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The Applications of Matchmoving for Forensic Video Analysis of a Fatal Sprint Car Accident: Part II

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Abstract

This paper presents the application of the photogrammetric process known as matchmoving to analyze a racetrack video and reconstruction of a fatal Sprint Car race accident. The use of high-definition 3D laser scanning technology made it possible to accurately perform the matchmoving process on racetrack video footage to determine the path, heading, speed, and acceleration of the involved Sprint Cars. In addition to the accident racetrack, another video of a Sprint Car race on a similar racetrack, taken by a drone, was also analyzed using the same matchmoving method to evaluate the speed and yaw angle of a drifting Sprint Car.

Keywords

Matchmoving, photogrammetry, high-definition scanning, video analysis, drone video footage, accident reconstruction, lens distortion correction, SynthEyes, forensic engineering, Sprint Cars

Introduction

Cameras surround us in our everyday lives. Today, more accidents and shootings are being captured on video, whether it be by surveillance cameras, police body-worn cameras, air units, dash cameras, or by witnesses using smart phones. With this widespread use of cameras, one of the first things that is done after an accident/catastrophic event is to secure any video footage that may have captured the accident. The proper scientific analysis of these videos is vitally important in reconstructing these accidents.

In recent years, with the advances of technologies like high-definition 3D laser scanning (also known as Light Detection and Ranging or LiDAR) and drones — as well as advancements in software — it is now possible to apply matchmoving to video footage, extract accurate information, and use it to reconstruct what happened.

Matchmoving is a process based on the science of photogrammetry that is used to solve for or “calibrate” a virtual camera to “match” the “movement” and lens characteristics of the real-world camera used to capture a given video. After calibrating the virtual camera, the motion of objects depicted in the video, such as vehicles, pedestrians, or other objects can be determined through the process of object tracking or object matching.

The second in a two-part series, this paper presents the application of matchmoving to a 13.8-second video clip of a racetrack video (**Figure 1**) to reconstruct the accident and determine the path, heading, speed, and acceleration of seven race cars and the movement of the pedestrian who was struck and killed.

Background

The accident occurred at a motorsports park with a

Figure 1
Still frame from track video moments before the fatal impact.

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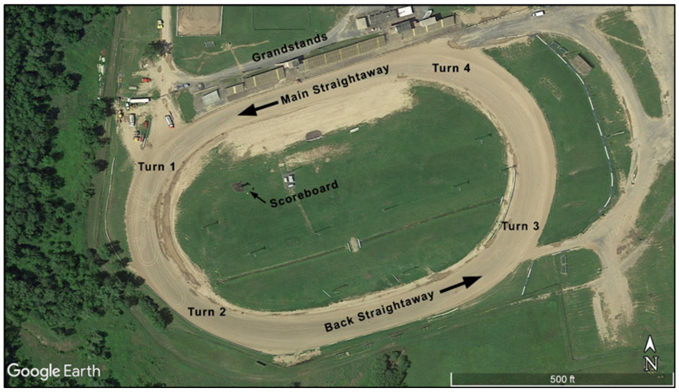


Figure 2
Google aerial imagery of the motorsports park with annotations added by authors.

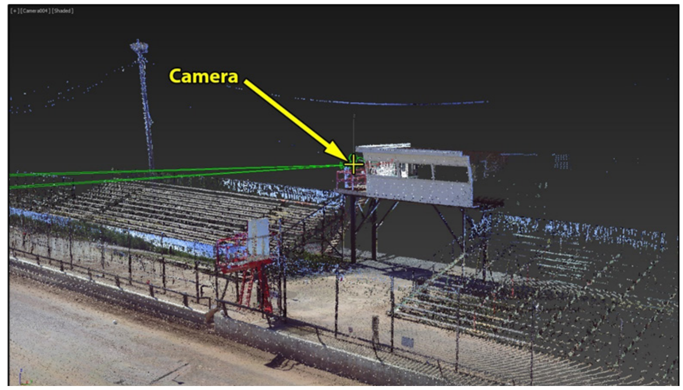


Figure 3
Photo of motorsports park grandstands showing the location of the camera that recorded the video of the accident.

low-banked dirt oval track with the straights running southwest and northeast and the grandstands positioned on the north side of the track. The track corners were divided into quadrants (1 to 4) with the cars racing counter-clockwise. Turn 1 was the first turn after passing the grandstands on the main straightaway as shown in **Figure 2**.

The driver in Sprint Car #13 (SC#13) and another driver in SC#14 were both competing with their Sprint Cars and entering into Turn 1 at approximately the same time when the driver in SC#14 attempted to overtake the driver in SC#13. The driver in SC#13 lost control of his Sprint Car during the maneuver and made contact with the outer edge track barrier where his Sprint Car came to a stop near the end of Turn 2.

After impacting the barrier, the driver in SC#13 immediately exited his Sprint Car. Because of this incident, the remaining Sprint Car drivers went under a "yellow flag." (During a yellow flag, drivers are alerted to exercise caution, and reduce speed for a hazard on the racetrack.) Also, a caution announcement was broadcast over the drivers' helmet headsets with instructions to stay low (toward the infield of the racetrack).

As the Sprint Cars slowed for the "yellow flag," SC#2, SC#20, and SC#28 passed SC#13, which was stopped on the inside corner Turn 2 of the track as the driver of SC#13 was walking behind the rear of his Sprint Car. SC#19 passed the driver of SC#13 at the mid to lower portion of the track. As the driver of SC#13 began to walk toward the middle of the track, he was passed by SC#10 and SC#45 on the inside corner of the track. As the driver in SC#14 approached the driver of SC#13 in Turn 2, the right rear of the SC#14 impacted the driver of SC#13, causing fatal injuries.

Motorsports Park Camera Video Footage

The motorsports park was recording the Sprint Car racing event with a video camera that was mounted on a tripod and positioned on the east side of the announcer's box located in the middle of the grandstands (**Figure 3**). The camera captured video of the event at 29.97 frames per second in full high-definition (FHD) resolution.

Despite being recorded from a tripod and having relatively high resolution, the video footage was a challenge to analyze for a number of reasons. First, the camera man was panning and zooming in and out throughout the video, which means the orientation and field of view (FOV) of the camera was constantly changing. Secondly, the accident occurred in Turn 2, which was approximately 550 feet away from the camera (**Figure 4**). Finally, because the race was at night, the low light and combination of the camera's shutter speed and aperture, vehicle speed, and the movement of the camera (panning and zooming) produced some motion blur in parts of the video.

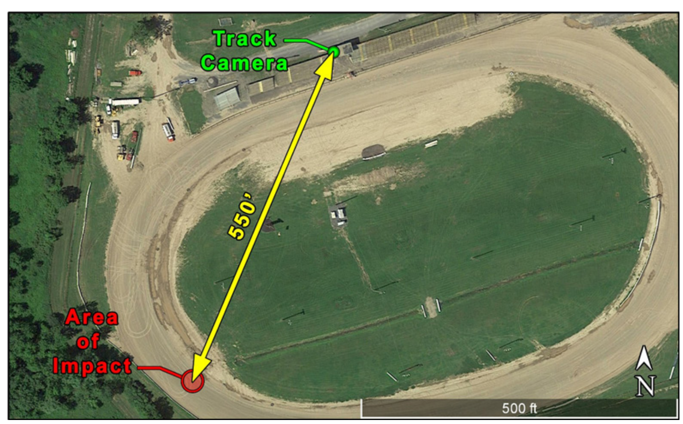


Figure 4
Aerial view of racetrack, depicting the distance between the track camera and the area of impact.

Rudimentary speeds of the vehicles could have been determined using the traditional method of using landmarks or sight lines to measure the distance a vehicle traveled between two points and dividing that distance by the time it took for the vehicle to travel between the two points. However, the lack of lane lines and the relatively low angle and far distance the camera was relative to the incident would make it practically impossible to yield reliable results regarding the vehicles' and pedestrian's lateral position on the track using typical analytical methods.

For this reason, the authors used an established photogrammetric method called "matchmoving" to reconstruct the speeds and paths of the vehicles and pedestrian. The matchmoving method is outlined in a paper titled, "Forensic Engineering Application of the Matchmoving Process." The matchmoving method has been used for decades for visualization purposes, but has only in recent years been able to be used for video analysis and accident reconstruction — thanks to the advancements of matchmoving software and the now established technology of high-definition 3D laser scanning[1].

High-Definition 3D Laser Scanning

In order to ensure the matchmoving process yielded accurate results, high-definition 3D laser scanning was used to capture three-dimensional point clouds of an exemplar Sprint Car vehicle, which was similar in shape and size to SC#13 and SC#14, and the motorsports park racetrack. Before scanning of the track, it was noted that neither the track geometry nor the grandstand geometry was changed since the date of the incident.

The point clouds were captured using a Faro Focus 3D X330 Laser Scanner and consisted of approximately 860 million data points for the racetrack and approximately 390 million data points for the exemplar Sprint Car (**Figure 5**). Each data point in the point clouds is defined by its three-dimensional coordinates (x, y, z) and is accurate to within a few millimeters. The point cloud models of the racetrack and the exemplar Sprint Car were used by the authors to perform videogrammetry analysis on the provided racetrack video footage.

Videogrammetry

The authors performed videogrammetric analysis on the provided racetrack video footage to determine the spatial movement of SC#14, the preceding six Sprint Cars and the decedent driver of SC#13, as depicted in the video.

The videogrammetric analysis involved first using the established scientific process called matchmoving[2,3] to define a virtual camera that "matches" the location, orientation, focal length, and lens distortion of the camera used to record the provided racetrack video footage. Further, a process called object matching was used to determine where objects (seven Sprint Car vehicles and a decedent driver) were physically located on the racetrack in each frame of the video.

Figure 5
Point cloud model of the racetrack (left) and the exemplar Sprint Car vehicle model (right.)

Matchmoving

The authors used a well-known software called "SynthEyes" to perform the matchmoving process. First, two-dimensional points (features) were identified and tracked through multiple frames of the video. Each feature represents a specific point on the surface of some fixed object on the racetrack (i.e., fence post, concrete barrier, scoreboard, etc.). Each tracked feature was then assigned and constrained to the feature's corresponding three-dimensional coordinates (x, y, z) as defined by the racetrack point cloud (**Figure 6** and **Figure 7**).

Using the 2D trackers and their given 3D XYZ coordinate constraints, SynthEyes was then used to mathematically solve for (or "calibrate") a virtual camera (relative to the racetrack point cloud) that emulated the lens characteristics and movement (panning and zooming) of the real-world camera that was used to record the racetrack footage.

The virtual camera's solution was determined to a high degree of scientific certainty. **Figure 8** shows the error rate between the constrained or "locked to" position of each 3D (xyz) tracker, and the 3D "solved position." The average error rate of all the constrained 3D trackers was 0.0017 feet (approximately 0.5 mm).

As further verification, the solved virtual camera's location in the racetrack point cloud, matched with the location where the real-world racetrack video camera was located in the stands at the time of the incident (**Figure 9**).

Figure 10 shows match of image by virtual camera

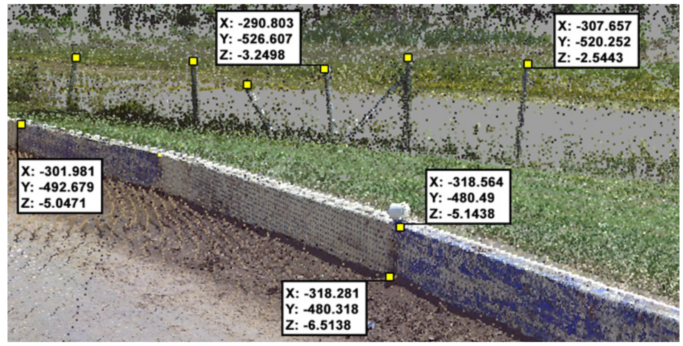
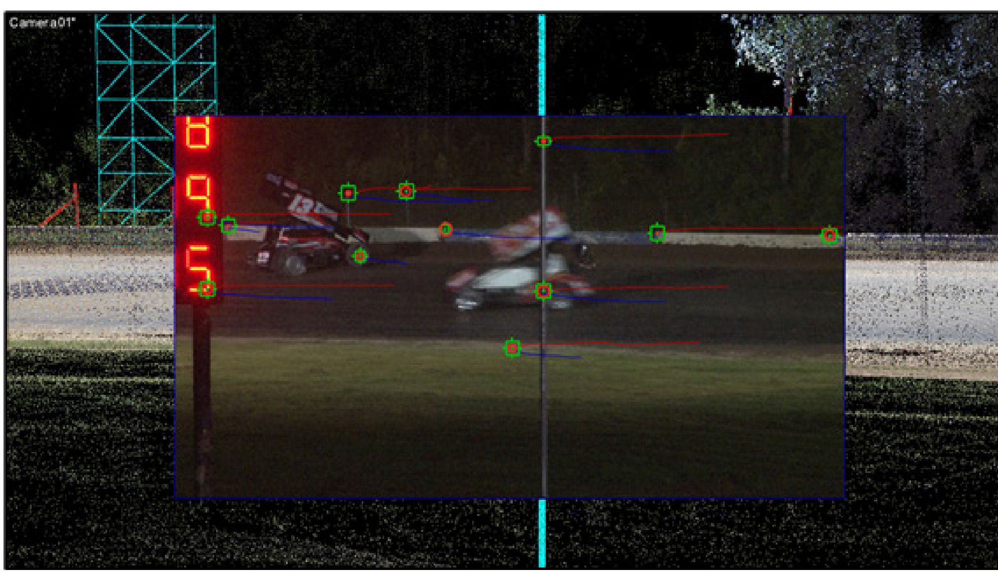


Figure 7
Sample of the 3D (XYZ) coordinates data
(extracted from the author's 3D racetrack point cloud)
used to constrain the corresponding 2D trackers.

Axes	Tracker	Locked To	Distance	Solved Position			Error
XYZ	#2	x=-323.542 y=-515.667 z=-3.0515		-323.541	-515.668	-3.049	0.003
XYZ	#4	x=-184.255 y=-195.603 z=9.078		-184.258	-195.602	9.074	0.005
XYZ	#6	x=-182.215 y=-197.105 z=5.894		-182.210	-197.107	5.892	0.005
XYZ	#7	x=-182.704 y=-196.79 z=8.92		-182.702	-196.791	8.917	0.003
XYZ	#8	x=-318.564 y=-480.49 z=-5.1438		-318.562	-480.491	-5.145	0.002
XYZ	#10	x=-185.536 y=-194.669 z=7.385		-185.538	-194.668	7.393	0.008
XYZ	#12	x=-185.526 y=-194.671 z=4.3866		-185.525	-194.672	4.388	0.002
XYZ	#28	x=-231.584 y=-529.991 z=-5.0209		-231.584	-529.991	-5.021	0.000
XYZ	#151	x=-255.4 y=-447.8 z=-11.1		-255.401	-447.800	-11.099	0.001
XYZ	#153	x=-250.112 y=-521.951 z=-5.0859		-250.112	-521.951	-5.085	0.000
XYZ	#282	x=-251.73 y=-448.4 z=-11		-251.731	-448.400	-11.000	0.001
XYZ	#283	x=-262.059 y=-536.37 z=-2.9811		-262.059	-536.370	-2.981	0.000
XYZ	#291	x=-345.719 y=-457.953 z=-5.5006		-345.719	-457.953	-5.501	0.000
XYZ	#292	x=-328.921 y=-514.48 z=-2.9217		-328.924	-514.479	-2.922	0.003
XYZ	#298	x=-182.176 y=-197.102 z=11.001		-182.172	-197.103	10.999	0.004
XYZ	#299	x=-333.945 y=-468.48 z=-5.3998		-333.945	-468.480	-5.398	0.002
XYZ	#300	x=-285.121 y=-503.865 z=-4.95		-285.121	-503.865	-4.950	0.000
XYZ	#302	x=-302.276 y=-492.26 z=-4.9496		-302.278	-492.259	-4.950	0.002
XYZ	#304	x=-239.618 y=-542.924 z=-2.7346		-239.618	-542.924	-2.735	0.000
XYZ	#305	x=-226.718 y=-547.141 z=-3.0185		-226.718	-547.141	-3.019	0.000
XYZ	#326	x=-235.676 y=-528.2 z=-5.092		-235.675	-528.200	-5.092	0.001
XYZ	#331	x=-267.628 y=-513.8 z=-5.12		-267.628	-513.800	-5.120	0.001
XYZ	#332	x=-355.724 y=-513.394 z=-3.9003		-355.724	-513.394	-3.902	0.002
XYZ	#336	x=-233.857 y=-408.773 z=-8.7813		-233.857	-408.773	-8.781	0.000
XYZ	#338	x=-211.284 y=-410.795 z=-8.875		-211.284	-410.795	-8.875	0.000
XYZ	#341	x=-212.867 y=-537.255 z=-4.848		-212.867	-537.255	-4.848	0.000

Figure 8
Table of the constrained trackers used to calibrate the virtual racetrack camera. The far-right column (highlighted by the authors in yellow) shows the error rate between the constrained or "locked to" position of each 3D (xyz) tracker and the 3D "solved position" in feet.



Axes	Tracker	Locked To
XYZ	#2	x=-323.542 y=-515.667 z=-3.0515
XYZ	#4	x=-184.255 y=-195.603 z=9.078
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XYZ	#298	x=-182.176 y=-197.102 z=11.001
XYZ	#299	x=-333.945 y=-468.48 z=-5.3998
XYZ	#300	x=-285.121 y=-503.865 z=-4.95
XYZ	#302	x=-302.276 y=-492.26 z=-4.9496
XYZ	#304	x=-239.618 y=-542.924 z=-2.7346
XYZ	#305	x=-226.718 y=-547.141 z=-3.0185
XYZ	#326	x=-235.676 y=-528.2 z=-5.092
XYZ	#331	x=-267.628 y=-513.8 z=-5.12
XYZ	#332	x=-355.724 y=-513.394 z=-3.9003
XYZ	#336	x=-233.857 y=-408.773 z=-8.7813
XYZ	#338	x=-211.284 y=-410.795 z=-8.875
XYZ	#341	x=-212.867 y=-537.255 z=-4.848

Figure 6
Tracked 2D points (in green, left) constrained to 3D x,y,z coordinates (right).

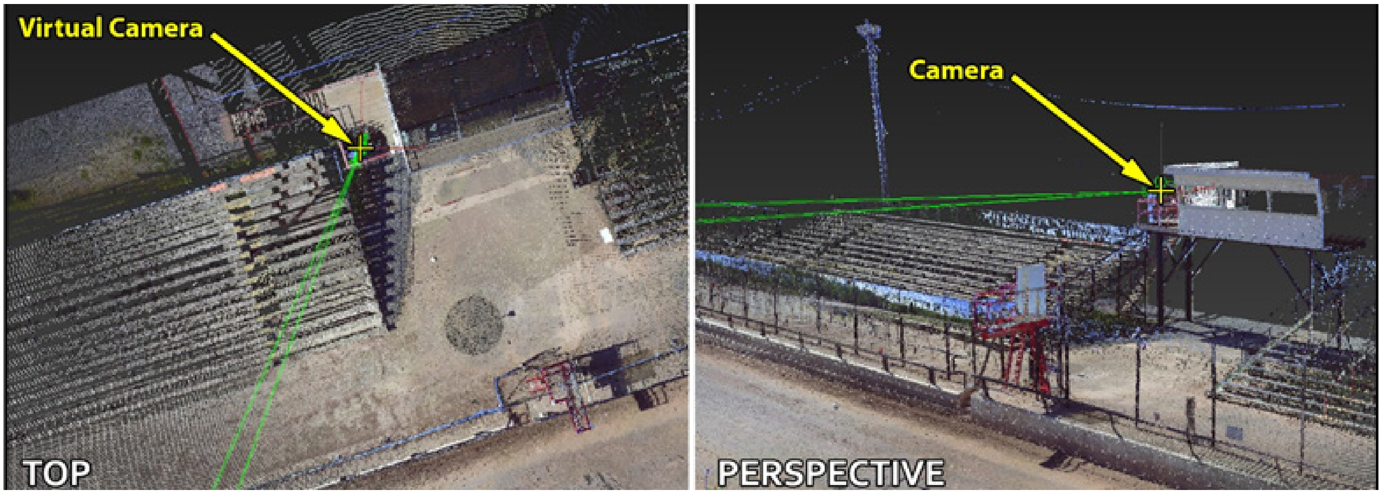

Figure 9
Top view (left) and perspective view (right) of the motorsports park grandstands showing the location of the virtual camera solved by matchmoving.

and the point cloud. Once the calibration of the virtual camera was confirmed to be accurate, the next step in the videogrammetric process was to use a process called "object matching" to determine the three-dimensional position of the vehicles and pedestrian in every video frame to determine their paths, speed, and acceleration.

Vehicle and Pedestrian Matching/Tracking

The calibrated virtual camera and the racetrack point cloud model were brought into a virtual scene in 3D Studio Max. In the virtual scene, a three-dimensional virtual model of a Sprint Car, which was based on the point cloud of the exemplar Sprint Car (SC#35), as shown in **Figure 11**, was positioned on the surface of the race track in the point cloud to match the location of SC#14 in each frame of the video, as viewed through the virtual camera (**Figure 12**).

It is important to note that when positioning the virtual Sprint Car model, the main constraint is that the bottom of the wheels of the model must be in contact with the surface of the racetrack. The virtual model is then moved laterally along the racetrack super elevation (toward or

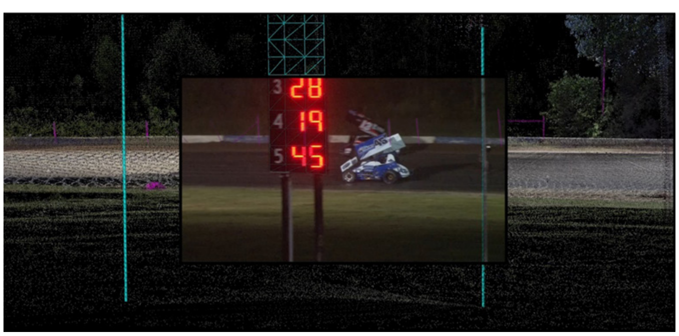

Figure 10
Matchmove "virtual" camera view verifying a correct solve.

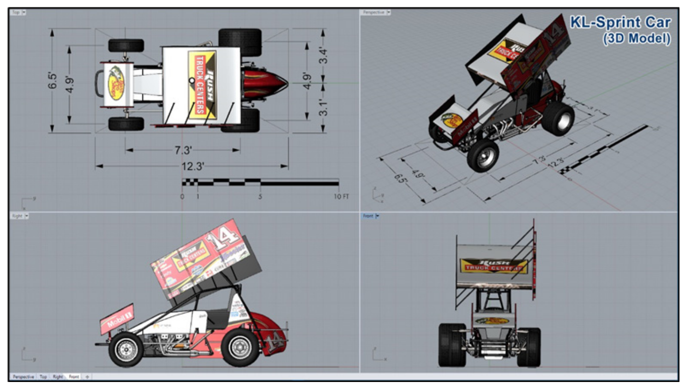

Figure 11
3D virtual model of Sprint Car based on point cloud of exemplar Sprint Car.

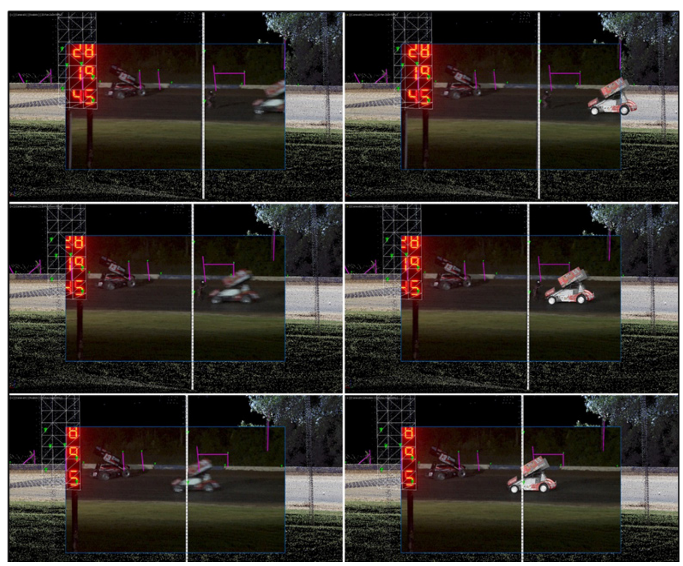

Figure 12
Frame by frame matching of SC#14. Left column: video frames. Right column: virtual Sprint Car model matched to position of Sprint Car seen in video.

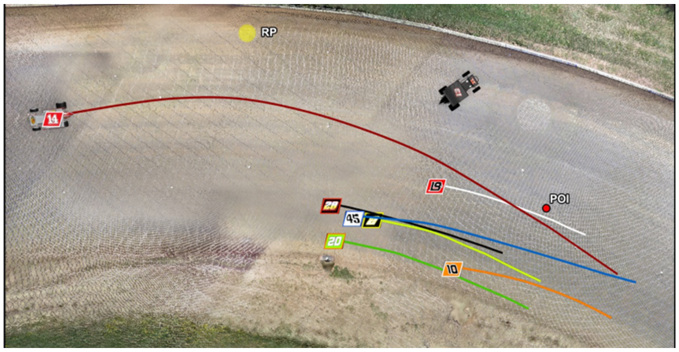

Figure 13
Seven Sprint Car paths resulting from videogrammetric analysis.

away from the camera) and oriented (heading) on the track surface until the model matched in size to the Sprint Car depicted in the video frame.

The authors also performed the same matching process for the six Sprint Cars that passed the decedent driver prior to SC#14. Once the vehicles had been tracked/matched, the 3D translation (x, y, z) and orientation angles (roll, pitch, yaw) data of each vehicle, for each video frame, was exported directly from 3D Studio Max program and imported into an Excel spreadsheet where the object's motion data (i.e., speed, acceleration, heading angle, etc.) was calculated and graphed. The vehicles' motion data was then evaluated to confirm that they were in line with the laws of physics. The resulting paths (**Figure 13**), yaw angles (**Figure 14**), speeds, and accelerations were plotted and graphed.

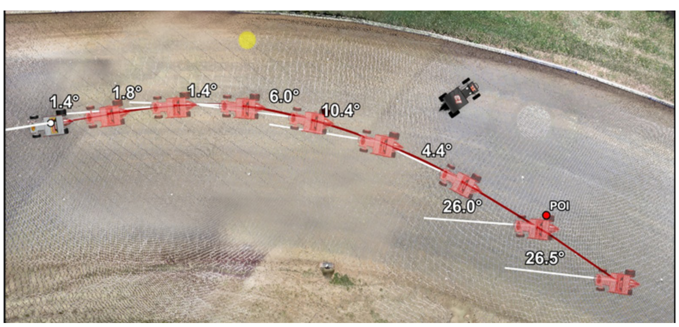

Figure 14
SC #14 yaw angle along path.

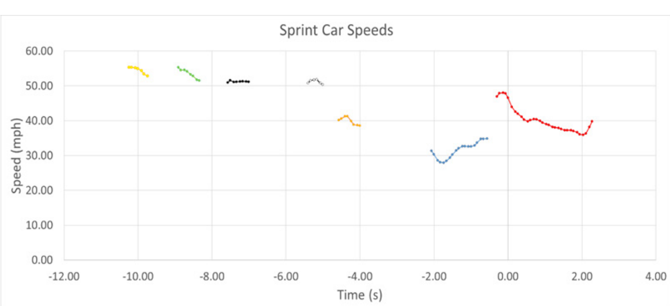

Figure 15
Speed data resulting from videogrammetric analysis.

Note: The Sprint Cars' paths shown are only those that could be seen in the track video. Plots of speed and acceleration are shown in **Figure 15** and **Figure 16**, respectively. The pedestrian and his path are shown in **Figure 17** and **Figure 18**.

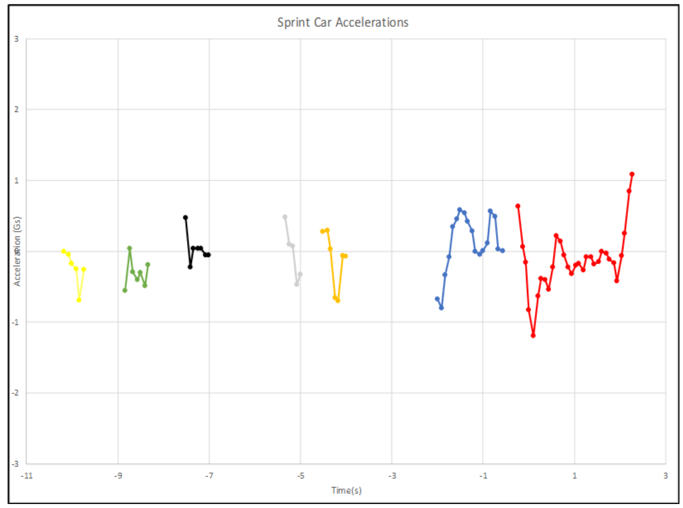

Figure 16
Acceleration data resulting from videogrammetry analysis.

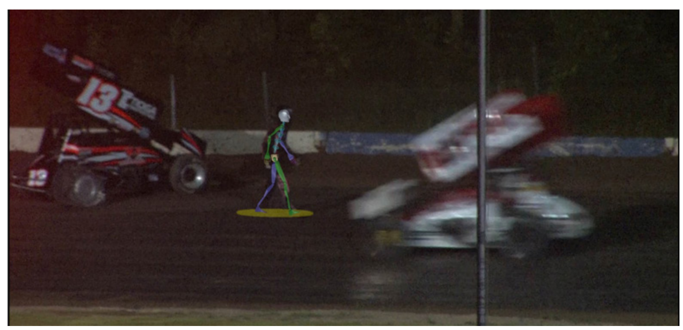

Figure 17
Virtual surrogate bi-ped model used to match
the motion of the driver of SC#13.

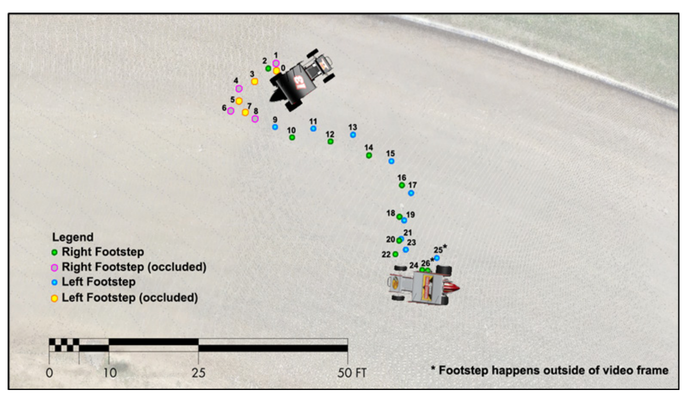

Figure 18
The footsteps of driver SC#13 determined through
videogrammetry. Red and yellow circles denote steps that
were occluded by the scoreboard in racetrack video.

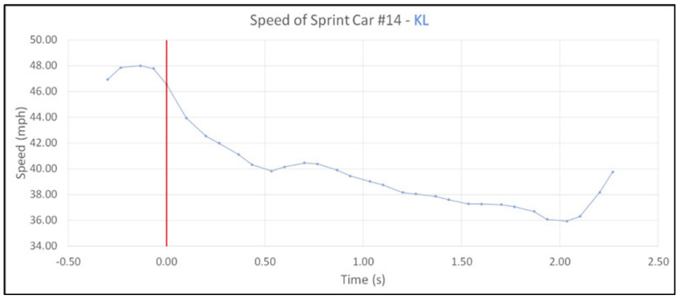

Figure 19
Graph of SC#14 speed data.

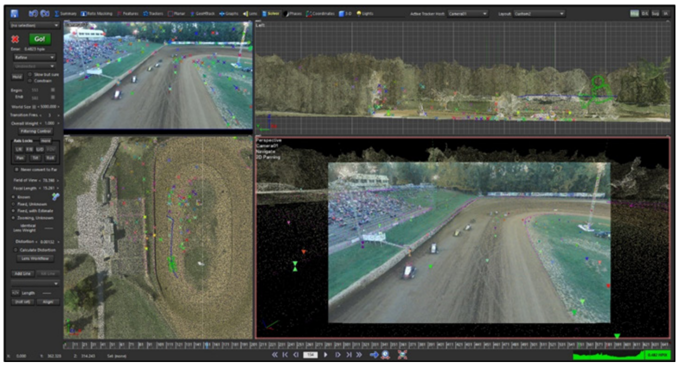

Figure 20
USGS LIDAR data used as constraint to accurately matchmove drone video footage during Sprint Car race.

Based on the review of the vehicle position, speeds, accelerations, and heading angle, resulting from the vehicle motion analysis performed by the authors, it was confirmed that the vehicle motions were valid and within the limits of a physics-based model of the subject event. Typically, accelerations would be expected to be in the vicinity of +/- 1G for Sprint Cars operating at low to moderate speeds and under caution. The vehicle motions, calculated speeds, accelerations, and heading angle were all based on frame-by-frame computations of the Sprint Cars' positions, which resulted in realistic and reliable data to analyze the incident sequence by these engineers.

The analysis of each car's movement started when the car comes into the frame of the video. All seven cars' positions, time, and speeds were analyzed at a frequency of 30 frames per second, resulting in 1,050 data points for each second of car motion from entering video frame until passing area of impact. Sprint Car #14 speed data is shown in **Figure 19**.

The position of SC#13 at rest position was also matched to the video. Additionally, the authors matched the SC#13 driver's walking motion by using a virtual biped surrogate model to match (track) the driver's body parts (legs, arms, head, etc.) relative to the racetrack surface in each frame where he was viewable in the video and not occluded by the scoreboard or passing Sprint Cars.

Results

Based on the videogrammetric analysis, the authors were able to conclude that driver SC#14's speed, acceleration, heading angle, and vehicle path toward driver SC#13 was different than the six Sprint Cars that passed the driver SC#13's location without incident. In fact, driver SC#14 was drifting sideways up the track when it struck driver SC#13, resulting in his death.

Supplemental Video Analysis (Another Case Study)

One of the claims was that driver SC#14 could not have been drifting up track at 50 mph. The authors utilized the same matchmoving method as described above on a video captured by a drone of a Sprint Car race in Lincoln Park raceway, on a similar dirt track to determine if a Sprint Car was capable of drifting up-track at lower speeds (40 to 55 mph).

Aerial Imagery and LiDAR data attained from the United States Geological Survey (USGS)[4] were used to accurately matchmove the video footage (**Figure 20**). Using object matching, the authors were able to match an exemplar Sprint Car model to one of the Sprint Cars depicted in the video (**Figure 21**). The position and rotational data of the Sprint Car were analyzed and showed that the Sprint Car was drifting at speeds below 50 mph (**Figure 22**). As demonstrated on **Figure 21**, the angle between the car heading and car velocity is called yaw angle and was found to be 26.8 degrees.

Matchmoving Done Wrong

It is important to understand that in order for the

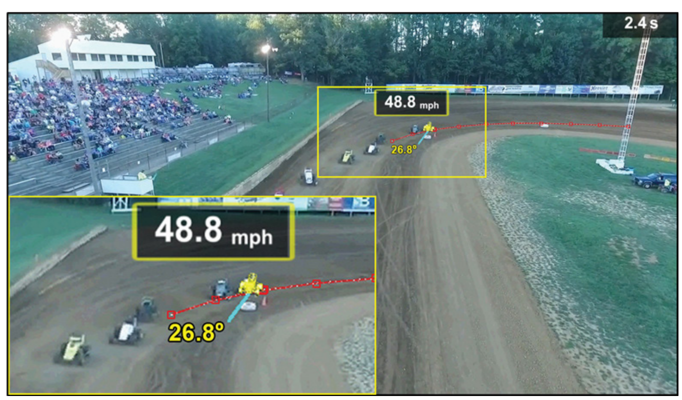

Figure 21
3D virtual model of Sprint Car matched to Sprint Car depicted in the video (yaw: a= 26.8°).

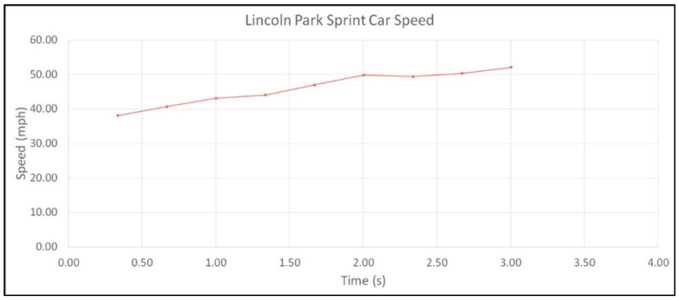

Figure 22
Speed plot of the matched Sprint Car.

matchmoving method to yield accurate results, there must be sufficient accurate 3D data points to use as constraints to calibrate the camera. The location of those 3D points must be the same as they were at the time the video was recorded.

For example, in the previously discussed motorsports park fatal incident, the concrete barriers that were around the outer perimeter of the track at the time of the incident are vital 3D features that were tracked in order to calibrate the virtual track video camera. Those barriers had not been moved between the incident and the time the authors scanned the racetrack. However, when the opposing expert scanned the racetrack, the barriers around the area of the incident had already been removed (**Figure 23**).

Since the opposing expert failed to scientifically calibrate the racetrack camera, they had to estimate the location of the missing barriers resulting in error (**Figure 24** and **Figure 25**).

The insufficiency or inaccuracy of the 3D point data did result in an inaccurate camera calibration, if a calibration can be solved at all. If the camera calibration is inaccurate (i.e., not in the correct place, panning and zooming), then the analysis will be fundamentally flawed — and any resulting analysis or conclusions derived are simply unreliable and without scientific merit. An example

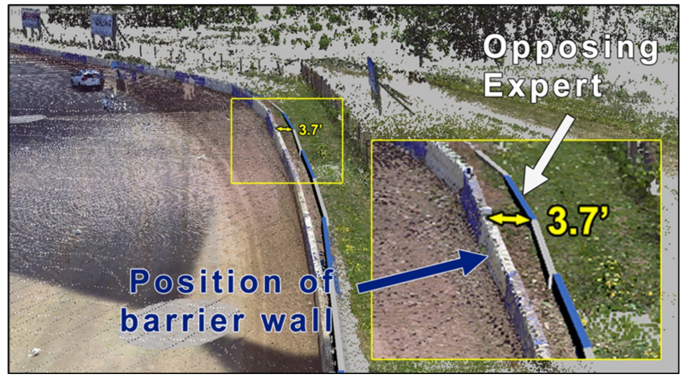

Figure 24
The barriers modeled by the opposing expert (white arrow) compared to the barriers (point cloud) documented by the authors.

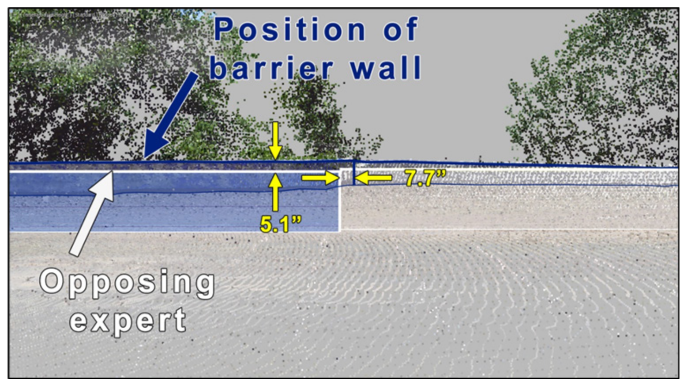

Figure 25
The barriers modeled by opposing expert (white arrow) compared to the barriers (point cloud) documented by the authors. Orthographic side view.

Figure 23
Left: Point cloud of the portion of the track where incident occurred (barrier wall highlighted in yellow); Right: Barrier wall had been removed/moved when the opposing expert scanned the racetrack.

of faulty analysis is discussed below.

A flawed or inaccurate calibration becomes evident when viewing the virtual scene through the virtual camera, and the tracked 3D features do not accurately match with those same features depicted in the video (**Figure 26**).

The error in the flawed camera calibration and analysis is further highlighted when attempting to match/track the position of the objects like the vehicles in the video frames. Physical constraints (i.e., the bottom of the wheels of the Sprint Car must rest directly on top of the surface of the racetrack) cannot be satisfied. The result is that the Sprint Cars are often "floating" above the surface of the racetrack or traveling below the racetrack level as shown in **Figure 27** and **Figure 28**. The inaccurate vehicle motion is shown in red in **Figure 29**.

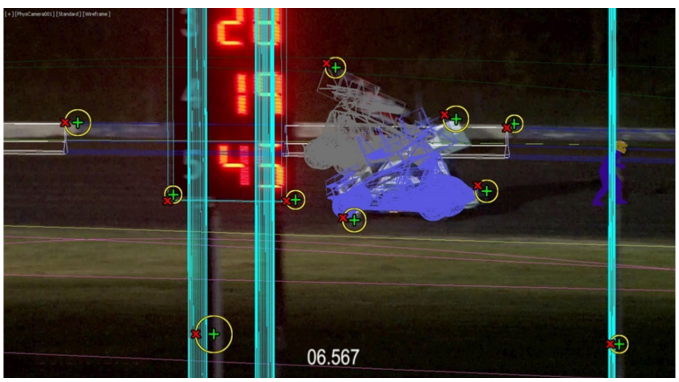

Figure 26
Sample frame from opposing expert's analysis illustrating the inaccuracy of their camera calibration and vehicle matching. Green plus signs mark where the point on an object (i.e., edge of barriers, scoreboard corners, vehicle wheels, etc.) are depicted in the video. Red "X"s mark where those points are projected when viewed through the virtual camera in the opposing expert's 3D scene.

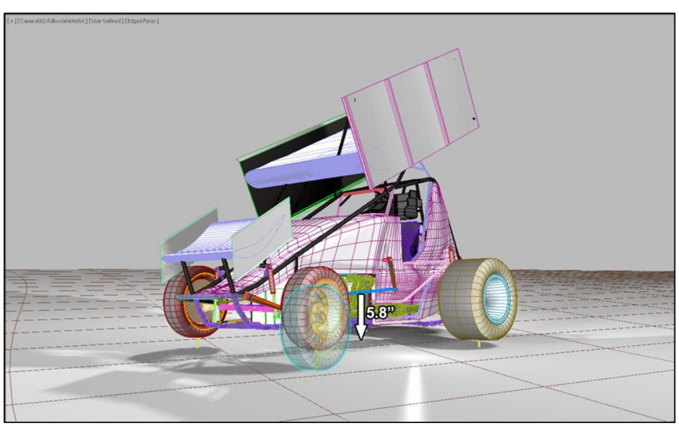

Figure 27
Opposition's Sprint Car floating above the surface due to poor calibration.

In the end, the ultimate evidence of a flawed and erroneous video analysis is that the resulting vehicle dynamics were not only inconsistent with the actual video, but they also violated real-world physics. The opposing expert's analysis of the Sprint Car speeds and accelerations shown in **Figure 30** and **Figure 31** violated real-world physics.

Conclusion

With advancements in matchmoving software programs, high-definition laser scanning, and other related technologies, the matchmoving technique has become very effective in forensic engineering investigations/accident reconstruction to accurately determine and analyze

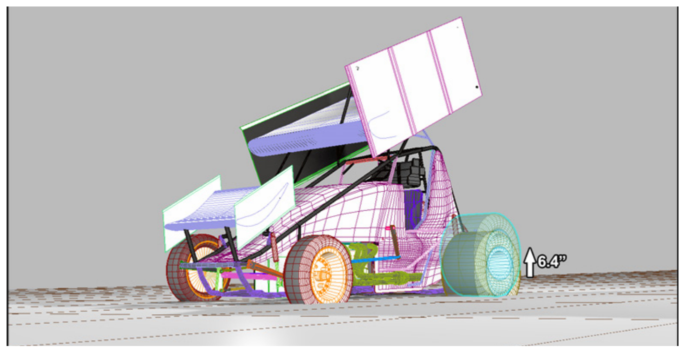

Figure 28
Opposition's Sprint Car traveling below the surface due to poor calibration.

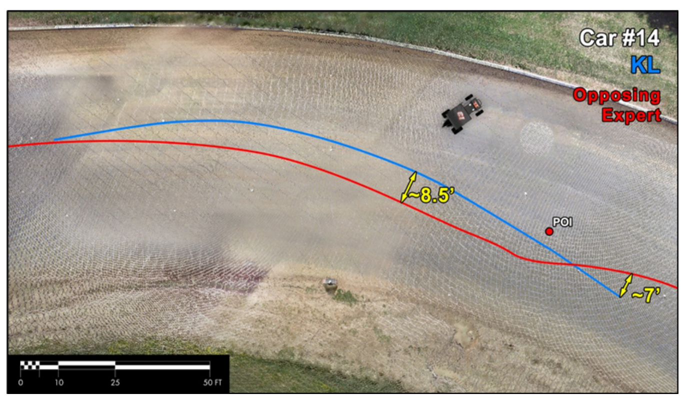

Figure 29
Opposition's inaccurate vehicle motion shown in red color.

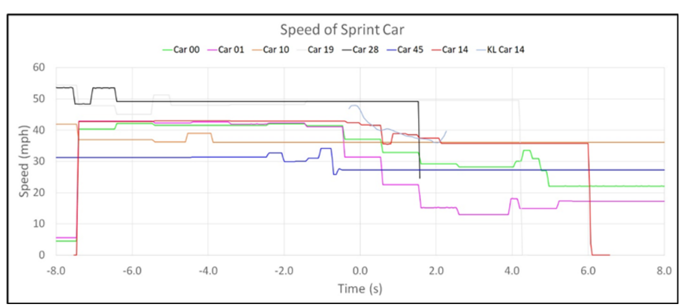

Figure 30
Opposing expert animated Sprint Car speeds.

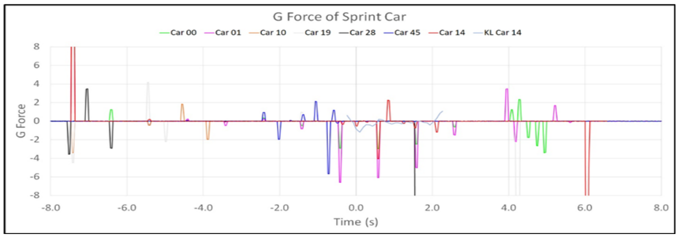

Figure 31
Opposing expert animated Sprint Car accelerations.

the orientation, translation, velocity, and acceleration of vehicles, pedestrians, or other objects depicted in video footage captured by moving cameras.

When an incident is depicted in a video, the match-moving method can yield much more precise, accurate, and reliable data than the traditional landmark or line-of-sight method. It is important to recognize that the matchmoving process has to be done correctly to yield accurate results. The simplest verification, whether or not the matchmoving process was done correctly, is to look through the virtual camera and evaluate the alignment between the 2D tracked features with the 3D (calibrated) markers or features. In a good calibration, the 3D markers should be aligned with the feature they represent in the image.

Most matchmoving software programs conveniently feature the ability to visually evaluate the error of each 3D markers position versus the 2D tracker position in each frame of the video and also report the matchmoving overall error. Finally, the matchmoving method described in this paper has been accepted and used by the authors in both state and federal court — and has passed Daubert challenges.

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