Developing a Photogrammetry Based System for Measuring As Assembled Suspension Geometry

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ABSTRACT

A measurement system based on photogrammetry was developed and used to measure the "as assembled" geometry of a double wishbone suspension. A standard methodology for photographing the suspension and special targets were developed to use with commercial photogrammetry software (Photomodeler Pro 5). Several types of targets were developed; these included targets to identify the center of rotation of the linkages and the orientation of the wheel mounting surface. After completion, the system was used with a 5.1 mega pixel Sony Cyber-Shot camera to measure the 3D geometry of a racecar suspension.

INTRODUCTION

This project was based at Colorado State University's Motor sports Engineering and Research Center (MERC). At the MERC, research is conducted to see how the setup of a vehicle's suspension affects its performance. Making small changes to the suspension affects the dynamics of the automobile. For maximum performance, the suspension must be set-up so that all the wheels are aligned. This set-up can be done in more than one way while the best setup may depend on the racetrack. For a simple example, a race engineer may wish to increase the camber of the tires to help the racecar handle the tight corners of one race track and decrease the camber to better handle a track with longer, wider turns. These small changes to a vehicle's suspension can have large effects on the handling of the automobile, as well as other parameters, such as ride height.

A racecar is usually set up and measured like a consumer automobile is aligned at a repair shop. Using special gauges, the angle of the tires are measured with respect to the horizontal, vertical, and longitudinal axis (camber, caster, and toe-in). In addition, each tire's position is measured relative to the body of the car in Cartesian **xyz** space (half-track, wheelbase, and ride height). There are accurate devices that are commercially available to measure all the aforementioned parameters; however, these types of measurements are inadequate to analyze the suspension. To predict the way a wheel orientation changes as the suspension travels through its range of motion, the pivot points of the suspension must be measured.

The double wish bone suspension was the focus of this project. This style of suspension is a type of four-bar mechanism consisting of an upper and lower A-arm, a wheel upright, and the body of the car (see Figure 1). In addition, the suspension contains a shock as well as the linkages to hold the shock and steer the car. For clarity, the shock and steering linkages (rocker, pushrod, and tie-rod) will be omitted from the work presented here.

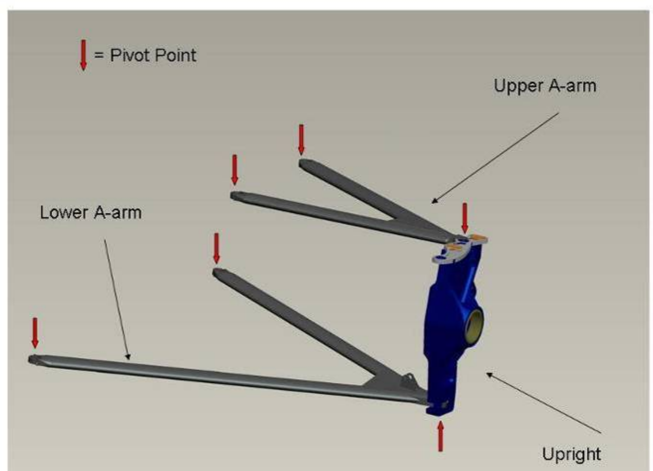

Figure 1 Double Wishbone Suspension (1/4 Shown)

At the MERC, special software is used to calculate the way a wheel's orientation changes as the suspension travels through its range of motion (this affects how the car will handle). In order to enter the racecar's geometry in to the specialized suspension software, a race engineer needs to know the **xyz** locations of the suspension's pivot points (see Figure 1). Despite having sophisticated CAD models of the suspension, manufacturing and assembly tolerances dictate that the suspension be measured after assembly. Measuring the "as assembled" geometry of a suspension has been the only proven method in obtaining accurate results at the MERC.

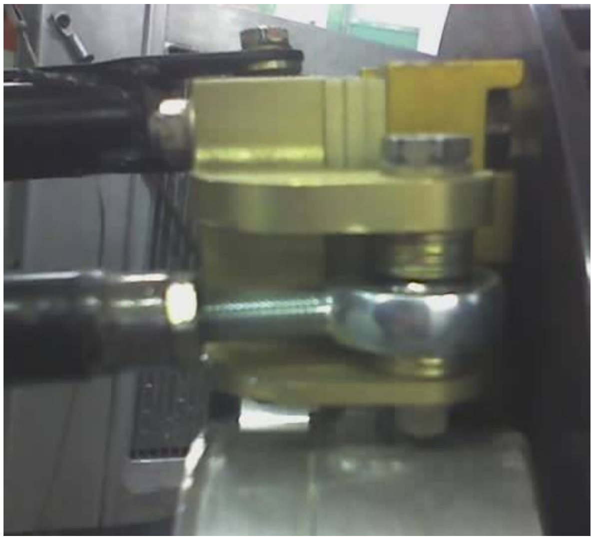

Figure 2 Spherical Rod-end

Typically, to obtain the data required for analysis a race engineer at the MERC measures the car by hand. One of the challenges in measuring the suspension by hand is that, typically, the pivot points to be measured are the center of a ball and socket joint known as a spherical rod-end (see Figure 2). Since the point of rotation is incased in the metal housing, it cannot be easily accessed or measured.

In addition to the concealed rod-ends, the process of measuring the 3-dimensional space of the car suspension is a complex procedure. First, a level piece of concrete must be found, which defines the **xy** reference plane. Then, using a battery of laser levels, plumb bobs, tape measures, strings, and pencil marks the centers of rotation are measured. The data is then entered into suspension software and a graph is produced showing how the wheel's orientation (typically camber and toe-in) change as the suspension travels through its range of motion (see Figure 15 and Figure 16). The data from the software is then checked against measurements from the actual suspension taken with toe and camber gauges. Typically, there is poor correspondence between the calculated and measured data. Therefore, the process must be repeated until a match is found.

MAIN SECTION

PHOTOGRAMMETRY BASED MEASUREMENT SYSTEM

To solve the problems at the MERC, our team developed a measurement system based on photogrammetry. Targets were developed to work in accordance with EOS Systems' Photomodeler software as well as to identify points on the racecar. In addition, a specific methodology was developed in order to reduce measurement time while ensuring accurate results (see Figure 3).

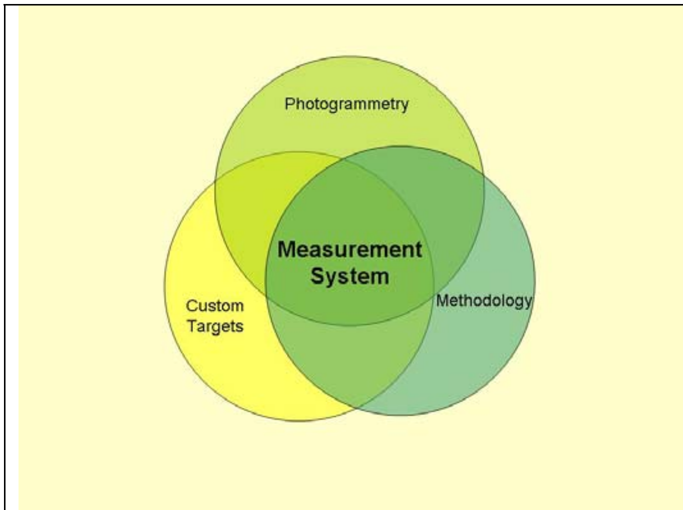

Figure 3 System Overview

Photogrammetry

Photogrammetry is a measurement technology that uses photographs to make measurements, ultimately constructing a 3-dimensional model. Through the method of triangulation, a "line of sight" between a camera's position and points on the object photographed are established. By establishing the "lines of sight" to common points in multiple photographs taken at different camera positions, each point's **xyz** position in space is measured.

To the user, this means that at least 2 photographs with 6 points in common must be taken with the same camera (and the same zoom setting) from 2 different positions (see Figure 4). Then, using the software, the 6 points must be identified and referenced to each other (referencing is simply telling the software which areas in the two photographs are the same points in real life). With this information, a 3-dimensional model of the points in space is produced, calculating both the **xyz** position of each point and the two camera positions. The user is then able to add additional photographs and points if the more recent photographs have some points in common with the original two photographs.

Photomodeler

Photomodeler Pro 5 was the photogrammetry software used in our system. Photomodeler was well suited to measure our suspension and is typically used to measure a variety of objects from large buildings to small models. In addition, Photomodeler Pro 5 was able to export the data in several formats which aided in

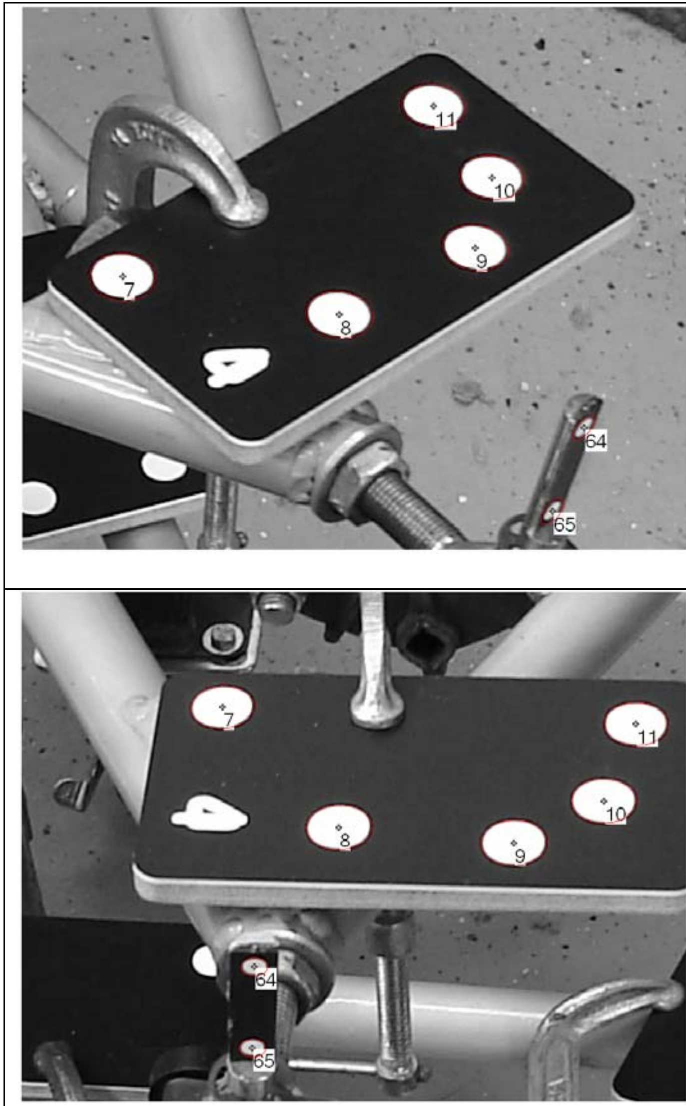

Figure 4 Two Photographs With Points 7,8,9,10,11,64, and 65 Referenced

further analysis. In order to take accurate measurements, the measurement system was based on a few key features of the software, including calibration, sub-pixel target marking, and scale.

Calibration

Photomodeler offers a calibration algorithm that measures the lens of the camera. By photographing the calibration grid in the same environment that the measurement photographs are taken, effects of temperature and humidity on the camera are compensated. Taking between 6 and 12 photos of the calibration grid, Photomodeler is able to automatically identify the dots in the grid and calculate the parameters of the camera (see Figure 5).

Sub-Pixel Target Marking

Photomodeler has several features to recognize points in the photograph. A point can be marked in a photograph by simply clicking on the photograph with the mouse; however, for the best accuracy, a high contrast target is required. By using targets with high contrast circular dots, as in the calibration grid, Photomodeler's sub-pixel marking tool can be used to identify a point (see Figure 6). To use the

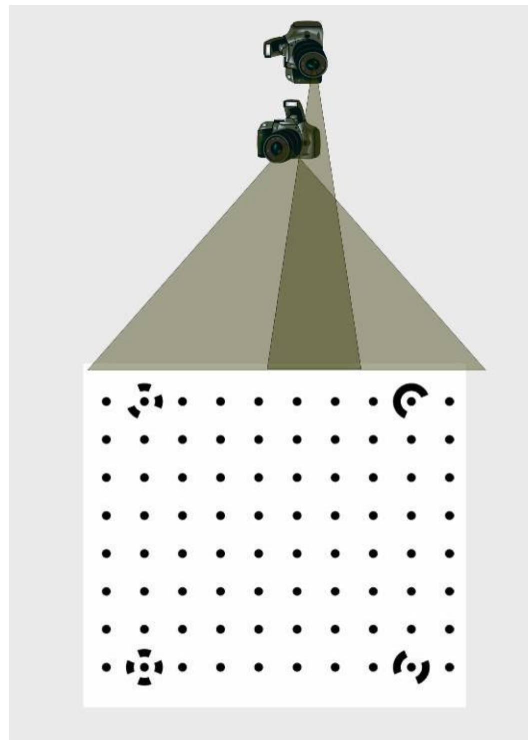

Figure 5 Calibration

sub-pixel marking tool, a box is drawn around the high contrast dot while the software identifies the high contrast region and marks the center. The center of the dot is then identified as a point and can be referenced in other photographs containing the same target. By using this tool, the point on the photograph is identified to a sub-pixel resolution, resulting in a better accuracy than manually selecting the points.

Scale

Once a 3-dimensional model has been constructed, it must be scaled to the appropriate size. In the current project, once all the points were identified and referenced, the 3-dimensional model was built and all points were shown relative to one another. However, the nominal size of the model it is still unknown. The racecar could be the size of a desktop model or a full-size automobile. The scale is set by simply selecting two points and entering the distance between them. For accuracy, the points chosen and the distance entered

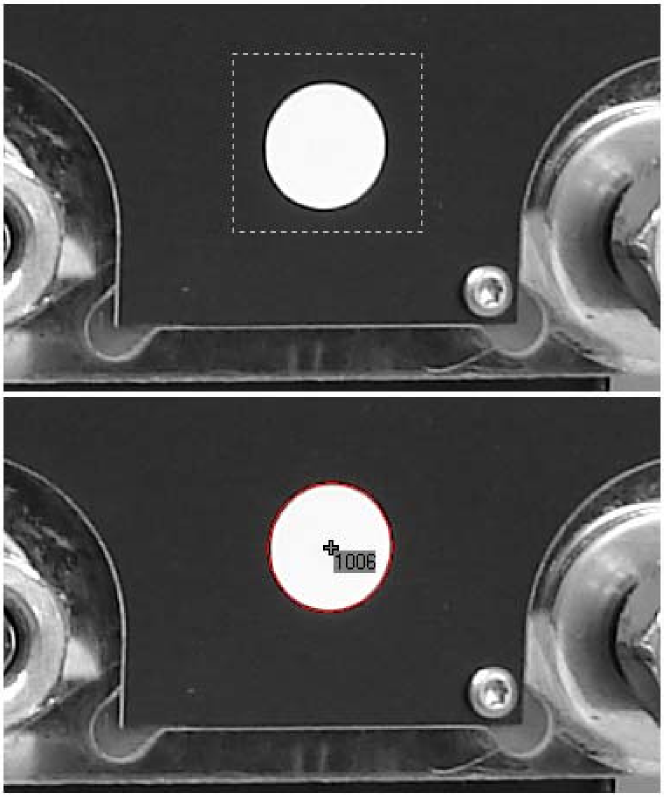

Figure 6 Sub-pixel marking – Selected Region (top) and Marked Boundary and Center Point (bottom)

should be near the size of the object photographed. For example, when choosing the scale for the racecar project we used a known distance of 32 inches and the largest distance measured was approximately 60 inches. However, choosing a known distance of 2 inches to scale our project of 60 inches may have resulted in error.

Accuracy

Photomodeler's accuracy is dependent on several parameters. Table 1 shows a table from Photomodeler's website [1], the parameters and their effects on accuracy are displayed. To estimate a nominal accuracy, the largest distance in the project is simply multiplied by the accuracy ratio in Table 1 [1]. For example, using accuracy ratio from the middle row Table 1[1] while measuring a 60 inch racecar, 60 multiplied by 1/5000 yields 0.012 inch accuracy.

METHODOLOGY

A photo shoot guide was written, aiding to the future use of our measurement system at the MERC. The photo shoot guide can be found in its entirety in the appendix. The following is a brief overview of the photo shoot guide, which was the method used to measure the racecar suspension.

Table 1 Parameters Affecting Accuracy [1]

	Camera Resolution	Camera Calibration Method	Angles between Photos	Photo Orientation Quality	Photo Redundancy	Targets
Lowest Accuracy 1 part in 100	Video 640x480	no calibration	most less than 15 degrees	few points per photo, low coverage	points mostly on only 2 photos	no targets, all user marked
		Inverse Camera				
Average Accuracy 1 part in 5,000	5-6 MegaPixel	Camera Calibrator	most between 20 and 90 degrees	15+ points/photo, 25 to 60% coverage	all points on 3+ photos	some naturally lit targets for key points
						many good quality naturally lit
Highest Accuracy 1 part in 30,000+	11 MegaPixel	Field Calibration*	most between 60 and 90 degrees	35+ points/photo, 50 to 80% coverage	most points on 8 or more photos	retro-reflective

Camera Settings

A single zoom setting was used for all the photographs taken. The camera was set to take black and white photographs, per Photomodeler's recommendation [1]. In addition, a tripod was used for all photographs and the self timer was set for each picture so that the camera was not shaken as a result of the shutter release button being depressed. In some cases when the exposure appeared too light or dark, a method called bracketing was used which captures multiple photos at different exposures.

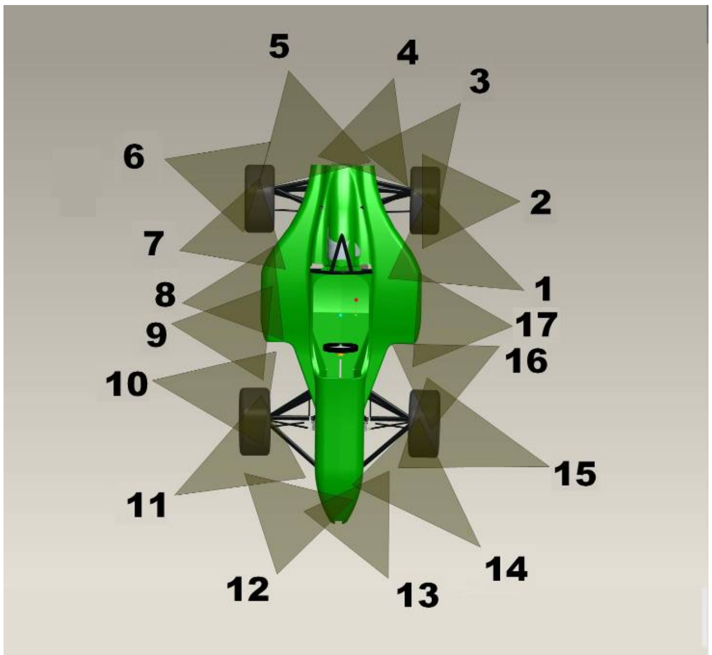

Figure 7 Approximate Camera Positions

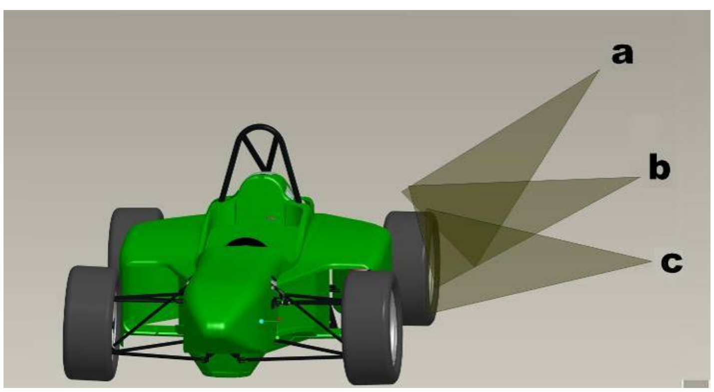

Figure 8 Tripod positions

Calibration

Eight pictures were taken of the calibration grid, two per side, one portrait and one landscape (or rolled [1]) as shown in Figure 5. Later these pictures are used to build a calibration project. The information from the calibration project is then used in conjunction with the measurement photographs to create a 3D model.

Measurement Photographs

To ensure accurate measurements, photographs were taken to meet the requirements for photo orientation quality, angles between photographs, and photo redundancy as stated in Table 1 [1]. First, we tried keeping track of the points and photos to ensure all the ramifications were met. However, we found that taking the photographs in the following method produced good results and was more time effective.

A tripod was used for all photographs taken. The camera was mounted to the tripod and the tripod was set to its highest position (*a* in Figure 8). Then, photographs were taken at several positions around the racecar. Figure 7 shows the approximate positions of the 17 pictures taken around the racecar. After the first revolution was made around the car, the tripod was lowered to position *b* and another set of 17 photos were taken. A final set of 17 photos was then taken at position *c*.

Though the positions of the camera need not be known exactly, taking photographs in an organized manor, as shown in Figure 7, can produce a good set of photographs to use in Photomodeler. In addition, taking the photographs in the sequence shown aided in sorting the photographs later as the model was built. For example, when measuring the right front quarter of the suspension 10th, 11th, 12th photographs taken at positions *a*, *b*, and *c* were found and contained the desired points the project without having to browse though all 51 photographs in the project.

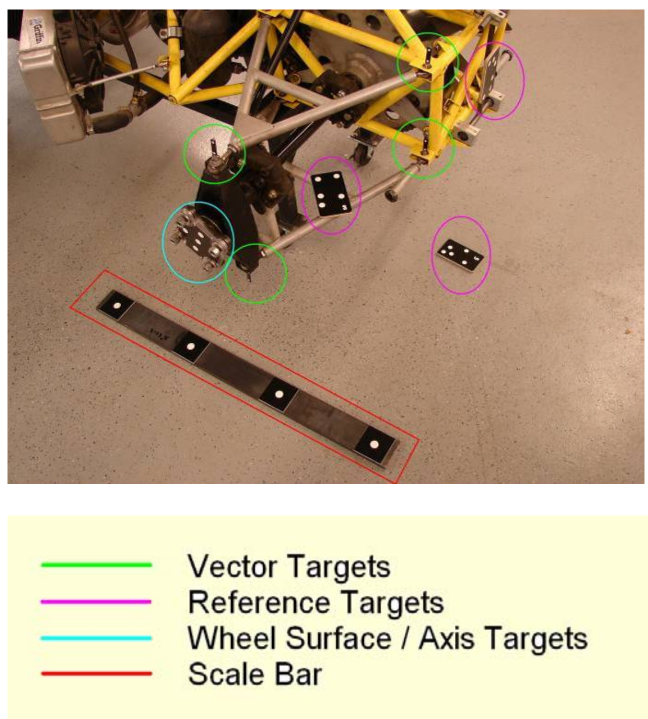

Figure 9 Target Overview

TARGETS

Several high contrast targets were developed to measure the racecar. Figure 9 shows all types of targets located on the suspension as they were during the measurement photo shoot.

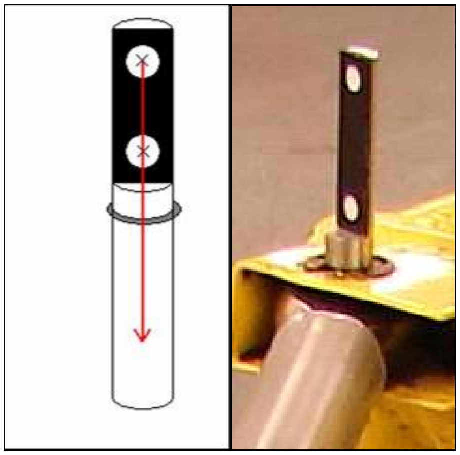

Figure 10 Vector Targets

Vector Rod End Target

To find the points of rotation of the suspension encased by the rod ends a "vector" target was designed to replace the bolt holding the spherical rod end in place (see Figure 10 - right). By using the vector established by the target to "point" (see Figure 10 - left) to the center of the rod-end, we can identify the center of rotation with a minimal number of points. The vector targets were fabricated from 3/8 "diameter bar stock and a piece of vinyl engraving stock which is a white piece of plastic with a thin (0.003") black layer on one side. The target was machined using a conventional milling machine. Then, without removing the bar stock, the plastic was glued into place. With the plastic secured a 3/16 end mill was used to cut through the thin layer of black plastic creating a high contrast dot.

Figure 11 Scale Bar

Scale Bar

In order to accurately size the 3D model produced by Photomodeler, the distance between two of the targets must be known precisely. A "scale bar" was designed to aid in scaling the 3-dimensional model (see Figure 11). Using a piece of 4" by 3/8" hot rolled steel 36" long as the frame, four pieces of vinyl engraving stock were glued at evenly spaced distances. A CNC router was then used to mill the high contrast white circles into the plastic. By using the CNC router, the distance between the two end dots was known to be exactly 32".

Wheel Surface Targets

To measure the surface where the wheel mounts to the upright, a target was made. A target was developed to mount onto the suspension where the wheel is typically attached (see Figure 12). A piece of polycarbonate plastic, which carried a piece of engraving stock, was used as the frame for this target.

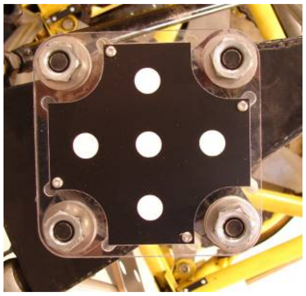

Figure 12 Wheel Mounting Surface Target

Figure 13 Reference Target

Reference Targets

Since the vector, scale, and wheel surface targets were not visible in all of the pictures taken of the car (for example, positions 9, 13, and 17 in Figure 7), it was necessary to have additional targets placed around the automobile. Reference targets (see Figure 13) were made. Medium density fiberboard was used as a backing for the vinyl engraving stock. Using a CNC router, the high contrast dots were milled into the engraving stock in a random asymmetrical pattern so that the dots were not easily mistaken when referenced between photographs.

DISCUSSION

Using the methods discussed here, Photomodeler was used to measure the racecar suspension. Figure 14 shows the 3D model of the results as well as the camera positions. The data from the measurement system was exported and used to analyze the racecar suspension. Unfortunately, there was not a known set of measurements that could be used to verify the results. Instead, to verify that the system met the need of the MERC, a "motion profile" was produced based on the measurements (from photogrammetry) showing how the

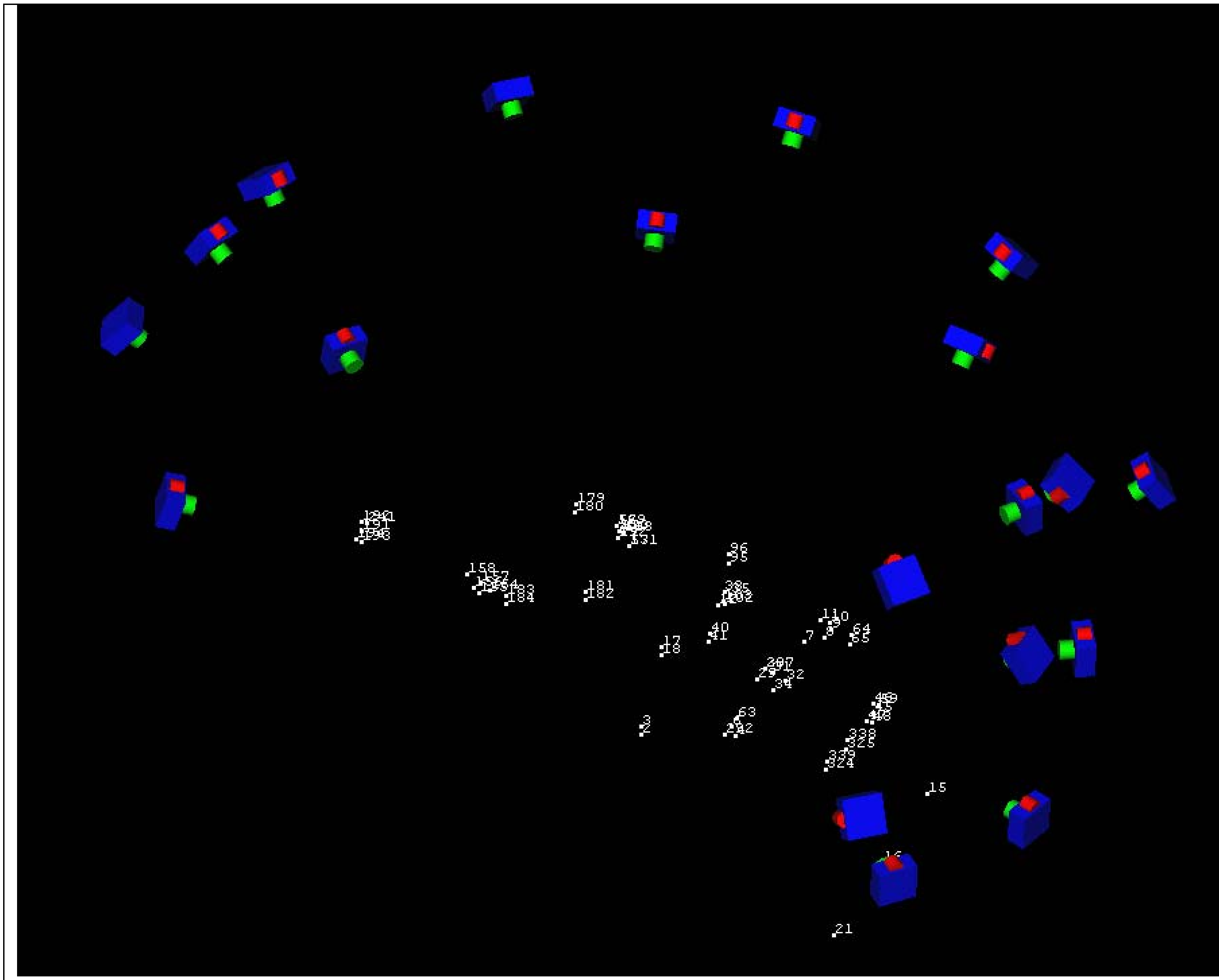

Figure 14 Results

camber and toe-in of the wheel changed as the suspension traveled through its range of motion.

The suspension was also measured using camber and toe gauges at ¼" increments of the travel. The data from both the measurement system and the camber and toe gauges are shown in Figure 15 and Figure 16.

RESULTS

The data in Figure 15 and Figure 16 corresponds better than the previous methods used to measure a suspension at the MERC and requires no iterations. A major source of error associated with this method of verification is the gauges used to measure camber and toe-in. The camber gauge used to create the "Hand Measurement" data in Figure 15 was accurate to 0.1 degrees. Studying the graph shows that most of the discrepancies between the two graphs results from the camber gauge's accuracy. In addition, it is difficult to ensure that the car is perfectly level when taking the hand measurements, so the graph may be shifted slightly up or down.

The toe-in graph is subject to error as well. Toe-in is measured by attaching a string which runs parallel to the wheel, and then to the car. A gauge that locates on the tire and holds two scales perpendicular to the tire's face. The projection of the string is read onto the scales and the toe-in is determined. Reading the scales on the gauge is problematic since the wheel is traveling up and down; however, independent of this problem, the accuracy of the scales are limited to the graduations, which were 1/32 (0.031) of and inch.

CONCLUSION

The photogrammetry based measurement system has been accepted as an improvement to the current methods and will be used in the future work at the MERC. An overall accuracy of the system was not determined due to the lack of a known 3-dimensional reference to verify the measurements. The alternative verification using the motion profile of the wheel was found to be satisfactory.

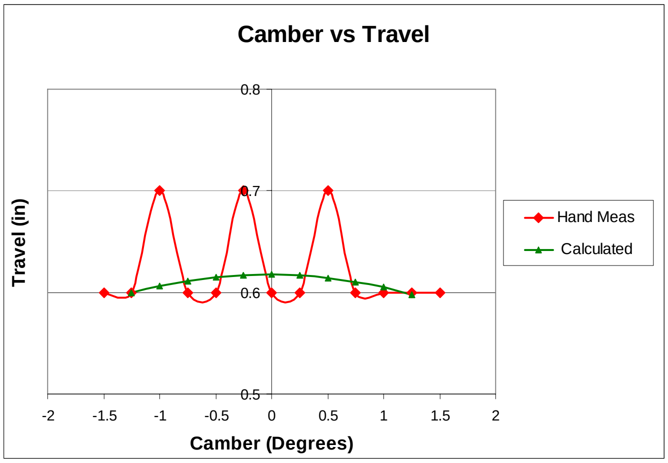

Figure 15 Camber vs. Travel

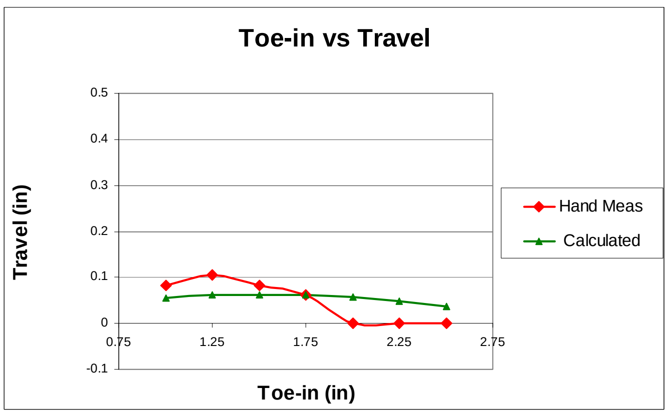

Figure 16 Toe-in vs. Travel

APPENDIX

Photo Shoot Guide

Camera

Almost any digital camera can be used with photo modeler. The accuracy of the project is related to the amount of pixels on the camera, so the more pixels the better. When possible the following settings should be used:

- The zoom lens cannot be used, to avoid confusion use the default setting when the camera is powered on (in other words turn on the camera and do not touch the zoom, if the zoom is bumped during operation simply turn the camera off and then back on to reset the zoom and continue photographing).
- Black and White mode is recommended for higher accuracy.
- The timer can be used to avoid "bumping" the camera during the exposure.
- The flash should be turned off to avoid shadows.
- The "EV" shift should be used on photo's that appear to dark or light.

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Michael Gerstner – Real Time Systems
Nick Ellis - Real Time Systems
Jared Olson – Structures

Dr. Patrick Fitzhorn - Advisor

REFERENCES

1. Photomodeler: www.photomodeler.com

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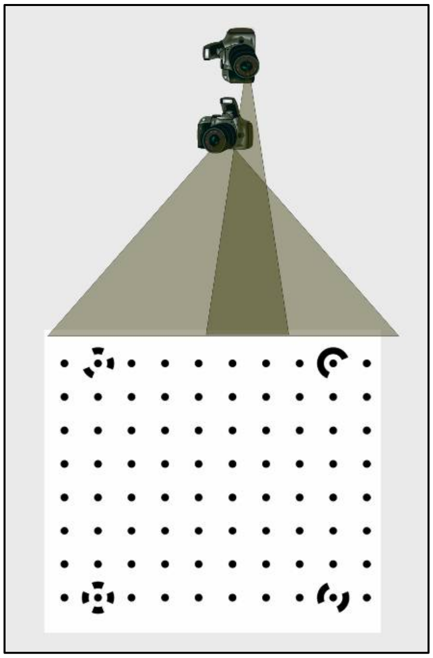
- A tripod should be used. [1]

[1] Since the flash must be turned off the exposure time is about 1/8 to 1 second, which is too long to hold the camera still by hand.

Calibration

For the most accurate results, the camera must be field calibrated. To field calibrate, simply photograph a special grid (see Figure 19). The grid can be found in the Photomodeler Pro 5 folder (typically under program file in the c drive) and should be printed close to the size of the project.



Photomodeler has a special calibration project built-in. A calibration project requires that between 6 and 10 photos of the grid be taken. For best results, a minimum of two photos should be taken per side (see Figure 19), one in a landscape position and the other in a portrait position (see Figure 17 and Figure 18).

Figure 17 Landscape position

Figure 18 Portrait Position

Figure 19 Calibration Grid Positions

GOOD vs. BAD

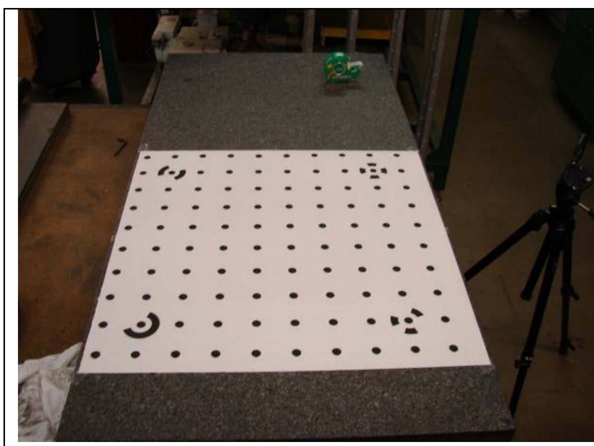


Figure 20 Bad Exposure

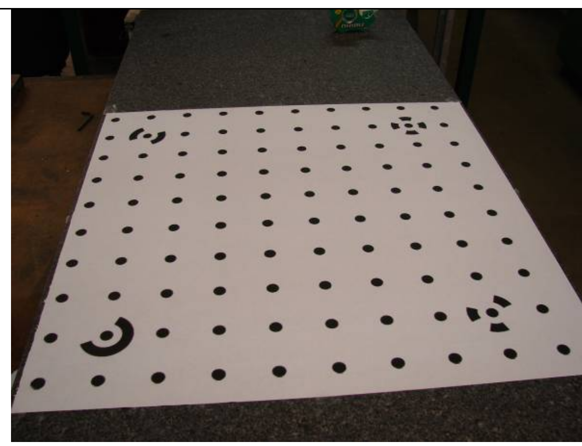


Figure 21 Good Exposure

For the best results in both calibration and measurement photographs, take a step closer to the subject. For example, the good photograph in Figure 21 "fills" more of the picture with the calibration grid than the bad photograph in Figure 20.

Targets

In addition to any specialty targets used to identify the points of interest, reference targets must be used to accurately identify points on photos where other targets are not visible. Later, this provides a way to relate photos with the points to be measured at each wheel to one and other. For example, Figure 22, Figure 23, and Figure 24 are photos used to measure the rod ends of a suspension and were taken from positions 2a, 5a, and 7a, respectively (see Figure 25 and Figure 26 for positions). Without the reference target in Figure 23, relating the two pictures (Figure 22 and Figure 24) with the rod end targets visible in Photomodeler would not be possible.

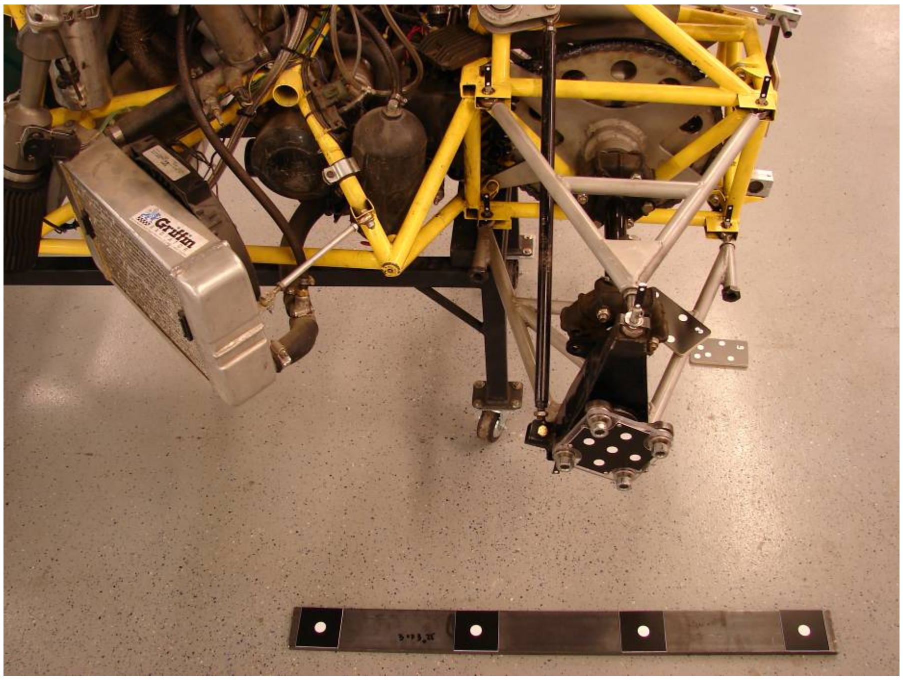


Figure 22 Photo From Position 2a

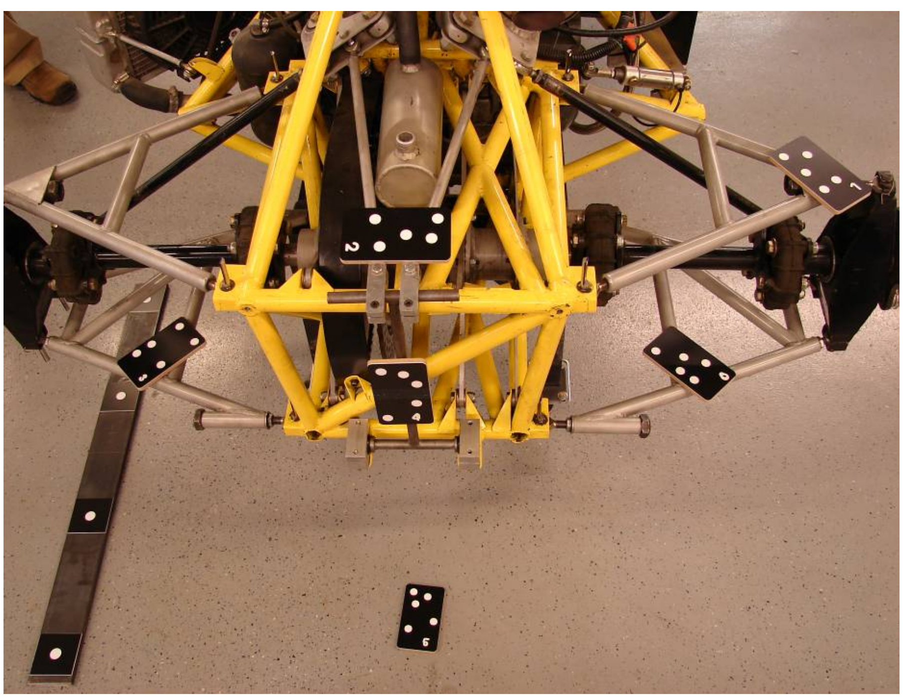


Figure 23 Photo From Position 5a

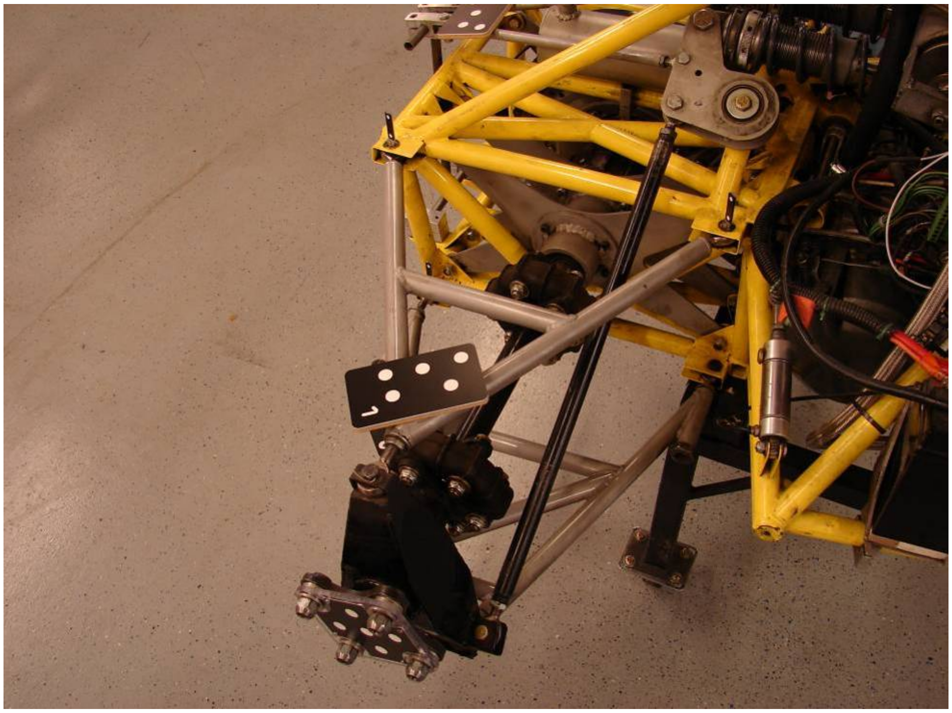


Figure 24 Photo From Position 7a

Photographs

Some things to consider when taking photos for measurement:

- A photo must have at least 6 points in common with other photos to be added to a Photomodeler project.
- For best accuracy, the photographs should have 25% to 60% overlap.
- For best accuracy, the photographs should be 20 to 90 degrees apart.
- For best accuracy, each point referenced must be in three or more photos.
- Both landscape and portrait style picture should be used.

To satisfy the accuracy criteria, the following strategy was developed. With the camera mounted on a tripod and the tripod in its highest position, photograph the car in the approximate positions shown in Figure 25. After each picture is taken, rotate the camera to the opposite position (i.e. landscape or portrait).

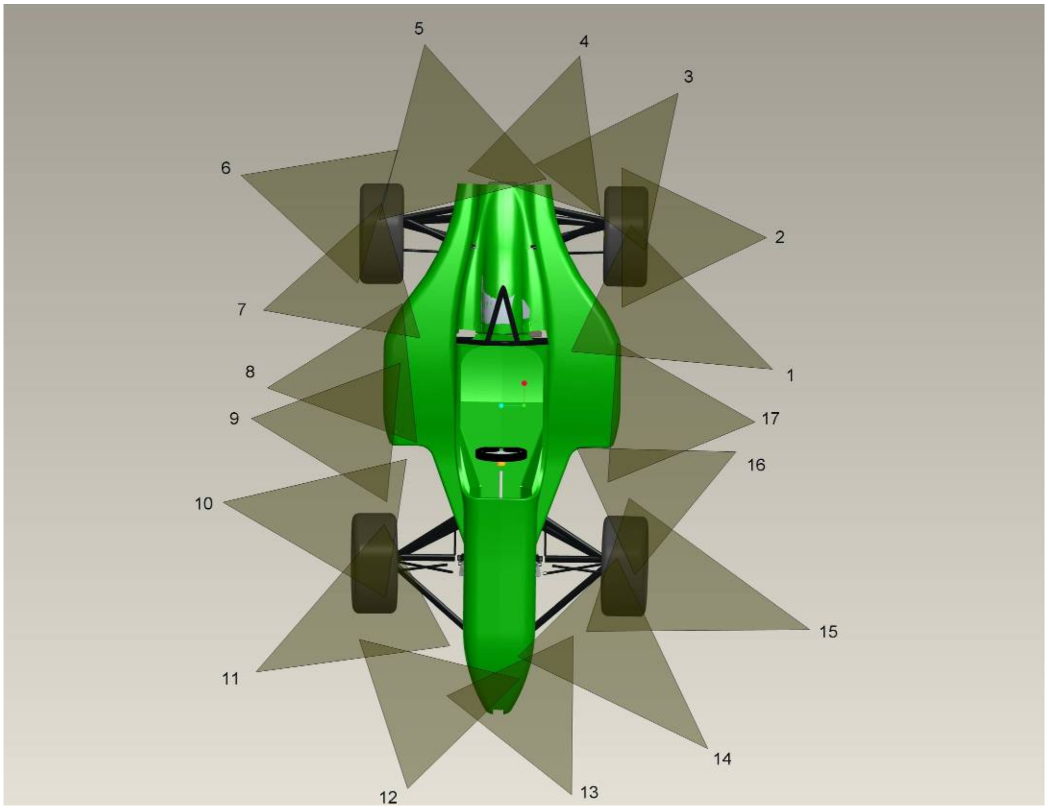


Figure 25 Suggested Camera Positions (Top)

After a picture has been taken at each position, move the tripod to a medium height and photograph each position again. Repeat once more with the tripod in its lowest position (see Figure 26). Using this method, a total of 51 photos can be used for measurement.

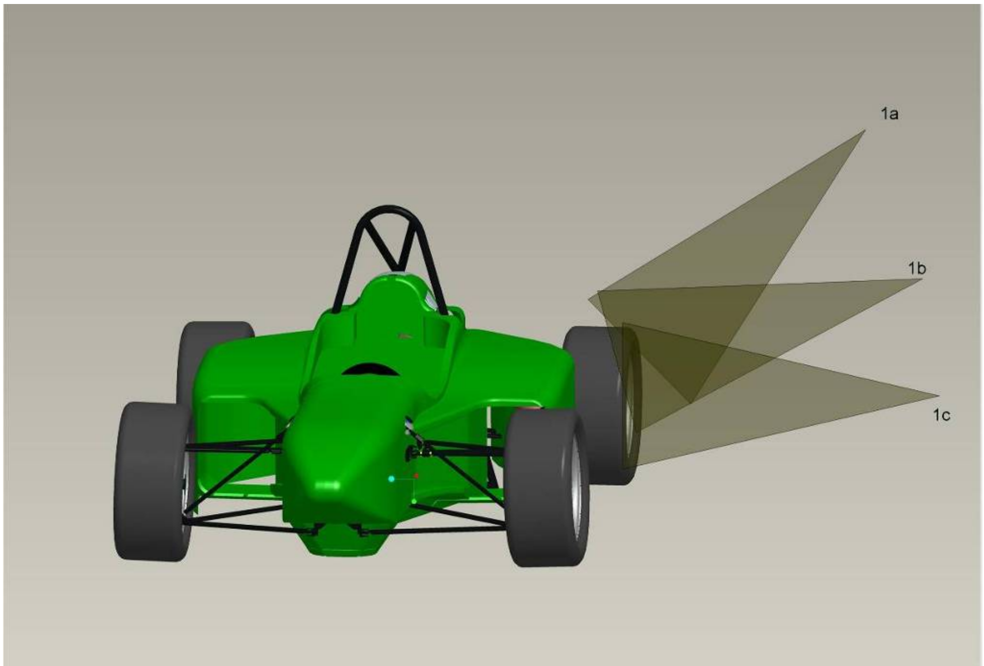


Figure 26 Suggested Camera Positions (Side)