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Performing Reverse Projection Photogrammetry of Surveillance Video with HVE

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Performing Reverse Projection Photogrammetry of Surveillance Video with HVE

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Abstract

The presence of video cameras in urban areas is becoming commonplace. The availability of low cost, high capacity digital storage provides a means to record weeks or months of continuous video surveillance. This has resulted in an increase of traffic events being photographically captured. Using photogrammetric methods, the positions of vehicles or other objects of interest can be located. Their change in position can be established between sequential frames and used in conjunction with the frame rate to calculate velocities and accelerations.

One photogrammetric method used for this purpose is Reverse Projection Photogrammetry. This method involves superimposing an image of the event over the event site. Using objects that appear in the image which are still present at the traffic site, the camera location, optical axis and effective focal length of the lens can be established. The location of an object of interest can be identified by intersecting a ray from the camera location with a definable surface such as the roadway. In the past, this method was performed using a transparency of the image and a “dummy” camera. Object locations were manually sighted and measured at the site. This is no longer necessary.

Instead, a three-dimensional computer model of the environment can be built, and the camera location and optical axis established virtually. Vehicle positions can be sighted by moving a computer model of the vehicle over the environment surfaces. HVE has proved to be useful for this purpose.

Introduction

Previously, video surveillance was used primarily for security purposes. Cameras were used to monitor commercial businesses as a deterrent to theft or burglary.

These cameras are aimed at the property being protected and seldom captured the motion of a vehicle involved in a collision. When they did, the vehicles were often at the edge of the field of view, and distant from the camera.

More recently, surveillance cameras have been used for traffic enforcement. Red light enforcement cameras are installed to continuously monitor an intersection for violations. They are in a prime location to capture a collision occurring within the intersection. Governmental agencies such as the Chicago Office of Emergency Management and Communications (OEMC) operate a network of surveillance cameras throughout the city. Additionally, the Private Sector Camera Initiative provides a means for organizations, companies and other agencies to link their camera systems into the OEMC’s unified surveillance network. These factors have greatly increased the likelihood of a traffic collision being photographically recorded.

Additionally, motor carrier operators have begun installing video cameras in their fleet vehicles, and law enforcement has used windshield or dash mounted cameras for decades. Even private citizens are purchasing low cost dash cams for use in their private vehicles. These facts further increase the possibility of capturing a collision on video.

The value of a video recording is not limited to images capturing the collision. The motion of vehicles occurring contemporaneous or proximate to an event site may be important.

Surveillance Systems

Digital video surveillance systems include the cameras, media storage and computer software used to manage the hardware and recorded video. Numerous companies offer video solutions, each with its own proprietary software. If an incident involved in litigation was captured on video,

the involved parties typically subpoena the video. Instead of providing the video in the software's native format, the file may be exported in a more common format such as an Audio Video Interleaved (AVI) or Windows Media Video (WMV) file. This can potentially compromise the video for photogrammetric purposes.

Converting the video file may alter the resolution or aspect ratio of the original and can also affect the frame rate. Additionally, exporting the video in an alternate format will remove valuable metadata. Metadata is information about other data. In this case, information about the video file and details about how it was generated.

Metadata may include a date and timestamp, or information about the camera and lens. Metadata stored by mobile cameras may also contain GPS coordinates, speed and heading. Dashcams used by law enforcement may indicate emergency light use, braking and radar speed detection readings.

Most surveillance software includes a viewer which can be used to view the file in its native format. These viewers typically enable frame-by-frame viewing, and permit exporting individual frames. Much of the metadata recorded with the video will only be viewable with this software. This applies even to files that are readable by other software such as Windows Media Player. Switching between multiple cameras may also be enabled. Obtaining the surveillance video in its native format with companion viewing software will ensure these issues do not compromise your analysis.

Resolution

Video recording has greatly improved in recent years. Modern smartphones are capable of recording videos in 1080p resolution, and consumer devices such as GoPro have reached 4K. However, older systems are still in use with significantly lower resolutions.

Early closed-circuit television systems were based on the Common Intermediate Format, or CIF with a resolution of 352 by 240 pixels and an aspect ratio of 4:3. Variants of this format were available such as QCIF and 4CIF which provided a resolution of one-quarter or four times CIF respectively. Display standards such as VGA (640 by 480) and SVGA (800 by 600) are still in use.

Modern systems are employing digital cameras with HD resolutions of 1920 by 1080 and a 16:9 aspect ratio. These higher resolutions enable greater precision in locating vehicles or other objects.

Upscaling and Aspect Ratio

The resolution of a video file may be different than the image captured by the camera. When this occurs, the image is upscaled to match the new resolution. Often, only the vertical resolution is affected. Therefore, the aspect ratio of the upscaled image is altered. In some cases, the image is presented in letterbox with time, date or other information placed in the mattes (black bars) above and below the image as in Figure 1.



Figure 1. Letterboxed image from a surveillance video with camera, date and time information displayed in the mattes. The image was compressed vertically. It was necessary to restore the image to the original aspect ratio for photogrammetric purposes.

The vertical location of objects will be affected by a change in the aspect ratio of the original image. In these instances, it is necessary to restore the image to its original aspect ratio using photo editing software.

Scanning

Analog video uses interlaced scanning to present images. This scanning method splits the horizontal lines across the image into two separate fields which are alternately refreshed. This can produce a jagged distortion in moving objects caused by a delay in refresh rate. The interlacing effect, or combing, is readily apparent in still frames and makes it difficult to precisely determine the location of a moving object. This distortion is visible in Figure 2.

Progressive scanning displays the entire image line by line in sequential order. Digital encoders can provide a progressive scanning option by using a deinterlacing filter. This eliminates the distortion caused by interlaced scanning but will not eliminate motion blur. (Figure 3.) This option may be available with the surveillance software and is typically enabled by default.



Figure 2. *Interlaced video divides the image into separate fields of horizontal lines which are alternatingly refreshed. Moving objects are subject to a combing effect which affects the ability to precisely locate the object.*



Figure 3. *This is the same frame as depicted in Figure 2 with a deinterlacing filter applied. The distortion is removed; however, motion blur is still present and unaffected by deinterlacing the image.*

Motion Blur

Motion blur results from the change in position of a moving object occurring during the interval of time the frame is exposed. The camera's shutter controls the length of time the image sensor is exposed to light. Whereas video cameras do not have a mechanical shutter, this process is controlled electronically.

Lower shutter speeds will enable more light to reach the sensor and improve the visibility in low light conditions. Higher shutter speeds will decrease the change in position occurring during exposure and improve the clarity of moving objects. Some motion blur is to be expected in a typical surveillance video. The amount of blur is affected

by the speed of the object, its distance from the camera and its motion relative to the optical axis. (Figure 3.) This will affect your ability to locate the position of the object and the precision of your analysis.

Frame Rate

A video is a collection of still images displayed in rapid succession to give the illusion of motion. The frame rate is the number of frames displayed per second. Most surveillance cameras record video at 15 to 30 frames per second (fps). Since the memory required to store video varies linearly with the frame rate, an hour of video at 15 fps will require half the memory than 30 fps. As a result, slower frame rates are used for some surveillance applications. Dual frame rates can also be used. In these applications, the video is recorded at a slower primary frame rate until motion is detected. This triggers the software to increase the recording to a secondary frame rate.

If the goal of your analysis is to determine the velocity of a vehicle which appears in a surveillance video, it is necessary to establish the frame rate at which the video was recorded. If a dual frame rate was used, it will also be necessary to determine the point at which the frame rate changes. The *Details* tab of the file properties in Windows will list the frame rate. (Figure 4.) However, this may not always reflect the frame rate at which the video was recorded. If a time stamp is displayed in the video or contained within the metadata, it can be used to more accurately determine the frame rate. (Figure 5.)

The most common frame rate is 30 fps. However, NTSC (National Television System Committee) video technically runs at 29.97 fps. This was due to legacy issues occurring when color broadcasts were introduced in 1953. Neglecting the disparity in the frame rate will not compromise your analysis. The disparity in the distance traveled in one frame is negligible. For example, the difference in the distance traveled by a vehicle at 100 mph in $1/30^{\text{th}}$ of a second versus $1/29.97^{\text{th}}$ is less than $1/16^{\text{th}}$ of an inch.

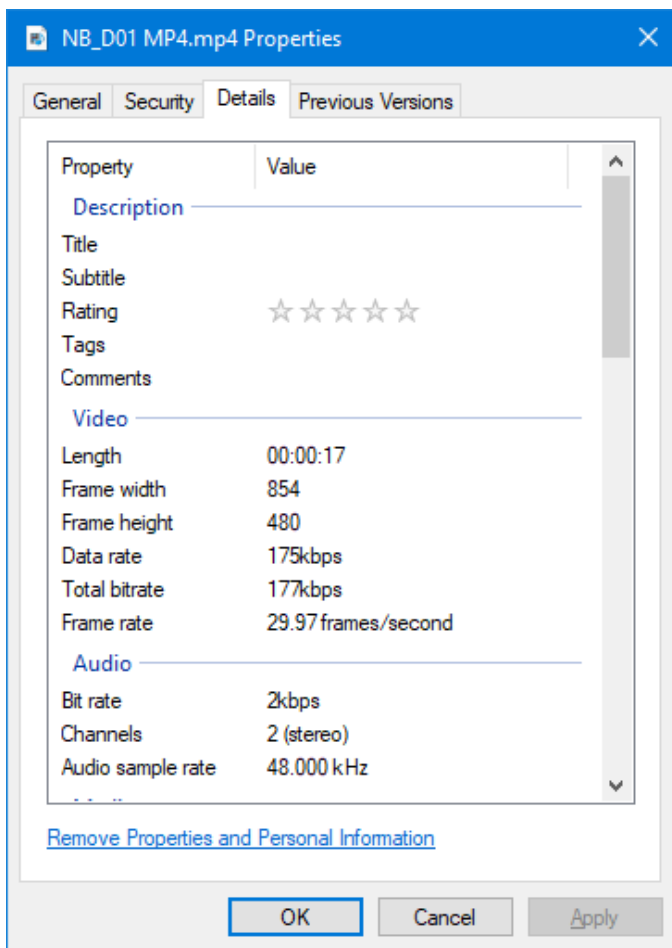


Figure 4. The Details tab in file properties displays the frame rate. Exported files may be encoded at a different frame rate than the original. The frame rate should be verified by alternate means when available.

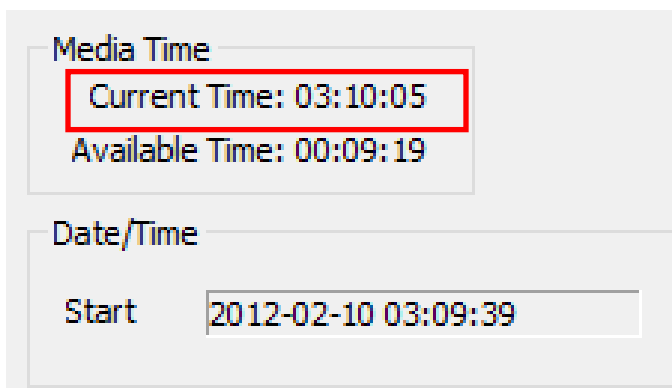


Figure 5. The viewer mode of this surveillance software includes a time stamp. Counting the number of frames in one second establishes the frame rate to the nearest integer.

Reverse Projection Photogrammetry

Photogrammetry is the process of obtaining measurements from photographs. In its simplest form, photo reconstruction involves approximating the location of objects in a photograph with respect to landmarks still present at the site. Measurements can then be taken to diagram the position of any object of interest. Reverse projection photogrammetry was created when specialized devices were constructed to hold a transparency containing the outlines of landmarks and items to be located, along with a peep hole used to sight object positions. Figure 6 shows an early device built for this purpose.

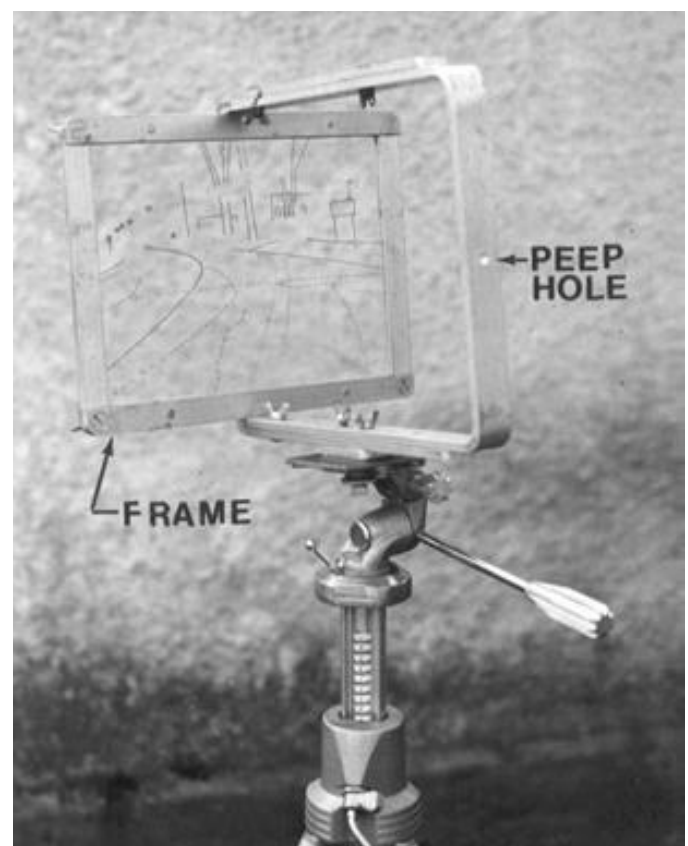


Figure 6. Transparency held by a tripod mounted frame used for reverse projection photogrammetry.

Later, single lens reflex cameras with removeable prisms were used. A slide transparency of the image was placed in the view finder and the prism replaced. The user could look through the view finder to align the camera and zoom lenses made it easier to establish the focal length.

Computerized Reverse Projection Photogrammetry

Computerized Reverse Projection Photogrammetry is a technique where this process is performed in a computer environment. This requires building a three-dimensional environment of the event site. A total station survey, or 3D scan of the location must be performed. In addition to the roadway surfaces, the survey should include the location of permanent landmarks which appear in the surveillance video. Figure 7 shows the location various landmarks that appear in the video. Additional detail was surveyed to establish the windows in the building, the roofline and the decorative wall. The methods used to build the environment are described in other sources and are beyond the scope of this paper.



Figure 7. Site photograph taken from the approximate position of the dash cam in a police vehicle.



Figure 8. Three-dimensional computer model of the above site built from a total station survey. In addition to the roadway, the building, light poles and wall were located.

Camera Location

Reverse projection photogrammetry requires establishing the location of the camera in three-dimensional space. In cases where the surveillance camera is stationary, its location can be established when the site is surveyed.

The metadata from a mobile camera may include GPS coordinates. This data can aid in identifying the camera position if the coordinate data is of sufficient precision. Figure 9 displays the GPS metadata available in the viewer software. This software included a Map-It function which displayed the location to a greater degree of precision. (Figures 10 and 11.) A GPS device capable of displaying the same precision is required to identify the coordinate location at the site. This point can be shot to establish the X and Y coordinates in the computer environment. Elevation data was not provided. The Z coordinate was estimated based on the height the camera was mounted above the ground.

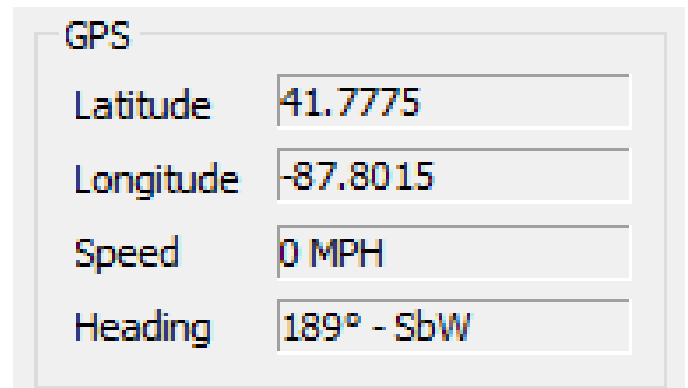


Figure 9. GPS metadata displayed in viewer software of dash mounted camera in a police vehicle.

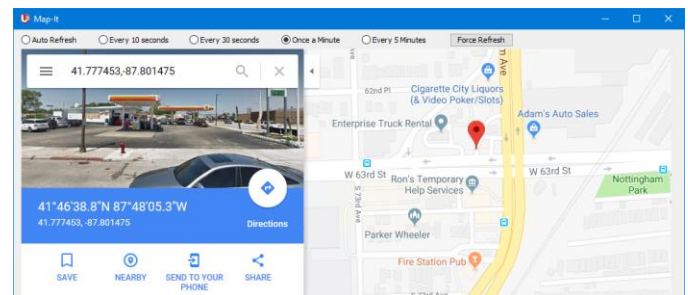


Figure 10. The Map-It function displays the GPS location and lists the coordinates to a higher degree of precision than the software.

41°46'38.8"N 87°48'05.3"W
41.777453, -87.801475

Figure 11. The displayed precision enables locating the coordinates within 0.36 feet.

The camera coordinates can be inputted into the Camera Setup dialog in HVE. (Figure 12.) The *View From* field identifies the camera location. A Traj Sim window in the Playback Editor provides greater flexibility in this process. This requires that the vehicles, environment and event be added to the HVE case file first. If the camera location cannot be established by other means, a trial and error approach is necessary.

Optical Axis

The optical axis is formed by a line passing through the center of curvature of a lens. It can also be described as the lens vector. In HVE, it is established by a ray originating at the *View From* coordinates and passing through the *Look At* coordinates in the Camera Setup dialog. (Figure 12.)

Identifying the *Look At* coordinates will complete the process of establishing the optical axis. This can be accomplished by identifying the coordinates of the intersection of the optical axis with a surface such as the pavement. This point will lie at the center of the image. The image center can be more easily established by extracting a still image from the video. Using photo editing software such as Adobe Photoshop or Corel PaintShop Pro, guides can be added to visualize the image center. (Figure 13.)

The process of establishing the *Look At* point often involves trial and error. The relative location of the image center to identifiable landmarks will aid in this process. Consider surveying the location of expansion joints, pavement cracks and pavement markings and include them in the computer environment. The Distance Tool in HVE can be useful establishing the coordinates to be inputted into the Camera Setup dialog. (Figure 14.)

Figure 12. The Camera Setup dialog in HVE. The camera location is given by the *View From* coordinates. The optical axis is the vector originating at the *View From* coordinates and passing through the *Look At* coordinates. The focal length is also specified in this dialog.

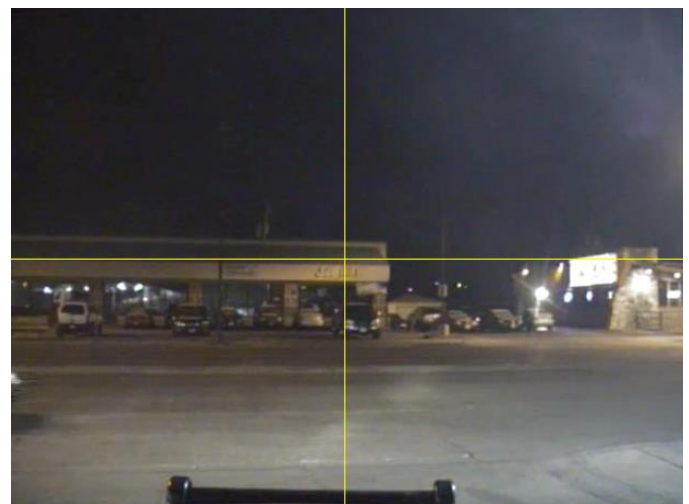


Figure 13. Yellow guides added to identify the image center. Establish the coordinates of a point in the environment which lies at the image center and input as the *Look At* coordinates. The optical axis of this frame intersects the building near the roofline.

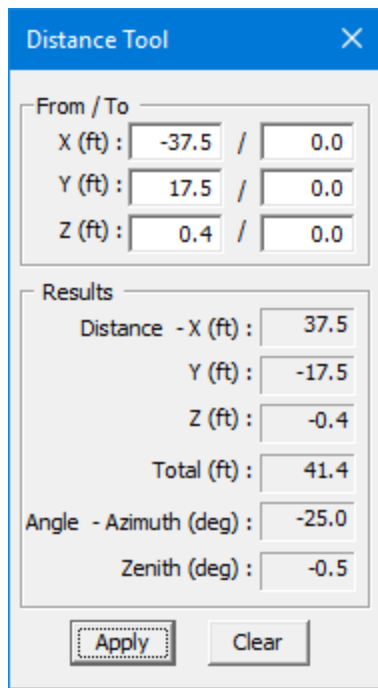


Figure 14. The Distance Tool can be a useful aid in identifying the Look At coordinates.

Focal Length

The focal length of a lens is the perpendicular distance from the film plane to the focal point of the lens. This establishes the angle of view, also called the field of view. Whereas the camera specifications may list the focal length, it is relative to the size of the image sensor. For photogrammetric purposes, it is the angle of view that needs to be duplicated.

The focal length of the HVE's virtual camera is based on a 35mm film camera. The image height is assumed to be 24mm. The vertical angle of view is displayed in the lower left corner of all HVE viewers and is calculated by:

$$\theta = 2 \tan^{-1} \left(\frac{h}{2f} \right) \quad (1)$$

where:

- θ = angle of view
- h = image height (24mm)
- f = focal length

The horizontal angle of view is proportional to the aspect ratio of the current view. The process of duplicating the angle of view requires comparing the image generated in the Traj Sim window with an extracted frame from the

video. Adjust the focal length listed in the Camera Setup dialog (Figure 12) as necessary to match the angle of view in the video. This value represents the effective focal length and will likely differ from the actual focal length of the surveillance camera.

In a conventional lens, light follows a direct path through the focal point and strikes the image sensor. Objects forming a straight line appear straight in the image. This is not true of fisheye lenses. In a fisheye lens, light entering the lens is bent into a funnel shape. Straight objects near the periphery appear curved in the image. The virtual camera in HVE is rectilinear and cannot duplicate the view of a fisheye lens.

Camera Swing

Rotation about the optical axis is known as camera swing. This is the equivalent to roll in vehicle parlance. Surveillance cameras are typically positioned so that the vertical axis of the image is plumb. In instances where this is not the case, it will be necessary to rotate the view in your photo editing software. This is necessary since HVE does not permit the user to edit camera swing. Instead, HVE aligns the vertical axis of the view to be parallel to the Z axis.

Camera Orientation

The entire process of determining the optical axis, focal length and camera tilt can be referred to camera orientation. Photo editing software can be used to evaluate the camera orientation. This can be done by superimposing an extracted frame from the video with the Traj Sim window from HVE. The Traj Sim window will need to be the same size, in pixels, as the extracted frame. Unfortunately, there is no way to specify the height and width of a Traj Sim window. However, it can be resized by clicking and dragging the window borders. The contents can be copied to the Windows Clipboard using *Alt+PrtScn*. It can then be pasted from the clipboard into your photo editing software and the dimensions determined. The Traj Sim window will need to be resized as necessary to match the dimensions of the video.

In your photo editing software, combine the Traj Sim window with the extracted frame. Compare the view using the layer transparency settings. The surveyed landmarks depicted in the environment model should align with their corresponding locations in the image from

the video. In HVE, adjust the *View From* and *Look At* coordinates and focal length as necessary until the views converge.

If the aspect ratio of the video was altered, either the vertical or horizontal alignment will be off. This can be rectified by resizing the extracted frame to restore the original aspect ratio. Similarly, the extracted frame can be rotated to account for camera swing. Figure 15 shows the Traj Sim window from HVE superimposed over the extracted frame from the dash cam of a police vehicle.



Figure 15. A Traj Sim window superimposed over an extracted frame from a dash cam video. The transparency setting was adjusted to visually evaluate the alignment of visible landmarks.

HVE Simulation

After the camera orientation is established, the process of locating vehicles or other objects of interest can proceed. This paper will specifically discuss the speed of a vehicle passing across the field of view of a dash cam mounted in a police vehicle.

In HVE, a computer model of the vehicle was created in the Vehicle Editor, and a vehicle specific geometry attached. An EDSMAC4 event was created. The lateral position of the vehicle in the roadway was approximated and an initial velocity of 6.82 mph was assigned. The output time interval and playback interval were changed to 0.01 seconds. This results in the vehicle traveling a convenient 0.1 feet each output time interval. At this point, the analysis is strictly positional. Therefore, the velocity is not important.

The path of the vehicle was evaluated in the same manner used to orient the camera. In this case, it was limited to the establishing the lateral position of the vehicle within its lane. If the motion were more complex, such as a vehicle turning a corner, steering inputs would be necessary. The initial position was adjusted as necessary and the event re-executed.

At this point in the analysis, the path of the vehicle has been established. If the vehicle's velocity and/or acceleration is important, it is necessary to establish its position as a function of time. The frames necessary to perform the speed calculations were extracted from the video. In the playback editor, the simulation was advanced until the vehicle's position was approximately the same as in the extracted frame being analyzed.

Figure 16 is an extracted frame in the sequence of images from the video used to determine the vehicle's speed. Figure 17 is a screen shot of the Traj Sim window in the Playback Editor. The timeline was scrubbed until the simulation vehicle was in approximately the same position as in the video. The Traj Sim window was copied to the clipboard superimposed over the extracted frame in Figure 18. The positions of the simulated and actual vehicles were compared and adjusted as needed. Figure 18 shows the superimposed images from the initial attempt. In this example, the simulated vehicle was too far behind the actual vehicle. The simulation was advanced, and the process repeated. Figure 19 shows a successful attempt to match the position of the simulated vehicle.

This process is repeated for every frame in the sequence. The distance traveled between frames divided by the time elapsed gives the average velocity of the vehicle between frames. The distance traveled can be obtained from Variable Output. The travel distance variable assists in determining this value, particularly in cases involving a curved path. Accelerations can be calculated from changes in velocity occurring during the frame sequences analyzed.

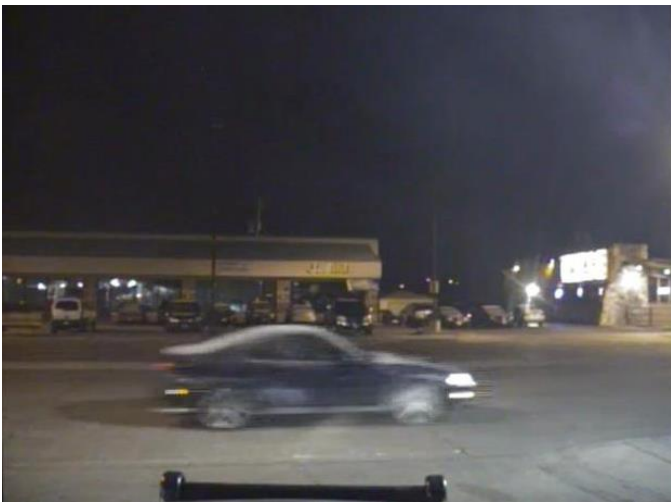


Figure 16. One frame in the sequence of frames extracted to determine the speed of the vehicle in the video.



Figure 17. A screen shot of the Traj Sim window from the EDSMAC4 event. The timeline was scrubbed to visually approximate the position of the vehicle in the video.



Figure 18. The Traj Sim window was superimposed over the extracted frame. The simulated vehicle is not aligned with the video. The simulation was advanced, and the process repeated.



Figure 19. The position of the simulated vehicle from Figure 17 was revised and the comparison repeated. The location of the simulated vehicle was confirmed.

Accuracy

If the frame rate was correctly identified, the determining factor in the accuracy of the analysis is how closely the vehicle positions can be established. This is affected by the following factors:

- Video resolution
- Distance between the vehicle and camera
- Visibility of the vehicle
- Path of vehicle relative to the optical axis

The video resolution and distance between the camera and the vehicle are directly related. Each pixel represents an angular distance. Increasing the number of pixels or reducing the distance between the vehicle and the camera, will reduce the physical distance each pixel represents and enable locating the vehicle more precisely.

It is necessary to be able to discern the vehicle or other object before its location can be established. This becomes difficult in low light conditions. The vehicle's lights may be readily visible, but their glowing appearance causes them to appear larger and therefore more difficult to precisely locate. This becomes more pronounced at low resolutions or when the vehicle is more distant.

The path of the vehicle with respect to the optical axis will also affect the analysis. The motion of objects moving perpendicularly to the optical axis can be more precisely located. Conversely, the positions of objects moving

nearly parallel to the optical axis becomes difficult to determine.

The number of frames in the sequence analyzed and the interval between them should also be considered. In the example documented in this paper, the vehicle's position was evaluated in 20 sequential frames. At 30 fps this represented a total time of 0.63 seconds. If the location of the vehicle was established to the nearest 0.1 feet, the variance in the velocity was plus or minus 2 mph for each frame. However, if the distance traveled between three frames, or 0.1 seconds, the variance decreases to less than 1 mph. This is provided that the total distance traveled for the 3 frames can be determined to the same degree of precision.

Appendix A displays the results of this analysis. The average velocity was calculated for each frame at an interval of 0.03 seconds. The calculations were repeated using every third frame, or a 0.1 second interval. Appendix B plots distance versus time for the data in Appendix A.

As this example illustrates, increasing the time interval used to calculate the vehicle's velocity reduces the sensitivity of the analysis. In cases where it is necessary to determine whether the vehicle is slowing or increasing speed, evaluating the motion over a longer duration would be preferred. This would permit evaluating the change in velocity occurring over a longer interval of time. Plotting the distance versus time curve will aid in this analysis.

Vehicle Simulation

The procedure described to this point has been strictly positional. Once the position and velocity data are established, a more complete kinetics analysis can be performed. An EDSMAC4 or SIMON event can be created, and the vehicle trajectory simulated using driver inputs at the velocity determined in the photogrammetric analysis. HVE's Video Creator can be used to create a video of the event from the perspective of the surveillance camera. An exhibit can then be created with the simulation and surveillance videos superimposed for comparison purposes.

Summary

This paper describes a method for using HVE to perform computerized reverse projection photogrammetry. The

ability to easily move a virtual vehicle within a computer environment streamlines this process. Additionally, HVE provides a means to evaluate the effects of driver inputs in conjunction with the positional data from the photogrammetric analysis.

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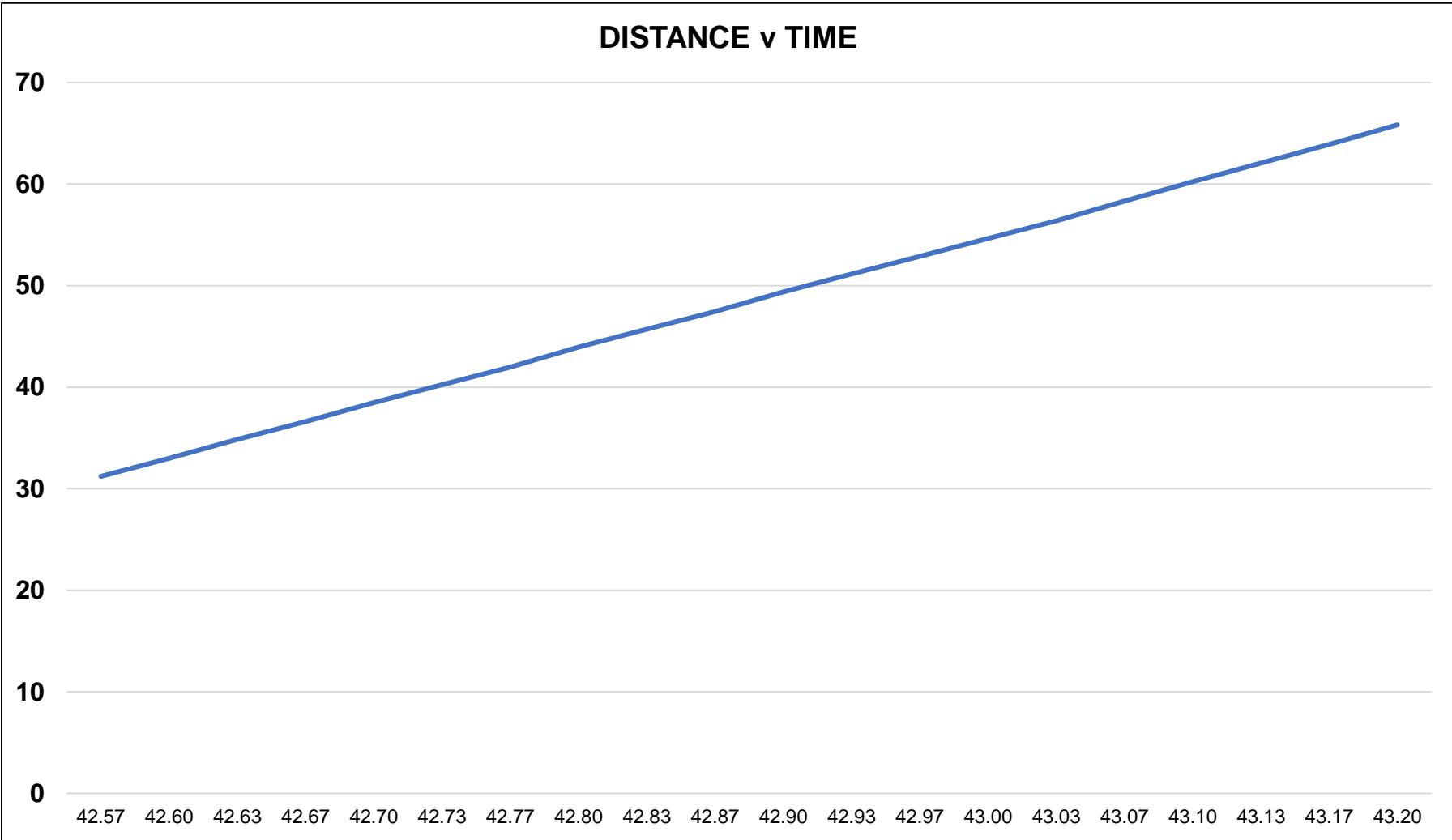
APPENDIX A

VIDEO TIME		SIMULATION TIME		SIMULATION DISTANCE				AVERAGE VELOCITY				AVERAGE VELOCITY			
				TOTAL		INTERVAL		0.03 sec INTERVAL				0.1 sec INTERVAL			
42.57	sec	3.15	sec	31.22	ft	1.76	ft	52.8	fps	36.0	mph	54.0	fps	36.8	mph
42.60	sec	3.33	sec	32.99	ft	1.77	ft	53.1	fps	36.2	mph				
42.63	sec	3.52	sec	34.85	ft	1.86	ft	55.8	fps	38.0	mph				
42.67	sec	3.70	sec	36.62	ft	1.77	ft	53.1	fps	36.2	mph				
42.70	sec	3.89	sec	38.48	ft	1.86	ft	55.8	fps	38.0	mph	54.6	fps	37.2	mph
42.73	sec	4.07	sec	40.24	ft	1.76	ft	52.8	fps	36.0	mph				
42.77	sec	4.25	sec	41.99	ft	1.75	ft	52.5	fps	35.8	mph				
42.80	sec	4.45	sec	43.94	ft	1.95	ft	58.5	fps	39.9	mph				
42.83	sec	4.63	sec	45.70	ft	1.76	ft	52.8	fps	36.0	mph	54.4	fps	37.1	mph
42.87	sec	4.81	sec	47.45	ft	1.75	ft	52.5	fps	35.8	mph				
42.90	sec	5.01	sec	49.39	ft	1.94	ft	58.2	fps	39.7	mph				
42.93	sec	5.19	sec	51.14	ft	1.75	ft	52.5	fps	35.8	mph				
42.97	sec	5.37	sec	52.89	ft	1.75	ft	52.5	fps	35.8	mph	54.2	fps	37.0	mph
43.00	sec	5.55	sec	54.63	ft	1.74	ft	52.2	fps	35.6	mph				
43.03	sec	5.73	sec	56.37	ft	1.74	ft	52.2	fps	35.6	mph				
43.07	sec	5.93	sec	58.31	ft	1.94	ft	58.2	fps	39.7	mph				
43.10	sec	6.13	sec	60.24	ft	1.93	ft	57.9	fps	39.5	mph	55.9	fps	38.1	mph
43.13	sec	6.32	sec	62.07	ft	1.83	ft	54.9	fps	37.4	mph				
43.17	sec	6.51	sec	63.90	ft	1.83	ft	54.9	fps	37.4	mph				
43.20	sec	6.71	sec	65.83	ft	1.93	ft	57.9	fps	39.5	mph				

The video time refers to the time indicated by the timestamp from the dashcam video. The simulation time corresponds to the timestep indicated by the EDSMAC4 simulation. The total distance indicates to the travel distance reported in variable output from the beginning of the simulation. The interval distance refers to the distance traveled during the timestep.

The average velocity calculated at an interval of 0.033 seconds varies by as much as 4 mph due to the precision to which the vehicle's position can be established. Increasing the interval to 0.1 seconds significantly reduces irregularities in the data. A regression analysis corroborates a velocity of 37 mph with a coefficient of determination (r^2) of 0.99.

APPENDIX B



A plot of the distance traveled with respect to time indicating a velocity of 37 mph.