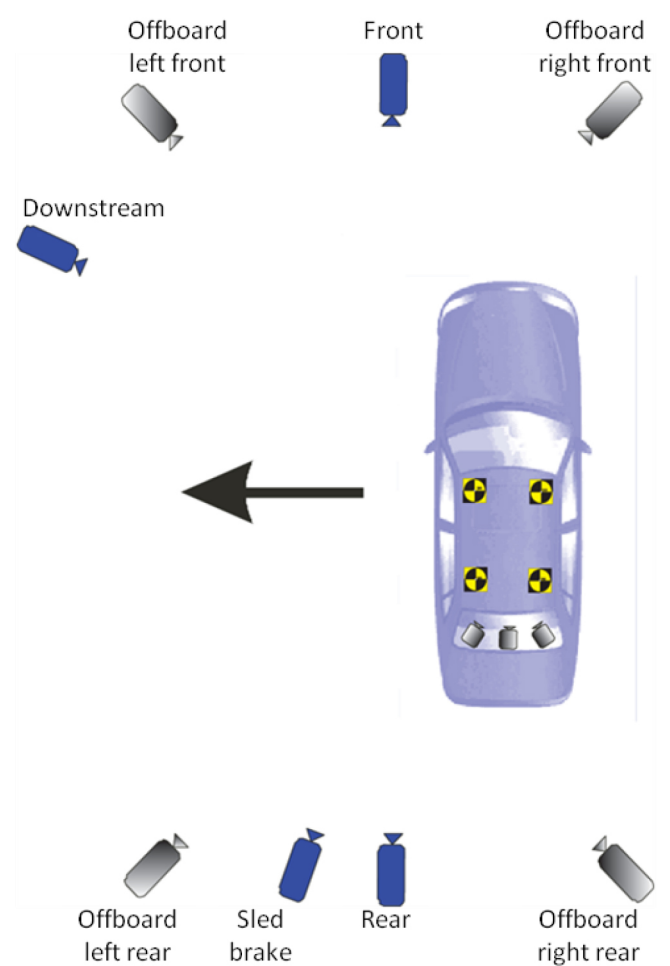


Figure 10. Offboard Camera Schematic

[Figure 11](#), [Figure 12](#), [Figure 13](#), and [Figure 14](#) show the views from the cameras used for offboard 3d photogrammetry.

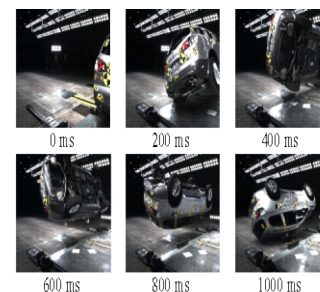


Figure 11. Right Rear Offboard Camera View

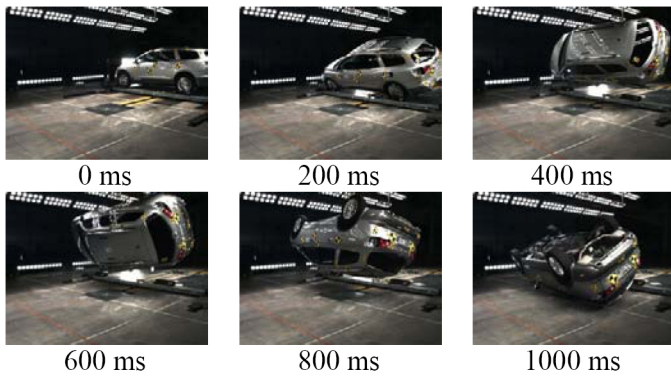


Figure 12. Left Rear Offboard Camera View

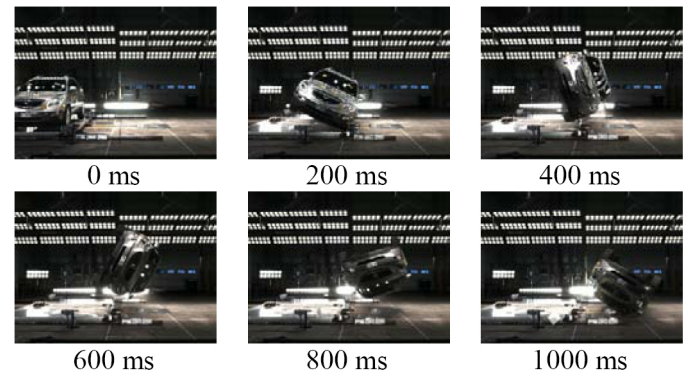


Figure 15. Front Camera View

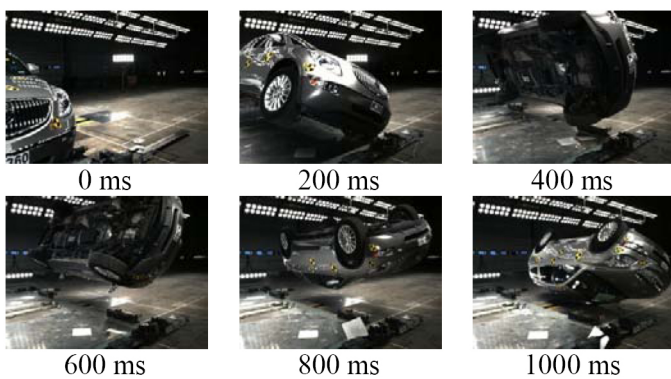


Figure 13. Right Front Offboard Camera View

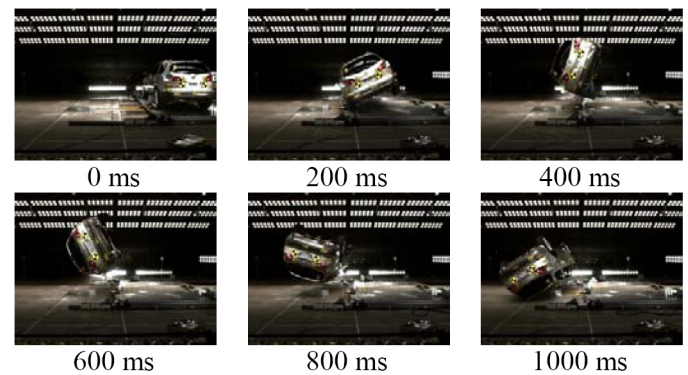


Figure 16. Rear Camera View

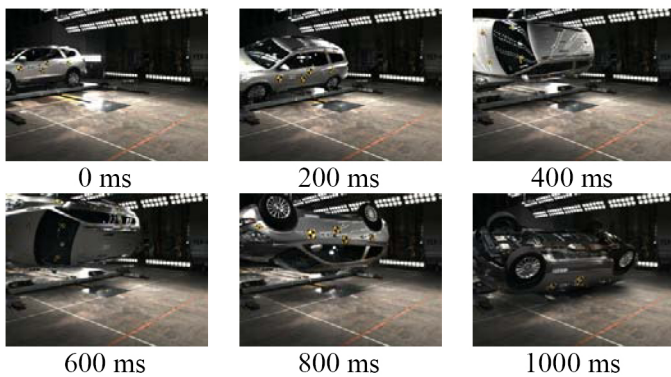


Figure 14. Left Front Offboard Camera View

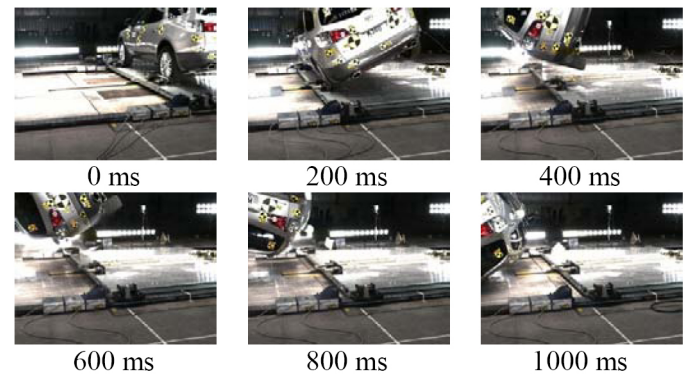


Figure 17. Sled Brake Camera View

The remaining off-board camera views are shown in [Figure 15](#), [Figure 16](#), [Figure 17](#), and [Figure 18](#).

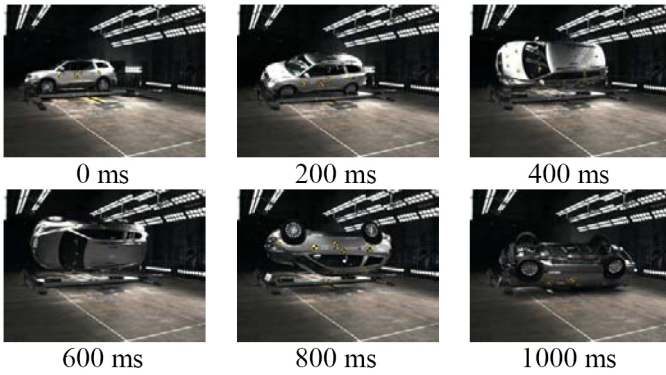


Figure 18. Downstream Camera View

DATA ANALYSIS

Dynamic roof deformation was calculated using the following three methods:

- String potentiometer motion resolved into vehicle coordinates through a nonlinear least squares trilateration method with a closed-form solution
- String potentiometer motion resolved into vehicle coordinates through a nonlinear least squares trilateration method using numerical methods
- Onboard 3D photogrammetry.

ANALYSIS OF STRING POTENTIOMETER MOTION

Two sets of three string potentiometers were mounted to the seat riser structure for the left front and right front seats and were attached to a point on the roof that was at the geometric center of the seat based on the seat attachments to the floor, as shown in [Figure 4](#). The data from each set of three string potentiometers were analyzed and resolved into vehicle coordinates to track the dynamic movement of the roof point relative to the seat structure. A schematic of the string potentiometer coordinate system is shown in [Figure 19](#).

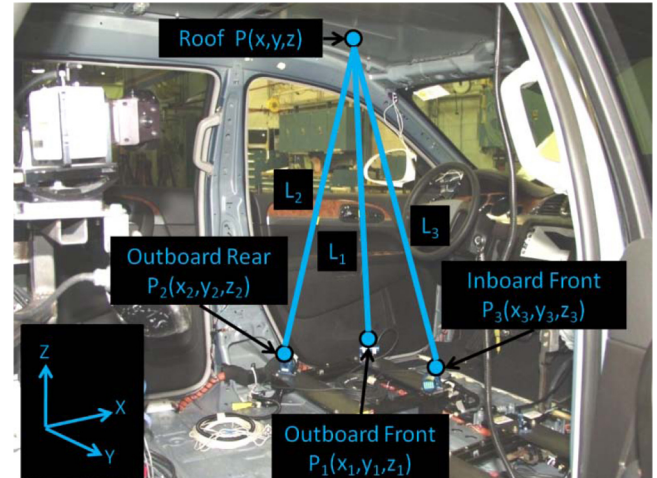


Figure 19. Location of Point P in 3d Space

DETERMINING DYNAMIC ROOF DEFORMATION BY TRILATERATION

Trilateration is the method of determining or tracking a point in 3D (or 2D) space by measuring its distance from 3 known points. It differs from triangulation in that no angles are used in the equations to determine the point location. Trilateration is used most notably in Global Positioning System tracking and has been used traditionally in surveying and navigation. [14]

Closed-form Solution

Yun [15] derived a closed form solution for [equations \(1\),\(2\), \(3\)](#) shown below for a nonlinear least squares trilateration method to determine the location of Point P as a function of time. Point P is shown on the roof in [Figure 19](#).

$$(x_1 - x)^2 + (y_1 - y)^2 + (z_1 - z)^2 = L_1^2 \quad (1)$$

$$(x_2 - x)^2 + (y_2 - y)^2 + (z_2 - z)^2 = L_2^2 \quad (2)$$

$$(x_3 - x)^2 + (y_3 - y)^2 + (z_3 - z)^2 = L_3^2 \quad (3)$$

The locations of the string potentiometers on the seat riser as well as the roof point (point P) were known pre-test. To verify the accuracy of the closed-form solution, the pre-test measurements were used to calculate the lengths of the three strings (L1, L2, and L3). Next, the pre-test location of point P was calculated and compared to the CMM measured location. The location of point P calculated by the trilateration method matched the actual measured location. These calculations were then able to be applied to the time-history data for the string potentiometers to calculate the location of Point P through time.