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ABSTRACT

This paper presents an image analysis of a laboratory-based rollover crash test using camera-matching photogrammetry. The procedures pertaining to setup, analysis and data process used in this method are outlined. Vehicle roll angle and rate calculated using the method are presented and compared to the measured values obtained using a vehicle mounted angular rate sensor. Areas for improvement, accuracy determination, and vehicle kinematics analysis are discussed. This paper concludes that the photogrammetric method presented is a useful tool to extract vehicle roll angle data from test video. However, development of a robust post-processing tool for general application to crash safety analysis requires further exploration.

INTRODUCTION

Photogrammetry, whose origins can be traced to the late 19th century, is a methodology to interpret and extract information from images and photographs. It is the science of measuring 3D objects from images and has been proven to be a robust method for measuring both the static and dynamic characteristics of many objects. Photogrammetric techniques have been used successfully in a wide variety of applications: aerial surveying, civil engineering and documentation of traffic accidents (Breen, et al. 1986). Photogrammetry has been applied to determine static vehicle crush and for estimating equivalent barrier speed (Fenton et al. 1999).

Photogrammetry potentially may be used as a method to measure dynamic 3-dimensional structural deformations that occur during vehicle crash testing. The method could consist of first placing coded targets at the points of interest. The motion of each target can be captured from two or more perspectives using digital cameras positioned at discrete angles. Processing and analysis of the recorded motion will yield the movements of these targets in a three dimensional space as a function of time. Application of photogrammetry in extracting 3D structural deformation and occupant motion time histories during vehicle crashes was made to analyze the structural deformation of vehicle interior using videos obtained from on-board cameras in a laboratory-based rollover test (Nakhla, McClenathan, McCoy and Chou, 2005). However, an investigation is still needed to determine an appropriate method to post-process crash film to provide:

- Dummy kinematics: relative displacement, velocity, and acceleration of each body segment of an ATD (Anthropomorphic Test Device), such as head, chest, leg, etc.,

- Vehicle kinematics: such as (1) vehicle 3D motion with three linear accelerations and three rotational rates about the vehicle longitudinal, vertical and lateral axes, and (2) structural deformations of a vehicle component as a function of time.

Potential applications of photogrammetry:

- Structural intrusion in side impacts
- Dynamic toe-board intrusion in rigid barrier and offset frontal impacts
- Air bag deployment shape analysis
- Occupant/airbag interaction analysis

The purpose of this study is to explore the feasibility of obtaining position, orientation, and velocity data of a vehicle using a camera-matching photogrammetric technique to analyze videos taken from off-board cameras in a rollover crash test. The position, orientation, and velocity information obtained through camera-matching may supplement the data that was obtained from either on-board instrumentation of the vehicle or post-test examination and/or measurements of vehicle damage, if any, during or after the test.

APPROACH

PROCESSING TOOLS

Basic photogrammetry utilizes two calibrated cameras with known locations and focus lengths to record images of targets whose locations are determined by using triangulation. Further analysis can be performed to obtain displacement, velocity, acceleration, or relative movement between targets. Several software packages, often referred to as motion analyzers, have been developed for image tracking (TEMA, Falcon, for example). A few commercially available packages are listed in Table I. The results of using Falcon Software in an occupant kinematics study were reported (Nakhla, McClenathan, McCoy and Chou, 2005). In this paper, Photogrammetric techniques using 3D Modeler Software are used to analyze vehicle motion occurring during a laboratory-based rollover test are presented.

Table I: Photogrammetry Software

Software program	Vendor	Remarks
AutoCAD	Autodesk San Rafael, CA	A 3D software program
3D Studio MAX	Discreet, A division of Autodesk	Used in many animation, video games.
Photomodeler Pro 3.0	Eos Systems Vancouver, Canada	
EDCRASH Vehicle Analysis Package, 4th edition	Engineering Dynamics Corp. Beaverton, OR	
V-Stars	Geodetic Melbourne, FL	3D
3D Modeler		3D
TEMA	Instrumentation Marketing Corp.	2D capability. 3D is currently under development
Falcon	Falknex Consulting for Measuring Technology GmbH Grafeling-Locham, Germany	2D/3D capabilities with animation
Visual Fusion	Boeing -SVS Albuquerque, NM	2D/3D

USING 3D MODELER IN ROLLOVER ANALYSIS

3D Modeler software package has previously been used in reconstructing rollover events (Fenton et al. 2001), and is employed in this study to apply photogrammetric methods to extract gross vehicle kinematics from images of a rollover SAE 2114 dolly test mode. The reconstructed model is shown in Figure 1, where meshes that were generated by photogrammetry technique are attached to the image of the test vehicle. These meshed will then move with the vehicle for the entire duration of the event that is analyzed. From the reconstructed mode, vehicle kinematics can also be generated in terms of pitch-, roll- and yaw-rate and longitudinal, lateral and vertical accelerations. Comparisons of the calculated roll rate and lateral acceleration with the measured counterparts allow establishing the feasibility and accuracy of this methodology.

Procedure

For this study, a single segment of digital video depicting a developmental dolly rollover test, i.e. SAE 2114 test procedure, of a SUV is used. The footage of this particular segment begins after the SUV has exited the dolly and just before the leading (driver's) side of the vehicle impacts the ground. Figure 1 shows the first frame from of the video segment. The segment ends as the vehicle exits the view of the camera as it rolls onto its passenger side, after approximately ½ roll. Total time of the segment is approximately ½ second. The frame rate of the video was 500 frames per second (fps). Camera-matching photogrammetry was used in analyzing the video segment.

Figure 1 **-** First Frame of the Video Segment Analyzed by Camera-matching Method

Camera-Matching Photogrammetry

The term photogrammetry encompasses any technique used to obtain reliable measurements from photographs. Photogrammetric techniques include single-photograph and multiple-photograph techniques and consist of both graphical and analytical methods (Gillen 1986, Tumbas 1994). The last three decades have witnessed increasing application of photogrammetric techniques within motor vehicle accident reconstruction. In current accident reconstruction, these techniques are an essential element of the reconstructionists' toolbox and have been used regularly to obtain the location of roadway physical evidence and vehicle damage measurements.

One common photogrammetric technique, called camera reverse-projection (Smith 1989, Woolley 1991, Main et al. 1995), uses a single photograph and seeks to establish the specific position from which that photograph was taken, along with the focal length and viewing plane of the camera that was used. This technique is commonly used to locate roadway physical evidence not only that is visible in photographs, but that is no longer visible at the accident site. To apply this technique, the analyst reproduces key features in the original photograph by tracing them onto a transparency. This transparency is then inserted into the viewfinder of the camera and, while at the accident site, the analyst inserts the transparency into the viewfinder of their camera and adjusts their viewing location and plane, along with the camera focal length, until the features viewed through the transparency overlay the corresponding features at the accident site. Once the viewing location, viewing plane, and focal length for the original photograph are known, points in the photograph can be located and documented at the accident site.

A similar single-photograph photogrammetric method, referred to as the camera-matching technique (Massa 1999, Fenton et al. 2001), uses three-dimensional animation software to replace the use of a transparency. To apply this technique, the analyst uses computer-modeling software to create a three-dimensional computer model of the environment contained in the photograph. The computer model would include features of the environment that are unlikely to have changed since the photograph was taken, such as road boundaries, roadway stripes, and buildings (Campbell III et al. 1993).

The computer-generated environment is then imported into the animation software package and a virtual camera is setup to view the environment model from a perspective that is visually similar to that shown in the photograph. The original photograph is then imported into the animation software and is designated as a background image for the virtual camera. This is analogous to inserting a transparent trace of a photograph into the viewfinder of an actual camera. The analyst then makes adjustments to the location, focal length, and viewing plane of the virtual camera until there is a reasonable overlay between the computer-generated environment model and the environment shown in the photograph. If a reasonable match is obtained, then the analyst has reconstructed the location, focal length and viewing plane of the camera used to take the original photograph.

Once the camera location and characteristics are known, the analyst can use the overlay between the environment model and the photograph to either trace non-permanent features from the photograph onto the environment model or to position computer models of non-permanent features into the environment model. Once these non-permanent features are transferred to the environment model, they can be measured relative to the known dimensions of the environment model. The accuracy of the camera-matching technique relates to the accuracy of the computer-generated environment model and the degree to which the analyst obtains a reasonable overlay between the environment model and the environment depicted in the original photograph.

To obtain position and orientation data for the SUV in the dolly rollover test video used for this study, the camera-matching technique to analyze each frame of the test video segment was utilized. In this case, the crash test facility constituted the permanent features present in each frame and the vehicle position and orientation constituted the non-permanent feature of each frame. The specifics of analysis and a discussion of the results are presented in this paper.

<u>Setup</u>

Prior to analyzing the rollover test video, the video formatted for use in standard video editing packages was digitized. Once the video was in the appropriate digital format, a software package called Steadymove™ was used to eliminate shaking from the crash test video, which originated from camera vibration during recording of the rollover event. Steadymove™ is included as a feature of Adobe Premiere Video Editing software.

<u>Analysis</u>

After preparing the video for analysis, the camera-matching photogrammetric technique was applied to each frame of the video to obtain the SUV's position and orientation at the time depicted by each frame. This process was carried out in an animation software package called 3D Studio MAX and consisted of the following steps:

- Model the basic geometry of the crash test facility and the SUV in 3D Studio MAX.

- Then, create a virtual camera in 3D Studio MAX and position the camera to view the computer-model of the test-facility environment. The camera was initially positioned with a location, viewing plane, and focal length that were visually similar to that shown in the video footage.

- Next, import the video footage into 3-D Studio MAX and set it to be a background image for the view of the virtual camera.

- Adjust the location, viewing plane, and focal length of the virtual camera to align the computer-generated test facility environment with the test facility environment shown in the crash test footage. The size of the SUV in the video was also compared with the SUV model size as a further guide for setting the virtual camera focal length. Once a reasonable overlay was obtained, the resulting camera location, viewing plane, and focal length were used throughout the course of the analysis. The coordinate system used was rotated approximately 15 degrees to the camera.

- Model the geometry of the SUV and place it in a location in the virtual camera view such that it aligned with the SUV position shown in the first frame of the video. Figure 2 depicts the overlay between the computer-modeled environment and vehicle with the video that resulted from this process.

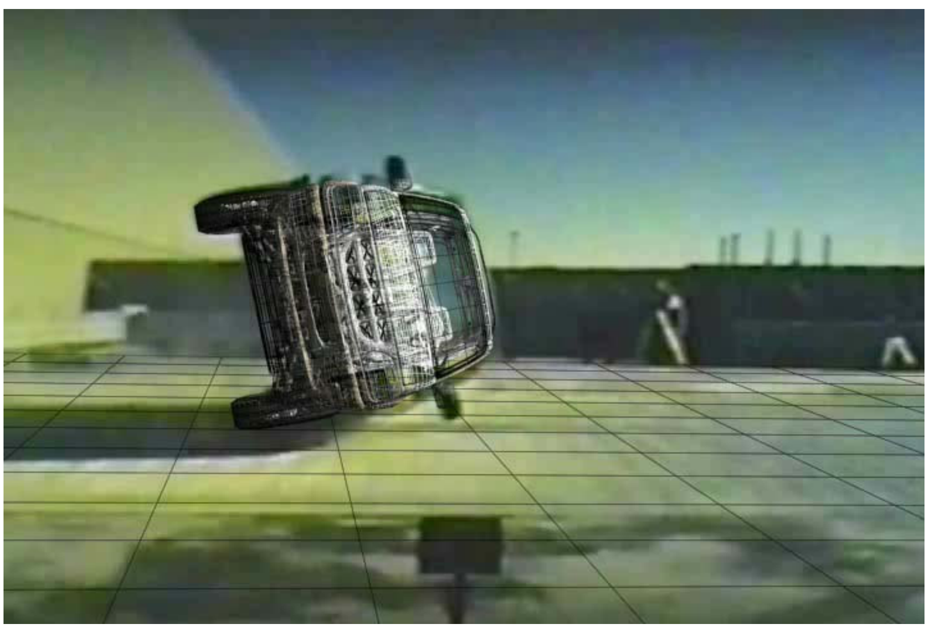


Figure 2 - Overlay of Computer Generated Environment and Vehicle with Video

- Finally, cycle through each frame of the video and create an animated sequence for the SUV model that matches the position and orientation of the SUV in each frame of the video.

Figure 3 is a graphic that contains three rows of images. The first row contains a series of five frames from the crash test video. The next row contains these

same five images with the computer-generated environment and vehicle aligned to the image. The third row of images is computer-generated and shows the SUV position and orientation from the previous row of images. In the third row, the camera view has been shifted to demonstrate the fact that once the vehicle position and orientation has been obtained from the camera-matching process, the animated motion sequence can be viewed in 3D-Studio from any vantage point
.

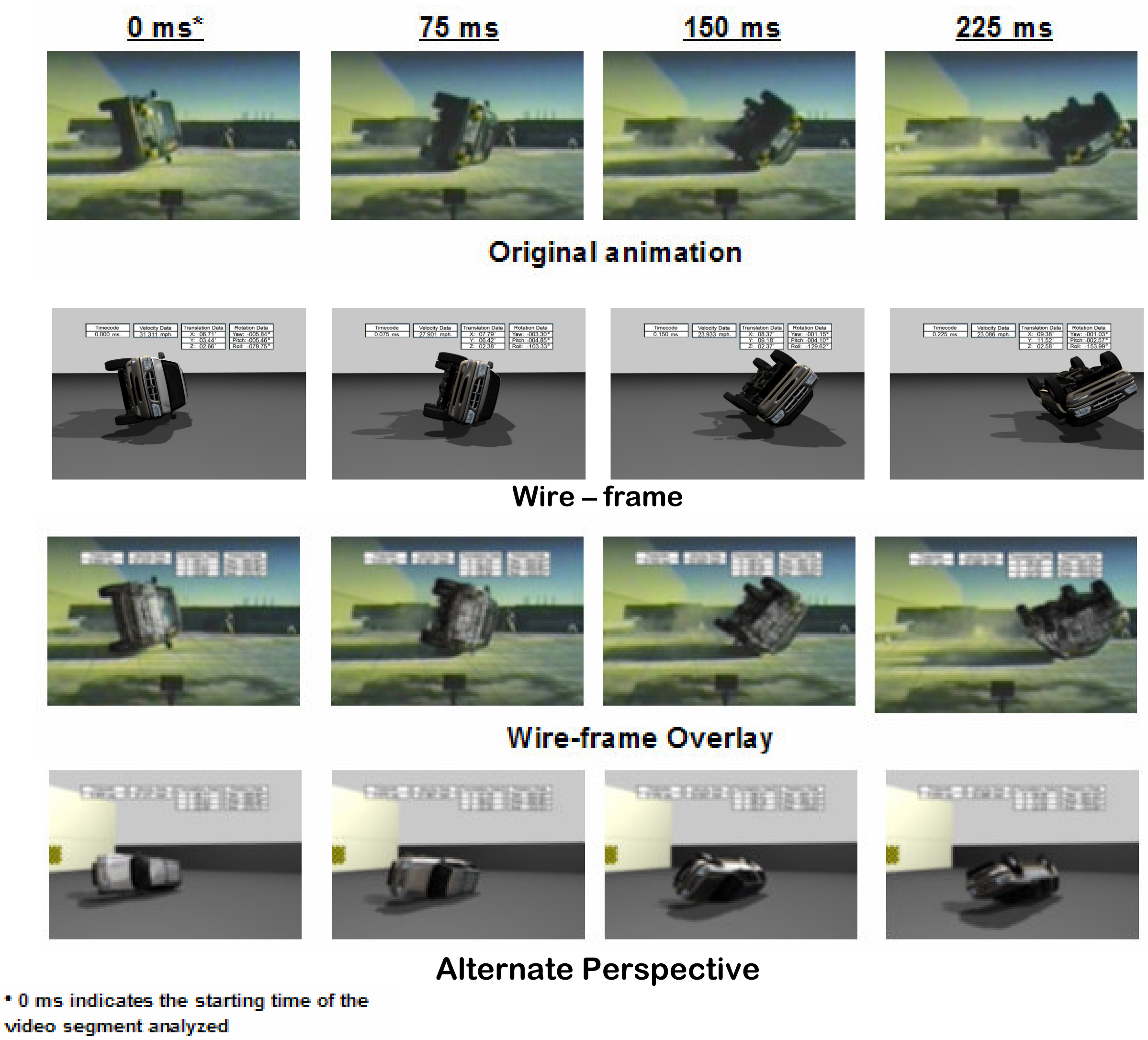


Figure 3 – Comparison of images – original animation vs. wire-frame vs. vs wire-frame overlay vs alternate perspective

Data Process

Once this animated sequence was created, the position and orientation data at each frame for the SUV was extracted and those data were analyzed in Microsoft Excel. When analyzed with video, the camera-matching process is an iterative procedure where the analyst attempts to achieve a reasonable match at each frame of the video while also maintaining continuity and coherence between frames. Any refinement of the position and orientation of the computer-modeled vehicle at one frame requires corresponding adjustments to the position at the surrounding frames. As a result, there was some jumpiness in the data extracted from 3D Studio MAX. Consequently, it was necessary to smooth the data for the x, y, and z coordinates of the center of gravity and the vehicle yaw angle.

Figures 4 to 7 depict both the data originally extracted from 3D Studio MAX and the smoothed data for the x-position, y-position, z-position and yaw angle, respectively. Position is measured in feet. In each of these figures, the colored and the black lines represent the originally extracted data and the smoothed data, respectively. For the x and y-position and yaw angle data, the smoothed curve was used in the analysis. For the z-position, the smoothed curve was not used until Frame #129. As the figures show, adjustments made to position data were minimal and did not exceed 1.8 inches. Adjustments to the yaw angle did not exceed ½ of a degree. It should point out here that the roll angle and pitch angle data were not smoothed.

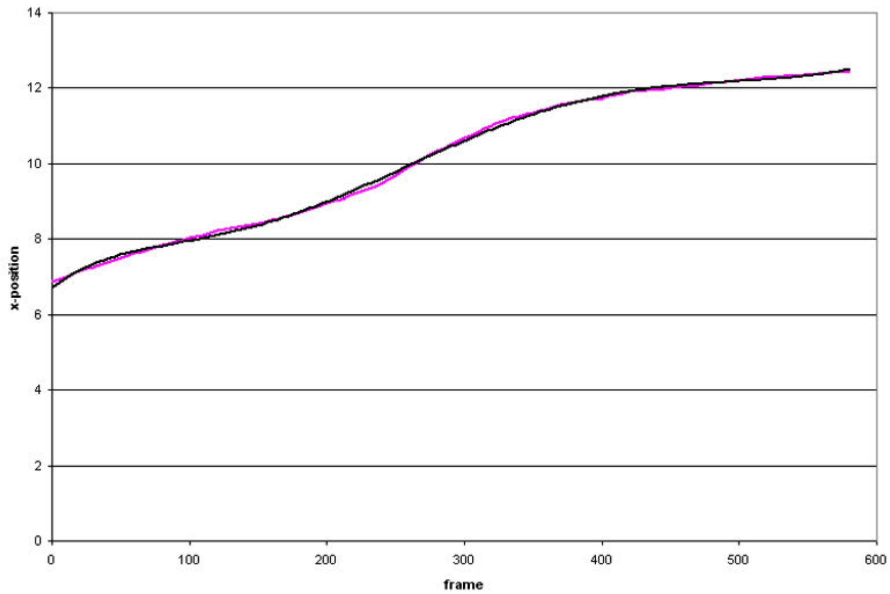


Figure 4 - Original and Smoothed x-Position Data

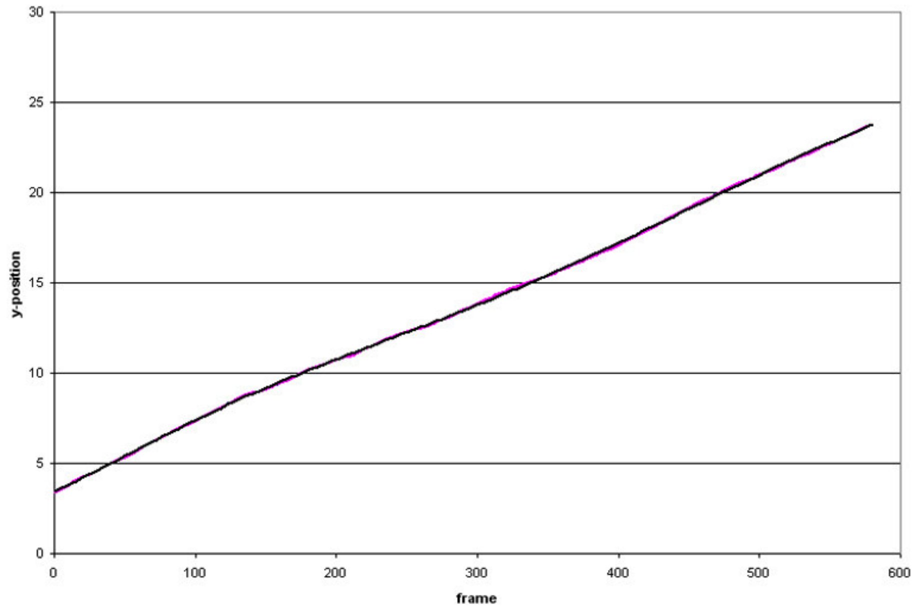


Figure 5 - Original and Smoothed y-Position Data

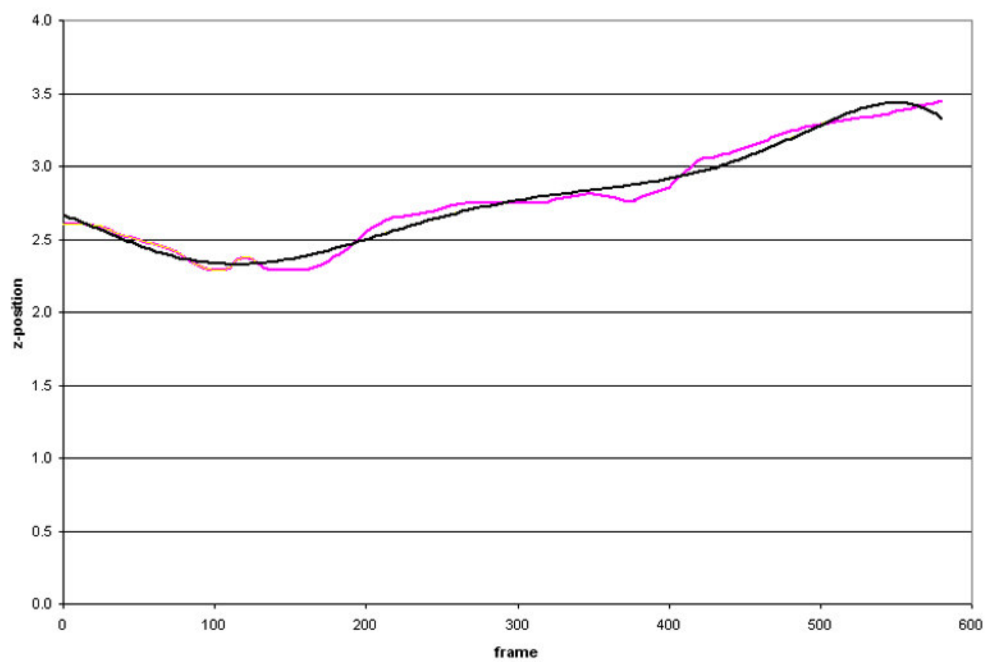


Figure 6 - Original and Smoothed z-Position Data

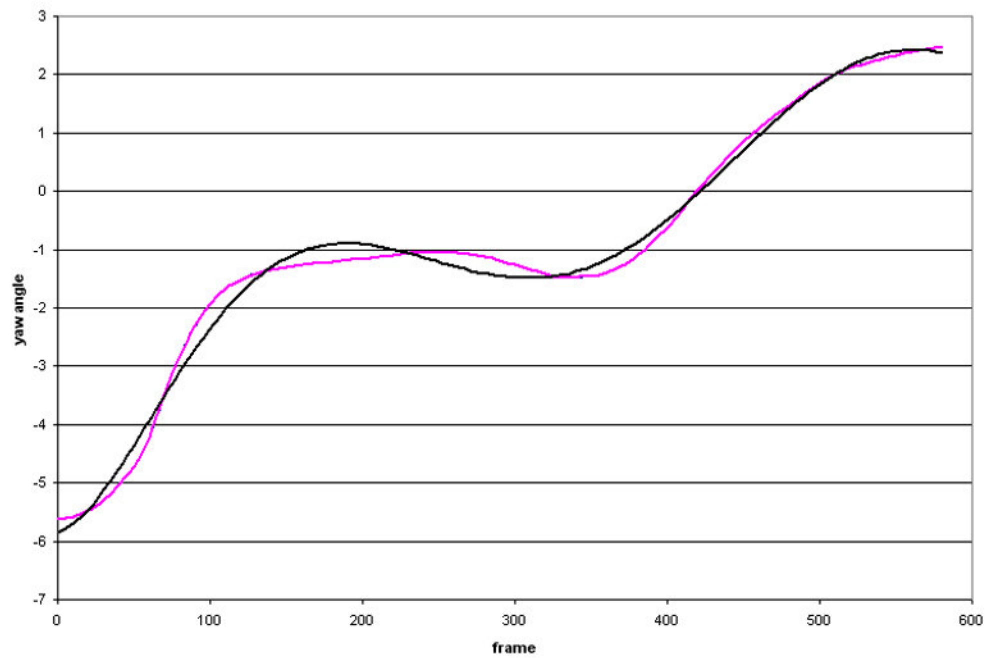


Figure 7 - Original and Smoothed Yaw Angle Data

RESULTS

The position and orientation data extracted from 3D Studio MAX were used to construct plots of the SUV's center of gravity velocity, roll angle, and roll velocity (or roll rate). Sensor data from the rollover test for the roll angle and roll velocity was used to determine the accuracy of those obtained form the camera-matching approach. It should be remarked here that the video analyst was not provided with any information regarding the setup of the vehicle instrumentation, the type of sensors used, or potential sources of error in the sensor data. Further, all analysis of the sensor data (i.e., filtering and integration) was completed by the test engineer.

Figure 8 shows the velocity time history of the SUV's center of gravity as determined by the camera-matching process. Figure 9 depicts camera-matching roll angle data overlaying that derived from sensor data. As the figure shows, there was excellent agreement between the roll angle data, derived from the camera-matching process and the roll angle data from test. Figure 10 compares the calculated roll rate from camera-matching approach with that derived from sensor output. It is seen that the general trends of the data are similar but discrepancies exist between the data sets as shown in Figure 10. The calculated roll rate time history depends on the differentiation technique used. This requires further investigation of an appropriate differentiation scheme to yield better results.

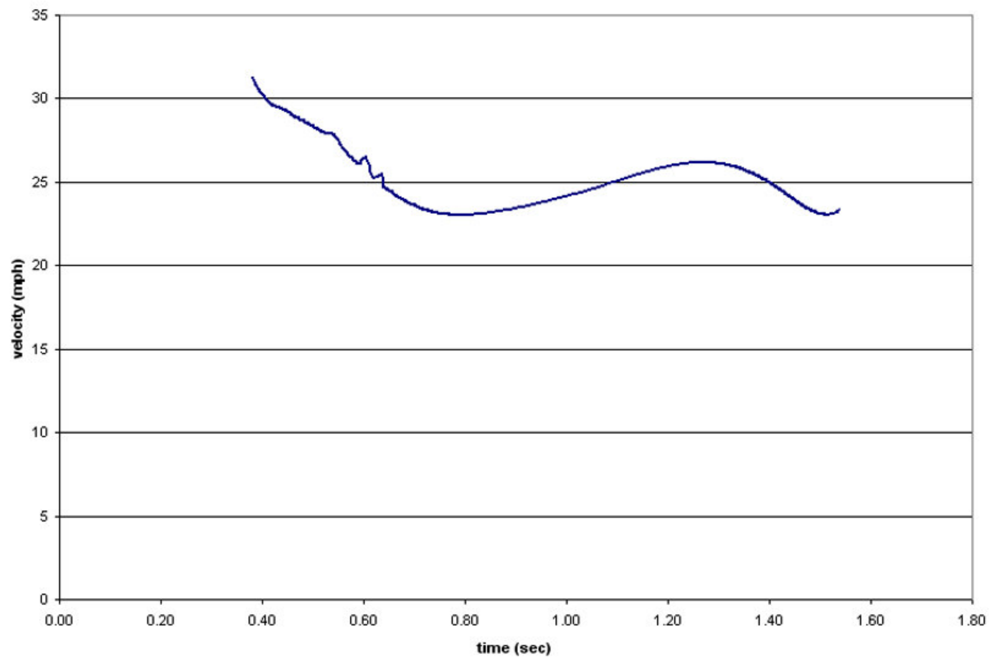


Figure 8 – Velocity time history at the C.G. of the animated SUV

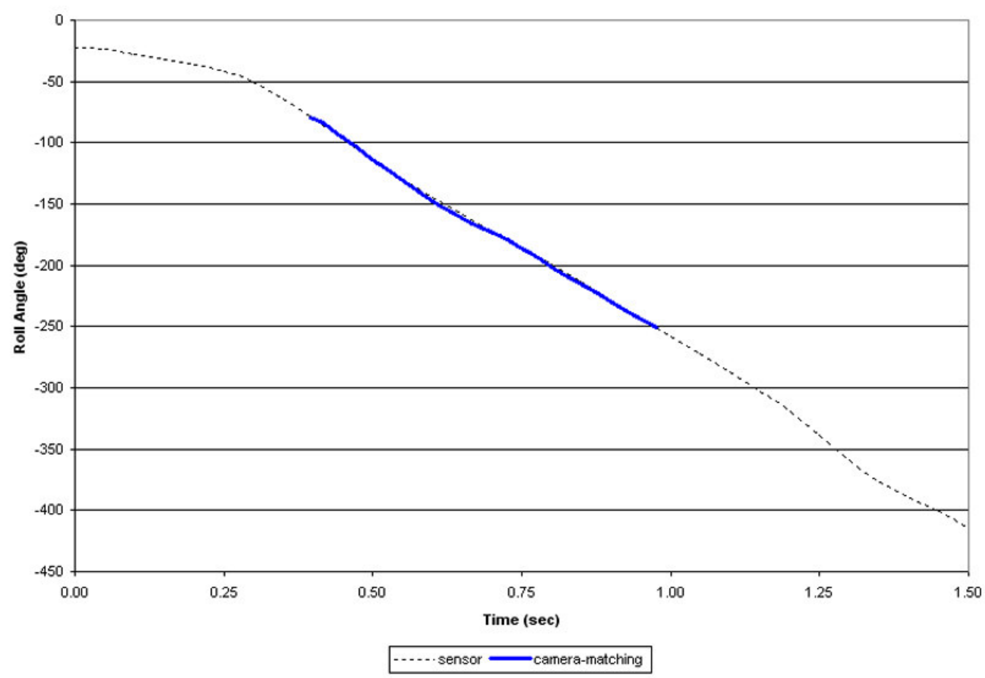


Figure 9 - Roll Angle Time Histories – calculated vs. measured

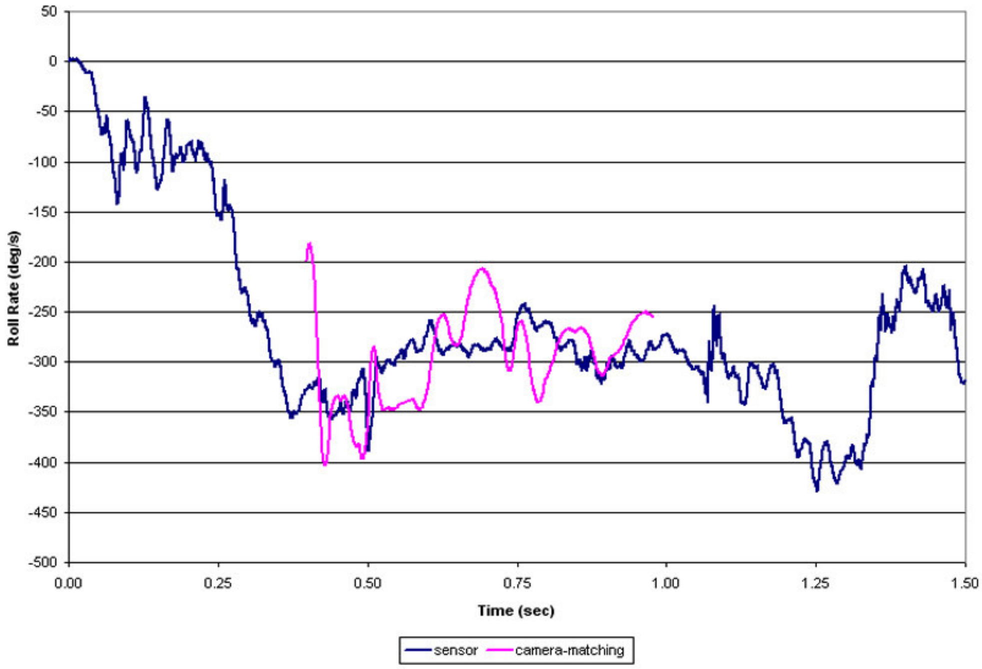


Figure 10 - Roll Rate Time Histories – calculated vs. measured

DISCUSSION

Based on analysis, observation and process developed during the course of this study, some areas for improvement, and issues associated with the photogrammetry are discussed below.

AREAS FOR IMPROVEMENT

There may be insufficient data to realize the full accuracy potential of the camera-matching technique in this case. Specifically, no dimensions for the crash-test facility shown in the video were available; therefore, the analysis relied primarily on the orientation of the ground plane and the size of the SUV in the view to set the location and characteristics of the virtual camera in 3D Studio MAX. The analysis would have been improved if the dimensions for the crash test facility were available.

An alternative would have been for the actual camera locations and settings to be determined. This option would be even better than the first since it would be the most accurate and the least time consuming. In general, it would not be difficult for a test facility to document the camera characteristics and locations at the time the test was run. Thus, this seems like a feasible improvement to the process described in this paper.

In addition to the benefits that could be gained by having prior knowledge of camera locations and characteristics, this process also would have benefited from having video with better image quality and from having multiple camera views for analysis. Improved image quality would give the SUV in the video more defined edges and would help improve the alignment of the computer-generated vehicle to the video. The use of multiple views for analyzing a single segment of time during the crash test would also make it easier and more accurate to adjust the vehicle position and orientation. Although segments of video from multiple cameras were used, the field of views of these cameras did not overlap sufficiently to allow for multiple camera views to be used for analyzing the same time period during the crash test. The combination of improved image quality with multiple camera views could potentially eliminate the need to smooth the data after it is extracted from 3D Studio MAX.

A significant drawback to the procedure carried out in this study was the manual nature of the process. Each frame of the video, nearly 500 frames in this case, had to be analyzed manually by an analyst familiar with the intricacies of 3D Studio MAX and experienced in the camera-matching process. The analysis conducted was, therefore, time-consuming and dependent on judgments made by the analyst as to the best mix of camera settings to achieve an accurate camera-match. Not only that, when utilized with video, the camera-matching process is inevitably iterative with the analyst attempting to obtain a reasonable match of the vehicle position and orientation in each frame while also maintaining continuity and coherence in the data on a larger scale.

ACCURACY DETERMINATION

One question associated with the photogrammetry technique or image analysis is accuracy. The accuracy of a photogrammetry measurement depends on several factors (Geodetic Services Inc, 2003). The most important ones, but not limited to, are:

- The resolution (and quality) of cameras used
- The size of the object that is to be measured
- Camera locations and their respective fields of view
- The geometric layout of the images relative to the object and to each other

Of course, the higher the resolution of cameras, the better the accuracy. The smaller the size of the object, the better accuracy can be achieved when analyzing the images.

A couple of reports published regarding the accuracy. Subject pertaining to triangulation position error image analysis was reported by Sanders-reed (2002). Switzer et al. (1999) addressed the factors that affected the accuracy of non-metric analytical 3D photogrammetry using PhotoModeler. Generally, metric cameras have stable internal geometry, are calibrated to account for distortion, and are used primarily for photogrammetry purposes, thus yielding results of better accuracy than non-metric cameras (Switzer et al. 1999). Error calculations of many separate analytical results showed that in general a maximum of 2-5% range of errors resulted from this type of analysis (McClenathan et al. 2005).

It is previously mentioned that only the camera locations and characteristics were used in this study. Use of multiple camera views could improve the accuracy of the process as described above, keeping in mind that the process would still be very time-consuming. However, the process could be significantly improved by using an automated motion-tracking algorithm that would exploit mathematical relationships between the camera characteristics and the video to track the motion of the vehicle. McClenathan et al. (2005) reported that Falcon has such capability using specifically developed icon.

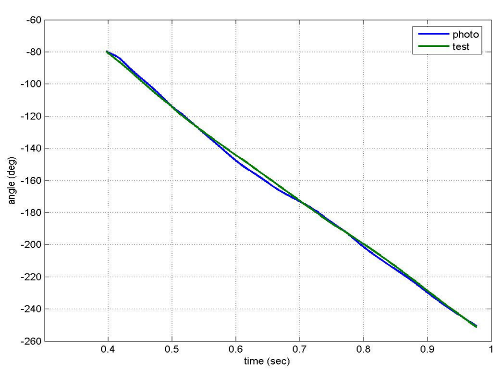
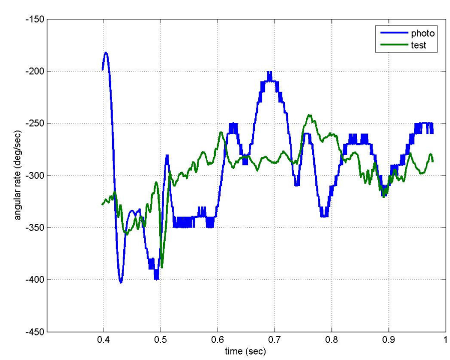
Several companies are currently developing automated software that will track certain markings, fiducial points, and other identifiable graphical patterns in video to recreate their motion. As the accuracy and effectiveness of these software packages improve, it will likely become feasible to track the vehicle position and orientation through time without employing the manual procedure used in this paper. Establishing accuracy is important when using photogrammetry technique.

Use of the roll angle data obtained from the image analysis presented above, will be used as an example to demonstrate a possible method to determine the accuracy of the method.

Referring to Figure 9, the roll angle time history obtained from the camera-matching technique appears to agree quite well with that measured by the roll rate sensor. However, a difference between the calculated and measured roll angle exists. This difference can be measured by calculating their residuals. Hence, the difference between the calculated and measured curves can be assessed using the sum of the least mean squares and by varying the factor that reduces the error between the calculated and measured roll angles.

In this example, the ratio of the residual of the baseline data is assumed to initially be one (1), this ratio is then varied to be 0.8, 0.5, 0.3 and 0.1. A ratio of 0.8 implies that a 20 percent of residual is reduced, i.e. an error is reduced by 20% between the calculated and measured roll angles. With these variations, the corresponding least mean squares and average differences are obtained. Table III, wherein Case Nos. I to V, designate studies corresponding to values of ratios of 1, 0.8, 0.5, 0.3, and 0.1, respectively. The study indicates that as the ratio of residuals approach zero, the calculated results from image analysis yield the same as the measured data. For each case, the least mean squares and average difference are calculated and plotted for both roll angle and roll rate time histories. It is evident that as the ratios of residual decreases, its respective least mean squares and average difference decrease. Therefore, as the least mean squares decreases, the error between the calculated and measured roll angle reduces. Consequently, the accuracy in roll rate increases as the error reduces. In Case No. V, where the ratio is equal to 0.1, the roll rate time history thus obtained is in excellent agreement with the measured data by angular rate sensor in the test. Based on this example, this leads to a conjecture that the calculated roll angle needs to be accurate within 0.5 degrees, because the maximum difference between the calculated and the measured roll angle in the baseline is about 5 degrees. Additional studies may be needed to further establish the accuracy required when using photogrammetry. However, whether or not any technique can actually attain this level of accuracy is the subject of further research.

Table III – Ratio of Residuals

Case No.	Ratio of residual	Roll angle			Roll rate		
			LMS	avg diff		LMS	avg diff
I	1		3.01	1.43		2172.2	37.3

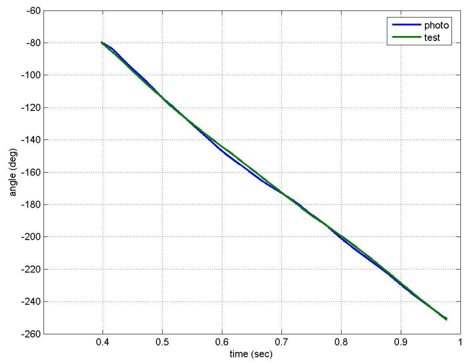
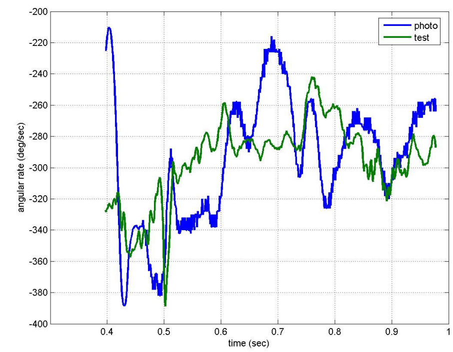
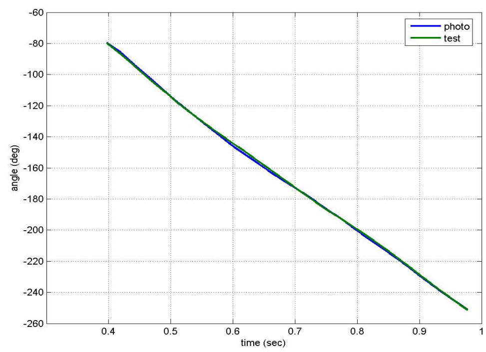
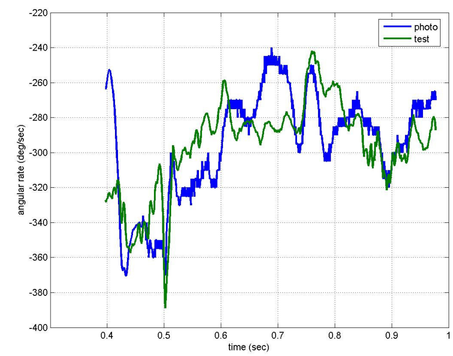
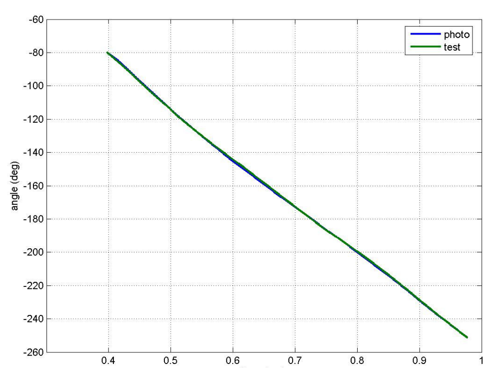
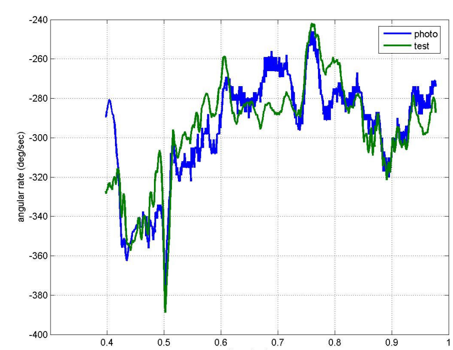
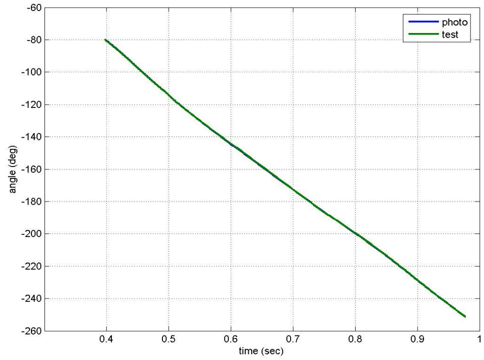
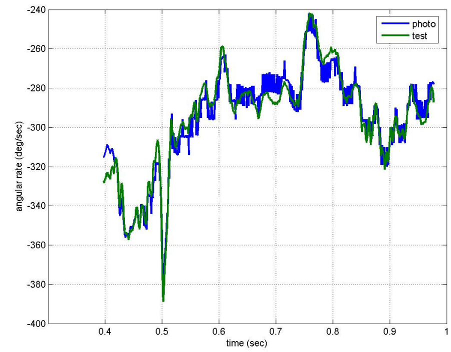
II	0.8		1.92	1.15		1390.3	29.9
III	0.5		0.75	0.72		545.77	18.7

Table III – Ratio of Residuals (continued)

IV	0.3		0.27	0.43		202.44	11.4

V	0.1		0.03	0.14		34.67	4.77

VEHICLE KINEMATICS

Should vehicle kinematics in rollover be considered as a rigid body motion, then one may treat the vehicle as a whole in a total system by prescribing a 6-degrees-of-motion at its center of gravity, namely, by using six known quantities to define its motion. Such prescribed motion can consist of three linear accelerations along and three angular rates about the vehicle-based axes. It should be noted, however, that such analysis and assumption is valid only prior to the vehicle contact with the ground. Mathematical treatment of this approach was presented by Friedewald (1996). Although Friedewald has provided some results from his analysis, the accuracy is still questionable. As previously mentioned, through the image-matching technique, a reconstructed computer model was generated. This model may potentially be capable of providing vehicle kinematics analysis as shown in Figure 3; however the accuracy has not yet been completely determined. It should be mentioned that recent advancement of angular rate sensor has come up with an IMU (inertia measurement unit) package with capability of measuring three linear accelerations and three angular rates. In future testing of laboratory-bases rollover modes, an IMU can be mounted at the vehicle center of gravity to provide 6-DOF information for comparison with outputs from the reconstructed computer model for assessment of the model's accuracy.

Once the accuracy of the reconstructed computer model is assessed, this model can then be used for calculating acceleration at any local locations in the vehicle. Outputs from accelerometers mounted at such locations, if any, can be used for further validation of the reconstructed computer model.

After the vehicle impacts with the ground, the vehicle structural will most likely undergo some deformation. The degree of deformation may depend on enormous number factors. With the aid of IMU measurement and the reconstructed computer model with yet-to-be-determined accuracy, the impact force could theoretically be calculated by solving the equations of motion. However, the feasibility and accuracy of such an approach may be difficult to establish. Further study and additional efforts are required.

CONCLUSION

Based on the results from the process outlined in this study, the following conclusions can be drawn:

- Comparing the results from the photogrammetric analysis to vehicle sensor data showed close agreement with the roll angle data. However, the roll velocity data did not show the same level of agreement. Improvements in image quality and greater knowledge of camera characteristics may improve the roll velocity results. The numerical differentiation technique used may also affect the results.

- This paper demonstrates that photogrammetry can be used as a tool to extract roll angle data from rollover crash test video However, the accuracy of the results for any given case must be determined before it can be utilized.

- The *manual* camera-matching process as described was time-consuming and costly. However, automated processes currently under development may make this process more user-friendly and cost-effective.

- Application of photogrammetry to post processing or analyzing image sequences of a rollover event represents a significant challenge to automotive safety researchers.

- It is recommended that development of post-processing tool though application of photogrammetry in crash safety analysis should be explored further.

Future work pertaining to this technical development may include, but not limit to the followings:

- Reanalyze the video from the onset of the dolly rollover event, rather than analyzing the event from 400msec using a better quality video when available. In this way, the initial test condition may serve as useful information in the determination of angular rate.

- Use quality digital cameras for crash event coverage with appropriate calibration done prior to test, so that facility setting, markings, etc can be traced.

- Further develop the method to determine the accuracy of the photogrammetry approach

- Develop analytical tool to calculate impact loads (or vehicle-to-ground contact force) based on kinematics of the generated vehicle motion from the current process. This may pose a very challenge task to automotive safety analysts.

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