

A Method to Quantify Vehicle Dynamics and Deformation for Vehicle Rollover Tests Using Camera-Matching Video Analysis

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ABSTRACT

This paper examines the use of camera-matching video analysis techniques to quantify the vehicle dynamics and deformation for a dolly rollover test run in accordance with the SAE Recommended Practice J2114. The method presented enables vehicle motion data and deformation measurements to be obtained without the use of the automated target tracking employed by existing motion tracking systems. Since it does not rely on this automated target tracking, the method can be used to analyze video from rollover tests which were not setup in accordance with the requirements of these automated motion tracking systems. The method also provides a straightforward technique for relating the motion of points on the test vehicle to the motion of the vehicle's center-of-mass.

This paper, first, describes the specific rollover test that was utilized. Then, the camera-matching method that was used to obtain the vehicle motion data and deformation measurements is described. Finally, the data obtained from the video analysis is analyzed and compared to data obtained from on-board instrumentation. Ultimately, the camera-matching technique is shown to be a viable technique for obtaining three-dimensional vehicle motion during a rollover crash test. As a means of obtaining vehicle deformation, the technique will need further development.

INTRODUCTION

This paper examines the use of a camera-matching photogrammetric technique to track the motion and dynamic deformation of a vehicle during a SAE J2114 dolly rollover test. The methodology presented enables vehicle motion data and deformation measurements to be obtained without the use of the automated target tracking employed by motion tracking systems. Since it does not rely on this automated target tracking, the method can be used to analyze video from rollover tests which were not setup in accordance with the requirements of such motion tracking systems. The method also provides a straightforward technique for relating the motion of points on the test vehicle to the motion of the vehicle's center-of-mass.

In 2006, Chou, et al. (2006), reported video analysis results for a 500 millisecond segment of another dolly rollover test [1]. In this earlier research, the authors primarily examined the effectiveness of the technique for obtaining roll angles and roll velocities from the test. The analysis reported by Chou, et al., was limited because the characteristics and locations of the cameras that recorded the crash test were unknown, as was the exact geometry of the crash test facility and the crash test vehicle.

This paper reports data and results from a more extensive analysis of a dolly rollover test. In this study, the geometry of the crash test facility and the locations and characteristics of the cameras that recorded the test were surveyed and documented. Knowledge of the camera characteristics enabled better modeling of the cameras in a three-dimensional computer environment than what was possible in the previous analysis by Chou, et al (2006). Also, it enabled correction of the crash test video for lens distortion. In addition, a number of targets were placed on the crash test vehicle and the vehicle geometry and target locations relative to this geometry were surveyed. More detailed documentation of the vehicle geometry enabled more precise matching of the vehicle motion visible in the video. The analysis reported here included a 2000 ms segment of the test and yielded motion data that included the x, y and z position and the roll, pitch and yaw angles for the vehicle throughout that time period. Based on this motion data and on knowledge of the vehicle and crash test facility geometries, translational and angular velocities, accelerations and deformations for the test vehicle were also obtained.

In this paper, we first describe the parameters of the rollover test that was utilized for this video analysis. Then, the camera-matching method that was used to obtain the vehicle motion and deformation is described. Finally, the data obtained from the video analysis is analyzed and then compared to data obtained from on-board instrumentation.

ROLLOVER TEST SETUP

The motion analysis reported in this paper used a laboratory-based J2114 dolly rollover test [2, 3] which was run with a Ford sport utility vehicle. The test vehicle is shown in Figure 1.



Figure 1 – Test Vehicle

This vehicle was instrumented with sensors to measure the vehicle-fixed longitudinal, lateral and vertical accelerations at the center tunnel between the seats and

the lateral and vertical accelerations at the lower A-pillar on both sides of the vehicle. Based on the axle weights of the test vehicle, the sensors mounted on the center tunnel between the seats were near the longitudinal position of the vehicle's center-of-mass. The vehicle was also instrumented with two angular rate sensors for each principal axis. These were mounted on the center tunnel just rearward of the seats. Nine high-speed, stationary cameras and one real-time panning camera recorded the test. The high-speed video was taken at 500 frames per second and the real-time video was taken at the NTSC standard frame rate of 29.97 frames per second.

Prior to the test, a number of targets, which are visible in Figure 1, were placed on the vehicle and their locations were surveyed. The overall geometry of the vehicle was also surveyed. In addition, features of the crash test facility geometry that would be visible in the crash test video were surveyed. Similar surveys of the vehicle and crash test geometries were later conducted after the test. These post-test surveys included physical evidence deposited by the vehicle on the test surface.

The rollover dynamics that occurred during the test are depicted in Figure 2, which contains a series of images that were captured by one of the high-speed cameras located downstream of the roll. As these images show, the vehicle rolled just past 360 degrees and then reversed its roll direction and came to rest on its wheels.

CAMERA-MATCHING VIDEO ANALYSIS

METHODOLOGY

This section describes the methodology utilized to track the vehicle motion in the crash test video. This methodology consisted of the following steps: 1) preparing the test vehicle with targets that would be tracked; 2) surveying the test facility and vehicle geometries; 3) creating a computer environment that included the geometries of the test facility and the test vehicle; 4) analyzing the actual cameras and the video images to determine characteristics, distortion and resolution so that these could be replicated with computer-modeled cameras; 5) accurately placing computer-modeled cameras in a three-dimensional computer environment and matching them to the test video; and 6) tracking the movement of the test vehicle by matching the location of the computer generated vehicle targets to the targets on the test vehicle for each frame of the video sequence. These steps are detailed in the following subsections.

Preparation for Motion Tracking

Prior to running the crash test, the test vehicle was marked with high-contrast yellow and black fiducial targets. It was the motion of these targets that was ultimately tracked in the video. In placing these targets,

the primary goal was to generate a wide range of points on the vehicle that would be visible and identifiable in the crash test video. Once these stickers were placed, their locations were surveyed so that they could be replicated on a computer-generated model of the test vehicle.

Also prior to running the crash test, 12-inch wide foam fiducial blocks were placed along the anticipated rollover path. These blocks were evenly spaced on both sides of

the roll path and were visible in at least one camera at all times during the rollover sequence. After placing these foam blocks, a survey of the test facility was completed. This survey provided the three-dimensional geometry of the rollover test facility, including the ground surface, the control joints in the concrete of the test surface, the walls surrounding the test surface, the light fixtures located above the test surface, and the foam fiducial blocks. This survey data provided the foundation for a computer model of the entire test area.

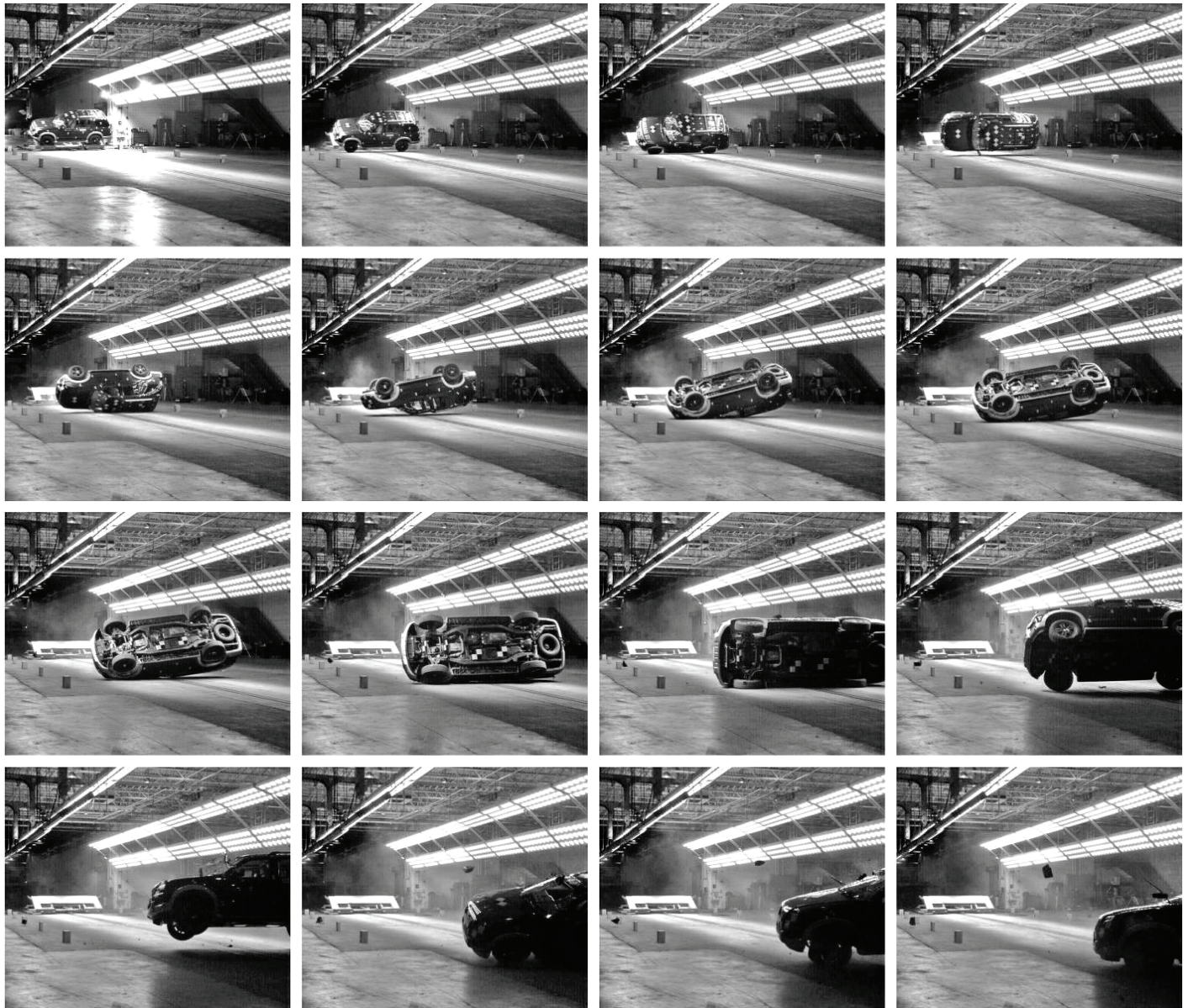


Figure 2 – Rollover Dynamics for the Test

Creation of the Computer-Modeled Environment

Prior to the test, the crash test facility was surveyed using Sokkia Laser Survey equipment. This raw data was processed and through analysis of photos and other inspection notes, a computer-generated model of the

test facility was constructed using modeling programs such as Carlson, AutoCAD 2008, and MAX 8. The geometry included the concrete block sections of the rollover facility floor, the control joints that separate these blocks, CMU walls that surround the rollover area and the lights above the rollover area. This geometry

was constructed in the computer modeling programs and the entire computer environment was then oriented relative to the general roll direction. In addition, markers locating the position and orientation of the camera were also identified from the survey data and used as position markers for computer-modeled cameras that were later incorporated into the scene.

A detailed computer model of the test vehicle was obtained from an online model library. The accuracy of this model was verified through comparison to the data from our pre-test survey of the actual vehicle. With the survey of the test vehicle aligned to the computer model, the target stickers that were placed on the test vehicle, and subsequently surveyed, could be transferred to identical locations on the computer model of the vehicle. These target locations were used to track the motion of the test vehicle.

Camera Characteristics and Specifications

In addition to creating a computer-modeled environment of the physical geometry of the facility, the optical and geometric characteristics of all the cameras were documented and analyzed in order to create computer-generated cameras that mimic each individual camera that captured video of the rollover test. The data for these cameras came from the survey of these cameras, analysis of the sensors, and analysis of the technical and specification drawings. Each camera was created

according to its specific characteristics, since these characteristics differed between cameras. These computer-modeled cameras were also located and oriented to be identical to the cameras surveyed at the facility at the time the dolly rollover test was conducted.

The high-speed cameras used for recording the rollover test were Redlake MotionXtra HG-LE digital video cameras. These cameras recorded the test at 500 frames per second with a maximum resolution of 752x1128 pixels and a pixel aspect ratio of 1.0. Figure 3 depicts the location of each camera relative to the test area and reports each camera's lens type and focal length and the image resolution with which each camera recorded the test. In the course of our pre-test documentation, the horizontal and vertical orientation of each of these cameras was documented using the laser survey equipment. When computer-modeled cameras were created for our video analysis, the camera characteristics reported in Figure 3 were replicated. The camera locations and orientations relative to the test area were also replicated when the computer-modeled cameras were setup within a three-dimensional computer model of the crash test facility. In addition to replicating the basic characteristics, locations and orientations of the actual cameras, the computer-modeled cameras used in the motion tracking analysis also utilized an accurately placed picture plane, which is the plane on which the camera lens focuses light and the plane on which the image sensors that record the digital image are located.

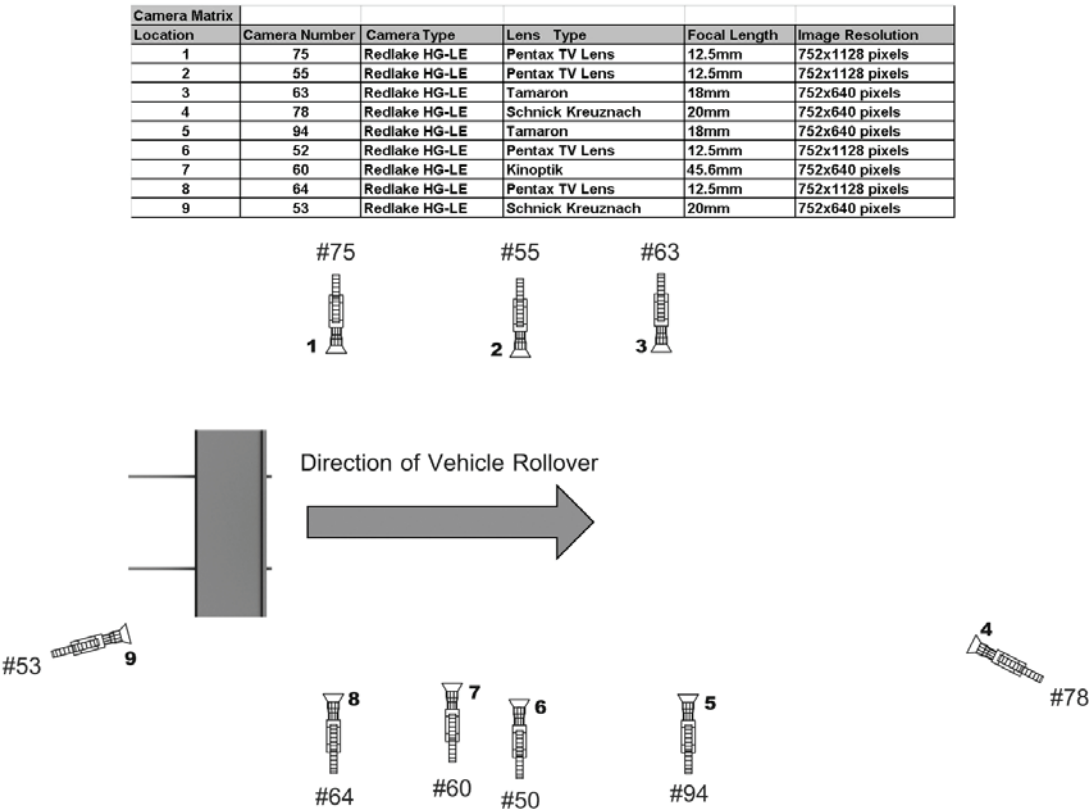


Figure 3 – Location and Characteristics of the Cameras

The image sensors in the digital cameras used to record this test were Complimentary Metal Oxide Semi-Conductor (CMOS) sensors with a 1504x1128 maximum pixel image resolution. This configuration yields a 1.7 megapixel video resolution. However, since this sensor is not a Charged Coupled Device (CCD) it tends to have a larger image resolution at the expense of light sensitivity. This characteristic means that when the test vehicle exits the lighted area (approximately 2 seconds after leaving the dolly), it becomes more difficult to identify the fiducial targets on the vehicle and hence the fidelity of the motion tracking in the dark area is reduced. For this reason, the motion of the vehicle was not tracked once it exited the lighted area of the test surface.

Another characteristic of the image sensors used in these cameras is that they have a four quadrant assembly with each quadrant containing one photodiode as shown in Figure 4.

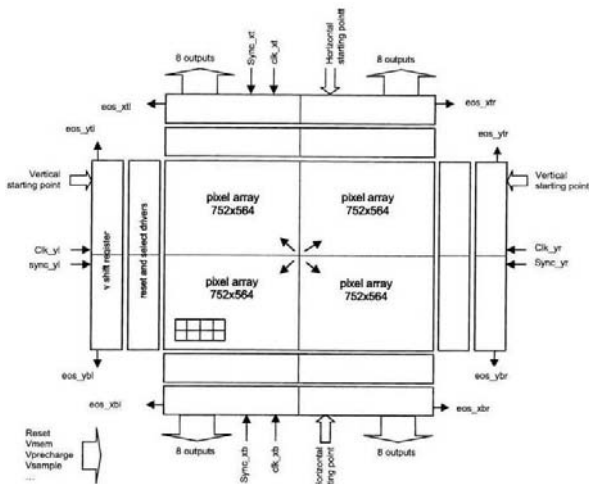
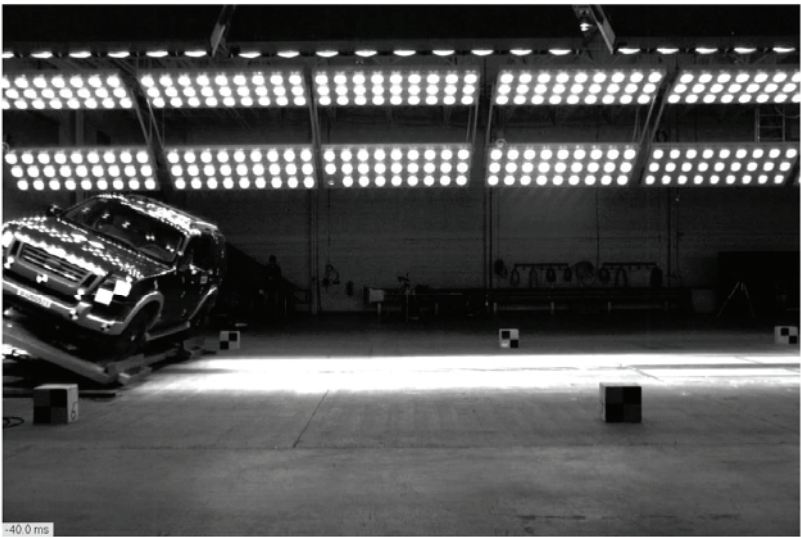


Figure 4 – Image Sensor

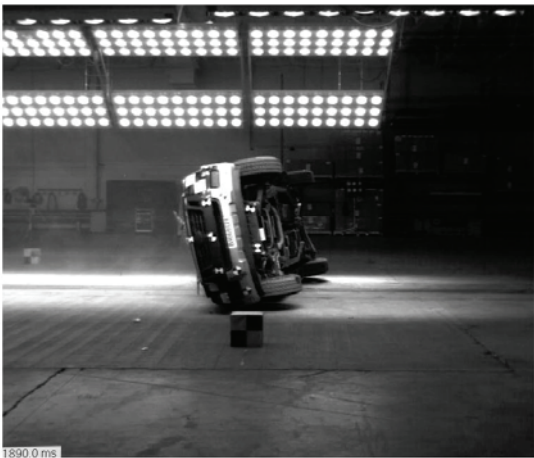
This configuration is useful for producing multiple sensor size configurations for various industries or consumers without having to change the sensor architecture. For example, 1, 2 or 4 quadrants could be active producing varying image resolutions. Because the configurations of the image sensor assembly differ it was relevant to analyze which configuration was used in the cameras in this test so the appropriate aperture width, which is determined by the sensor size, could be established for the computer-modeled cameras used in the video analysis.

Ultimately, it was determined that there were two different image sensor configurations in use during this test. Both configurations used quadrants one and four, though their pixel resolutions were different. For the cameras utilizing the full capabilities of the image sensors, the one and four quadrant sensor resulted in an image size of 752x1128. For the cameras that utilized only a portion of the available sensor image of quadrants one and four, a resolution of 640x752 resulted. This configuration produced two different image aspect ratios. The larger image had an image aspect ratio of 1.5. The active quadrants were areas 1 and 4 producing an image size of 752x1128. The smaller image produced an image aspect ratio of 1.175, and a resolution of 752x640 pixels. The difference between these resolutions can be seen in a frame captured from each camera shown in Figure 5.

For the Redlake CMOS sensors, 1 pixel of the image sensor measures $12 \times 12 \mu\text{m}^2$, and hence the camera aperture width for each of the actual cameras was 9.0mm. This aperture width was used in creating the computer-modeled cameras used for the video analysis. Figure 6 depicts examples of two of the computer-modeled cameras used in the analysis.



1128x752 pixel resolution (1.5 Image Aspect Ratio)



752x640 pixel resolution (1.175 Image Aspect Ratio)

Figure 5 – Frames Captured from Two High-Speed Cameras Used to Record the Test

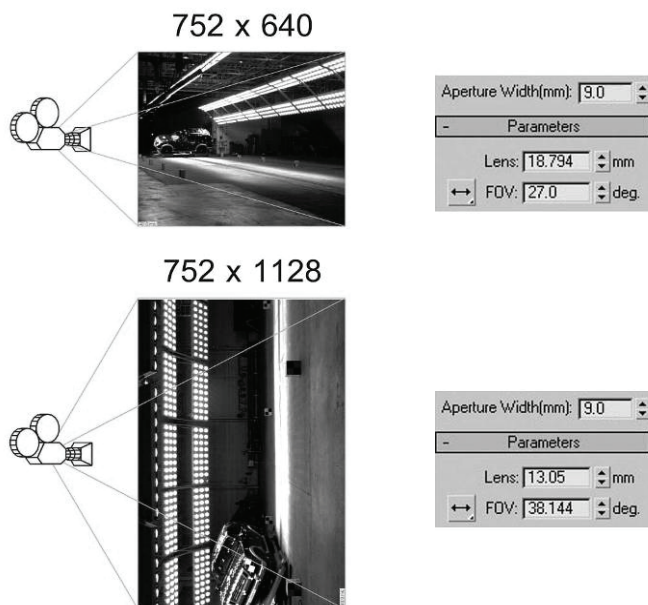
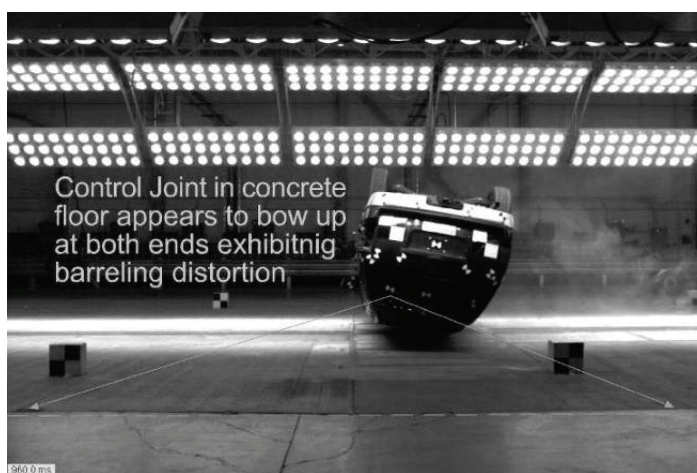


Figure 6 – Computer-Modeled Camera Characteristics

Lens distortion was visible in the test video, and therefore, needed to be accounted for in the camera-matching analysis. Lens distortion occurs in two basic forms, barreling and pin cushioning. Barreling and pin cushioning are opposite effects that distort the image by squashing or stretching the edges of the image, respectively. In general, barreling occurs from wide focal lengths while pin cushioning occurs from zoom focal lengths.

As demonstrated in Figure 7, there existed some barreling of the images as a result of lens distortion inherent in the camera lens focal length. An example of the barreling effect can be seen in the lower portion of the left image of Figure 7 where a concrete control joint on the floor of the test facility can be seen to curve up at both ends. As a result of this distortion, objects on the edges of the image appear squashed and if used in a video analysis would yield distances shorter than the actual distance.

Video compositing and editing software was used to eliminate the distortion from each video frame that was used for the motion tracking. Because barrel distortion is dependent on the camera system and the lens and focal length, analysis was performed on each video sequence to see if a different distortion correction was needed for each sequence. Due to the difference in focal length and in unique aspects of lens manufacturing, each lens ultimately required its own distortion correction.



Unrectified Image



Rectified Image

Figure 7 – Lens Distortion Correction

Tracking the Vehicle Motion

Having created a computer-modeled environment that contained the geometry of the test facility, the test vehicle and a series of computer-modeled cameras that replicate the actual cameras, test video from each camera was then designated as a background image for its corresponding computer-modeled camera. For

instance, the first two cameras in line with the rollover sequence face each other and lay perpendicular to the roll path. Identified as Cameras #75 and #64 in Figure 3, these cameras were associated with video sequences obtained from that location and given the same name such as “camera#75.avi” and “camera#64.avi”, respectively. At this point, each computer-modeled camera could be used to simultaneously view the