1.1 Project goals

The primary goals of the Phase I effort were

- Determine if a geometrically accurate composite image (mosaic) of the undercarriage of a vehicle could be generated from multiple cameras placed under the vehicle. [In the original proposal the images were captured by parking a vehicle over a two-dimensional array of cameras. In the modification to the original proposal the images were captured by driving the vehicle over a linear array of video cameras.]
- Provide tools to assist an operator in the detection of anomalies.
- Store and retrieve images in a database.
- Compare stored and current views.

In addition the system must satisfy certain operational requirements including

- Robustness - contain no moving parts, operate under realistic environmental conditions, and have a stable software control system.
- Portable - it must be modular and fit in a small truck, and have a low profile so that can easily drive over it.
- Simple to use - the operator must be able to use it without any special training in image processing, engineering or computer programming.
- Affordable - the system components must be made from commercial off the shelf products.

1.2 The Mosaic Approach

An introduction is needed stating why a mosaic approach was selected in the first place.

A mosaic image of an object is a composite image built from a collection of smaller images, where none of the small, input images captures a complete view of the object. In general, creating a geometrically accurate mosaic image requires knowledge of the position of the camera at the time of exposure relative to the object, and the shape of the object. For the Under Vehicle Inspection System scenario we are able to determine the position of the cameras relative to the undercarriage, however, the structure of the undercarriage is not known in advance. As a result, the cameras must be configured in such as way as to minimize errors caused by viewing an object with an unknown shape and/or determine shape information about the object. In practice it is not feasible to achieve an optimal camera configuration or to determine complete shape information about the object. Thus, our efforts have been directed towards designing optical software systems that will produce the best possible result. The relationship between the geometric accuracy of a mosaic, and the camera configuration and the three-dimensional shape of an object are discussed in detail in Appendix

A mosaic example: The individual images on the left are fit together to form the composite view (mosaic) on the right.

1.3 Laboratory Prototype

To determine the feasibility of the system designs, a laboratory prototype (shown in Figure 1) was constructed. The system gave us the ability to capture image sequences of a mockup vehicle undercarriage for a wide variety of conditions. The system simulated an upside down configuration of an operational system. The cameras looked down on a vehicle undercarriage mockup, which rested on a 4 by 8 foot sheet of plywood. The mockup was made from a combination of scrap auto parts (a gas tank, muffler, pipes, etc.) and body panels carved from Styrofoam. A metal pipe frame supported the camera rig, which was designed to hold four cameras in any geometric configuration. A pair of crossbars, which rested on rollers, connected the camera rig to the support structure. This allowed us to easily reposition the camera support rig over any part of the undercarriage mockup. The system was designed so that it could be rapidly reconfigured, which gave us the ability to test important engineering parameters including:

- The motion of the vehicle. By moving the camera rig and varying the distance between exposures we were able to simulate the motion of the vehicle and/or the configuration of the cameras relative to the vehicle.
- The camera configuration. We were able to arrange the cameras in a two-dimensional and a one-dimensional configuration, change the spacing between cameras, change the focal length of the camera lenses, and adjust the distance from the cameras to the undercarriage
- Lighting conditions. Proper lighting is essential for the proper functioning of the system. We are able to try difference relationships between the position of the cameras and the lights. For example, placing small, bright light emitting diodes between the cameras.

1.4 Bed-of-cameras design

The original system concept (Figure 2) was based on a two-dimensional *bed-of-cameras* concept in which the vehicle parked on top of a device comprised of a large array of cameras spaced approximately eight inches apart. The device was designed to capture an instantaneous view of the vehicle's undercarriage by simultaneously triggering the cameras and assembling the images into a single high-resolution mosaic image. Because the vehicle is stationary at the time of exposure, geometric distortions introduce by a moving vehicle is not a factor.

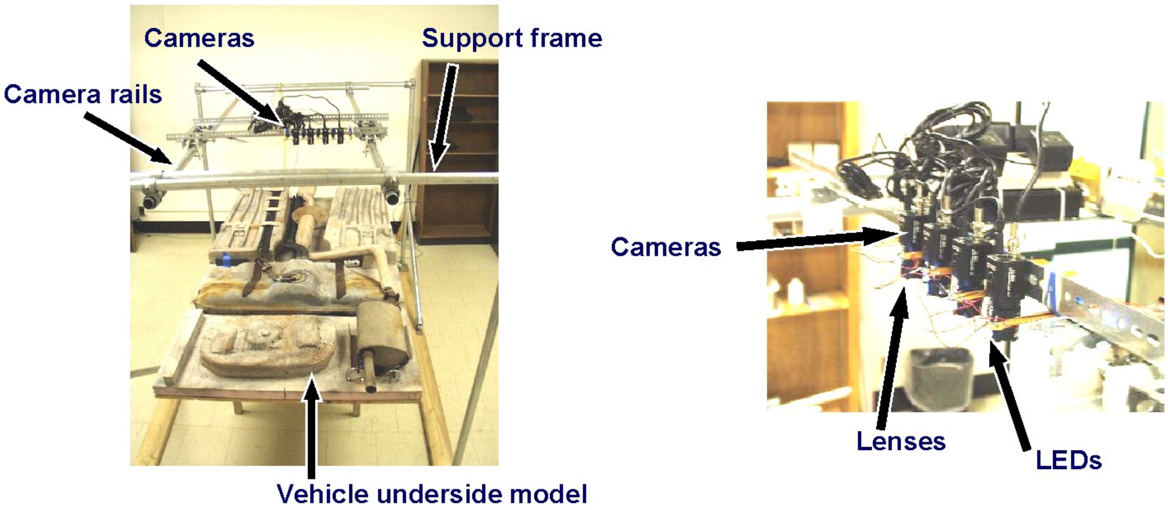

Figure 1. The laboratory prototype (left) and a close-up of the camera rig (right) configured to test linear camera array design.

Figure 3 shows a test of the bed-of-cameras concept. The laboratory prototype was used to acquire a 10 by 6 array of images of a mockup consisting of a collection of auto parts. The camera rig was configured to hold the four cameras in a square pattern with 8-inches on a side. The rig was then systematically moved over the mockup at 16-inch intervals along the length and width of the mockup. Each time the rig was moved a 2×2 set of images was taken. We then attempted to mosaic the images to form a composite mosaic image of the undercarriage.

Unfortunately, automatic mosaic generation was not successful. Analysis of the automatic mosaic failure showed that the cameras were too close to the undercarriage and spaced too far apart. A detailed theoretical analysis of the of the conditions required for automatic mosaic generation showed that the camera separation (S) should not exceed 6-inches and that the minimum distance from the undercarriage to the cameras (D) should be at least 18-inches. Please see Appendix A form more information on the viewing geometry considerations.

In summary, the bed-of-cameras concept had several flaws, which made the design impractical for under vehicle inspection:

- **Physical size**. The platform must be big enough to hold the nominal vehicle a Chevrolet Suburban. This would have required a platform approximately 10 feet wide and 16 feet long.

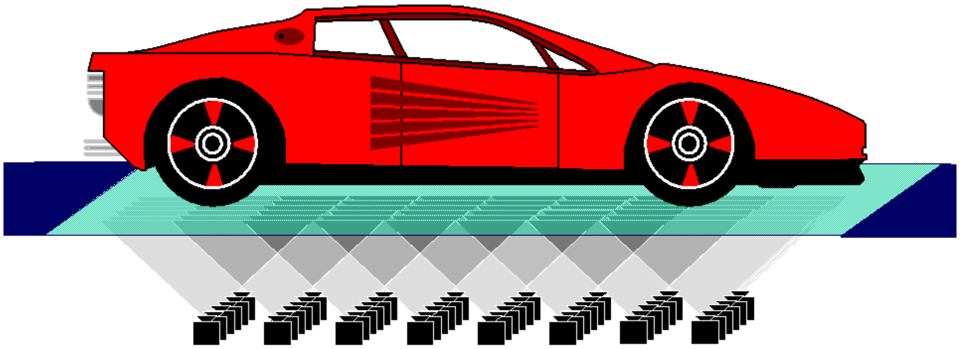

Figure 2. Conceptual diagram of the two-dimensional array of cameras concept. The vehicle parks on top of the bed of cameras and the system captures an instantaneous view of the undercarriage of the vehicle. In this figure, the objects are not to scale and there are many more rows of cameras and cameras per rows.

- **Optical complexity**. Using an 8-inch separation between cameras, a 10′×16′ platform would require about 360 cameras. Maintaining, cleaning, aligning and calibrating this number of cameras and lenses would be a very labor intensive and technically challenging task.

- **Image geometry.** Careful analysis of the be-of-cameras design showed that the viewing geometry was inadequate to produce consistent, geometrically accurate mosaic images of the undercarriage. Analysis showed that the camera spacing needs to be decreased and the cameras to undercarriage distance need to be increased. Decreasing the camera spacing to 6-inches with increase the number of cameras from 360 to 640 cameras, increasing the cameras to undercarriage distance will substantially increase the thickness of system.

These flaws led us to consider a new system design that would allow us to decrease the camera spacing and increase the camera to undercarriage distance. [I did not prove or give evidence about why the S needs to be decreased and/or D increased. Please ask Gay to fill in if needed]

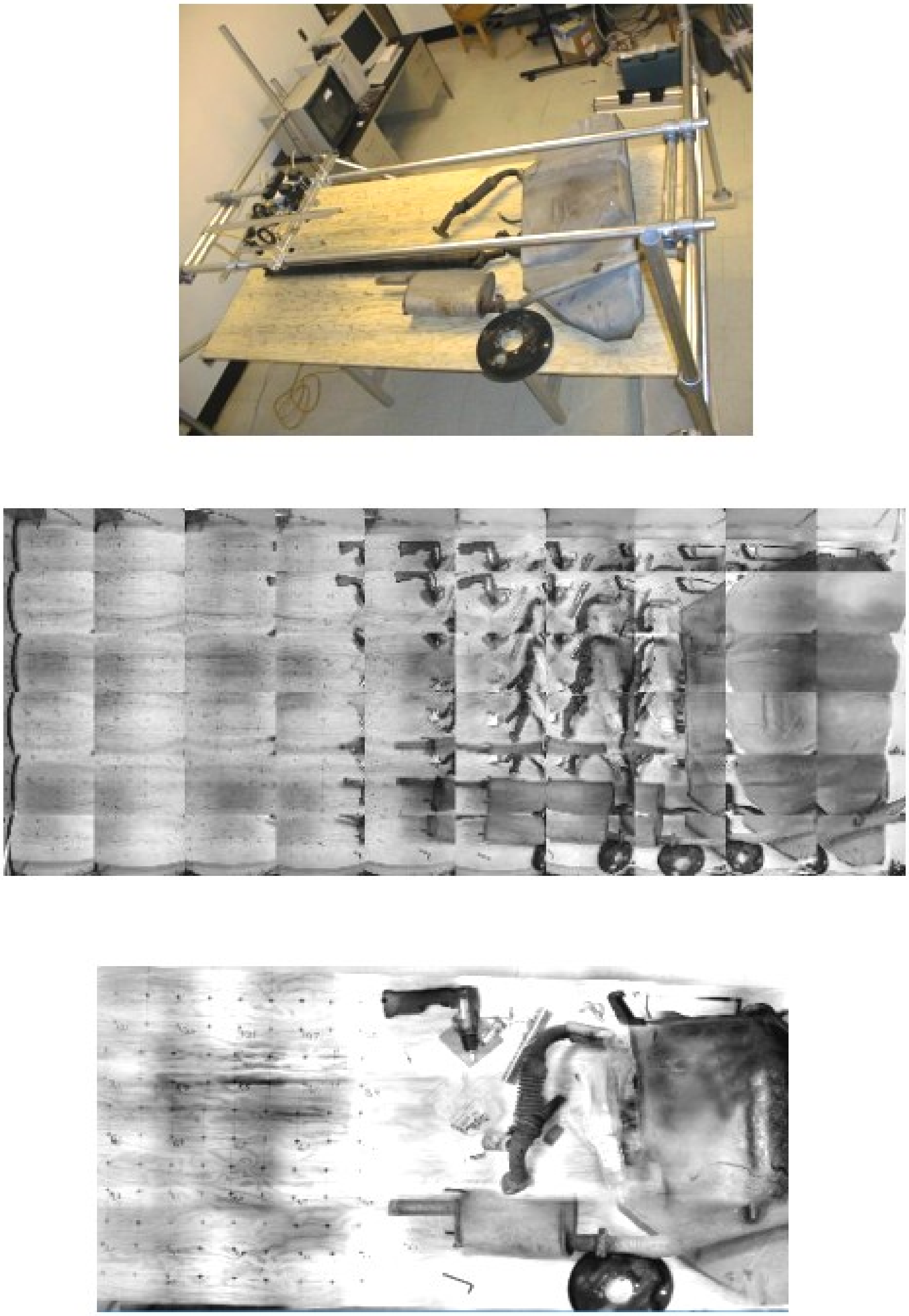

Figure 3. A digital photo of the bed-of-cameras test setup showing the camera rig configured in a 2 by 2 array with an 8-inch spacing between cameras (top). The 2D array of images captured by moving the camera rig over the mockup (middle), and a hand generated mosaic of the mockup (bottom).

2. Linear Camera Array - The *Virtual Bed-of-Cameras* Concept

2.1 Overview. By changing our approach, we were able to significantly simplify the system design and improve the viewing geometry. Instead of building a mosaic image from an instantaneously acquired two-dimensional array of images of a stationary vehicle, we will build a mosaic from a collection of one-dimensional image columns of a moving vehicle. Because a line of cameras is used instead of a bed-of-cameras, we were able to space the cameras closer together and increase the distance between the undercarriage and the cameras.

A conceptual diagram (not to scale) of the linear array of cameras is shown in Figure 4. To the driver of the vehicle the system looks like a slit in the ground. Under the slit is a mirror that reflects the view of the undercarriage into an array of cameras. As the vehicle drives over the slit a series of images are taken, one column at a time. As depicted in Figure 5, the sequence of image columns is equivalent to a 2D bed-of-cameras. A *virtual bed-of-cameras* is synthesized by estimating the position of each camera relative to a fixed point on the vehicle at the time of exposure. Because the images are acquired one column at a time, we were able decrease the spacing between the cameras and increase the distance from the undercarriage to the cameras.

The mosaic generation program first assembles each column of images into a column mosaic. Next it calculates the movement of the vehicle from the previous acquisition and adds the new column mosaic to the full mosaic in its proper geometric position. The process continues building up a full mosaic until the vehicle finishes driving over the camera array.

The system builds five full mosaics. Each mosaic is a composite view of the vehicle's undercarriage from a different viewpoint, which is equivalent to viewing the undercarriage from the left side, the right side, the front, the rear, and straight up. These multiple perspective views enable the operator to see around occluding objects. In the remainder of this section the operation of the systems is described in detail.

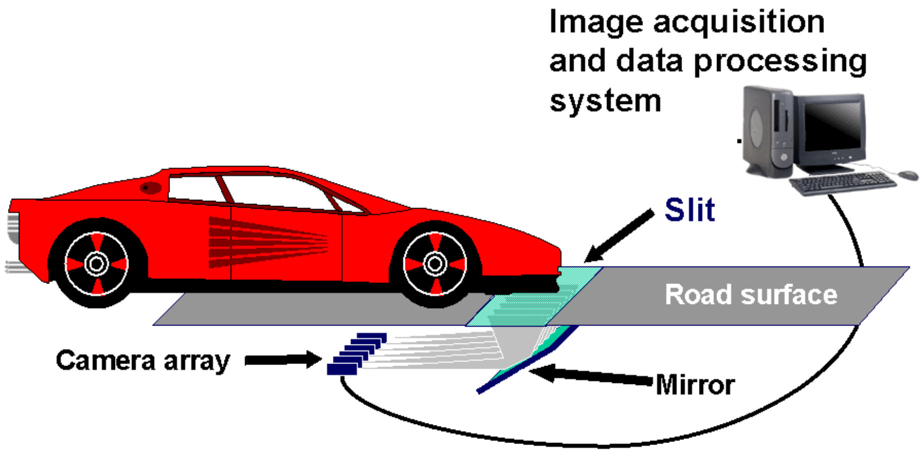

Figure 4. A conceptual diagram (not to scale) of the UVIS linear array of cameras design. As the vehicle drives over a slit in the road a mirror reflects the image of the undercarriage into an array of cameras.

2.2 Calibration considerations. The new design is significantly less complex. However, special care must be taken model and remove geometric distortions introduced by the camera optics and small alignment variations between cameras. Geometric distortion is removed from the images by first modeling the distortion mechanism and computing a image warping formula that compensates for the geometric distortions, and then warping each raw image to remove the distortions. Modeling is done once during manufacturing or updated occasionally in the field, while warping is done in real-time to each raw image immediately after it is captured. The following is a description of the calibration procedures required to model the sources of geometric distortion:

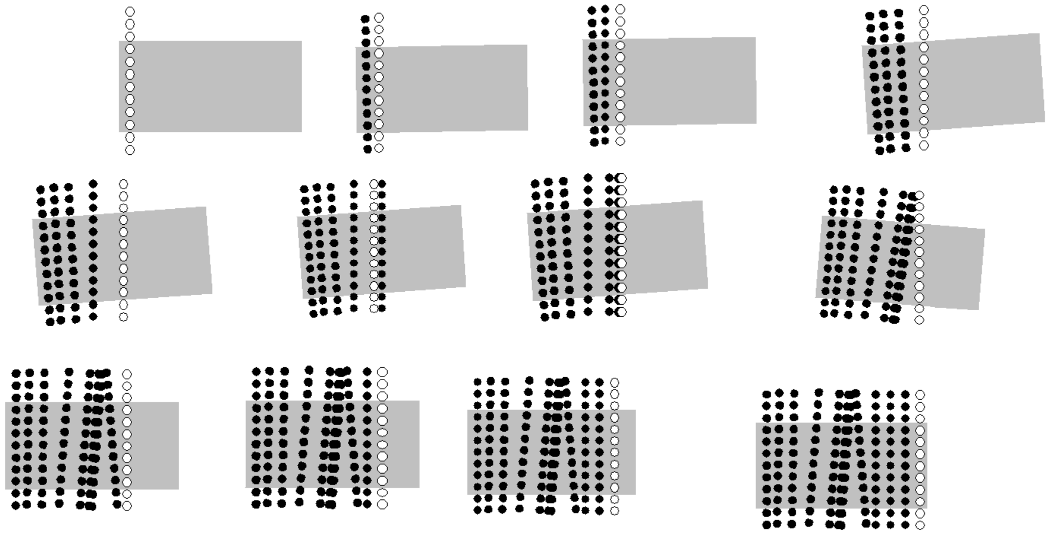

Figure 5. Starting from the top-left corner, a sequence of 12 graphics showing how the *virtual bed-of-cameras* concept works. The vehicle (gray rectangle) drives over a linear array of cameras (open circles). As the vehicle moves over the camera array the system captures a sequence of image columns. By calculating the motion of the vehicle between the acquisition of each image column the system is able to synthesize a bed-of-cameras (closed circles).

2.2.1 Lens distortion. Before the cameras are installed a set of parameters that describe the geometric distortions introduced by the optics are measured. Each camera has its own set of calibration parameters. After each image is taken it goes through a procedure that uses these parameters to remove the geometric distortion. The process is illustrated in Figure 6, which shows two original (uncorrected images) of a calibration target and the undercarriage mockup, and the same images after applying the distortion correction.

2.2.2 Rectification. When the cameras are installed, they are attached to a rigid mounting structure. In general it is not possible to perfectly align each camera in the structure, and slight variations in alignment will result in noticeable geometric distortion in the final product. To remove this type of alignment distortion, the images are *rectified* using a *block adjustment*

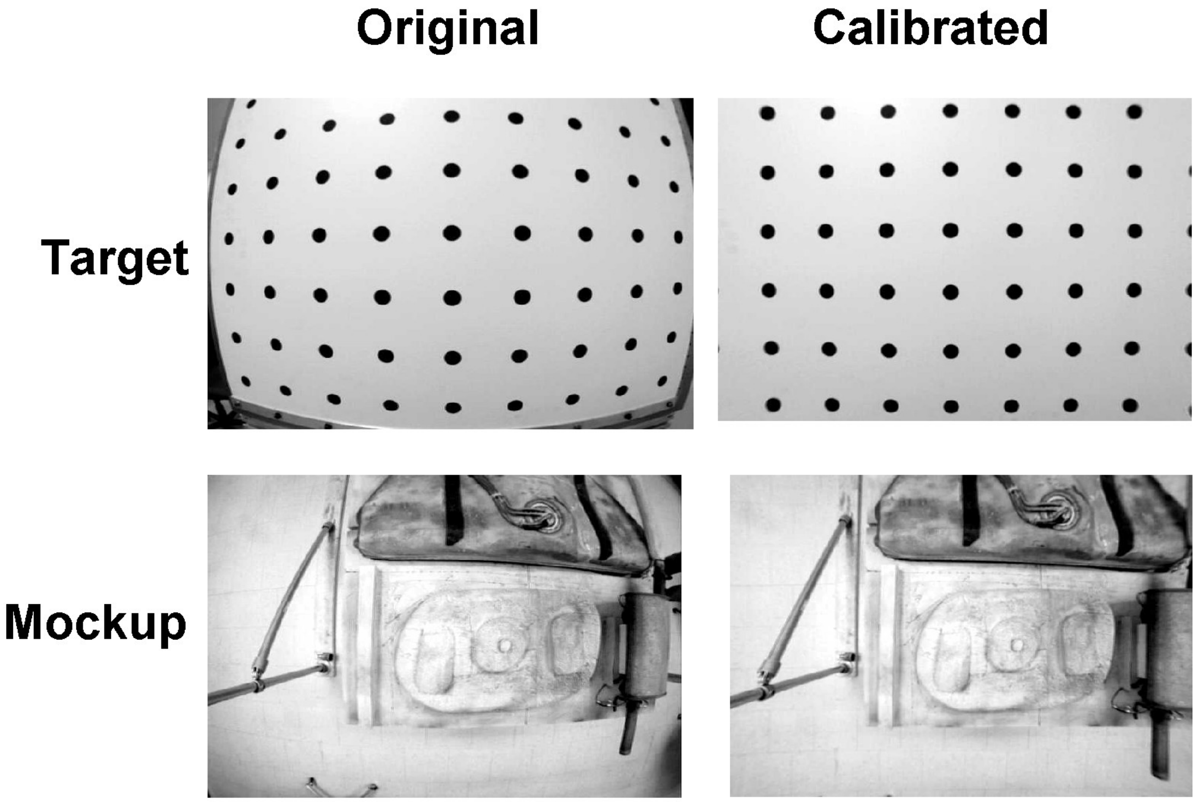

Figure 6. Original, uncorrected images of a calibration target and the mockup (left column), and the same images after correcting for geometric distortion (right column).

calibration procedure. In this procedure small variations in the orientation of the cameras are measured once during the manufacturing corrected. The results is equivalent to realigning the cameras such the principal rays of each image are parallel to each other and perpendicular to the vehicle undercarriage.

<u>2.2.3 Column alignment.</u> After compensating for lens distortion and camera misalignment, the position of the image column relative to a fixed location on the vehicle must be determined. We take advantage of the fact that the vehicle is a rigid body. Consequently, we only need to determine the translation (i.e., the movement parallel and perpendicular to the camera array) and the rotation (i.e., the turning of the vehicle) between the acquisitions of each image column. These parameters are easily determined by observing the motion of a few features on the vehicle's undercarriage.

2.3 Image Acquisition. The image acquisition system simultaneously triggers the camera array and stores the images in computer memory. The images are then assembled into a set of multiple viewpoint mosaics.

The original bed-of-camera concept and the laboratory prototype use an array of network cameras. A network camera consists of a standard video camera with built-in digitizer, microprocessor and network interface chips. This configuration allows the camera to be

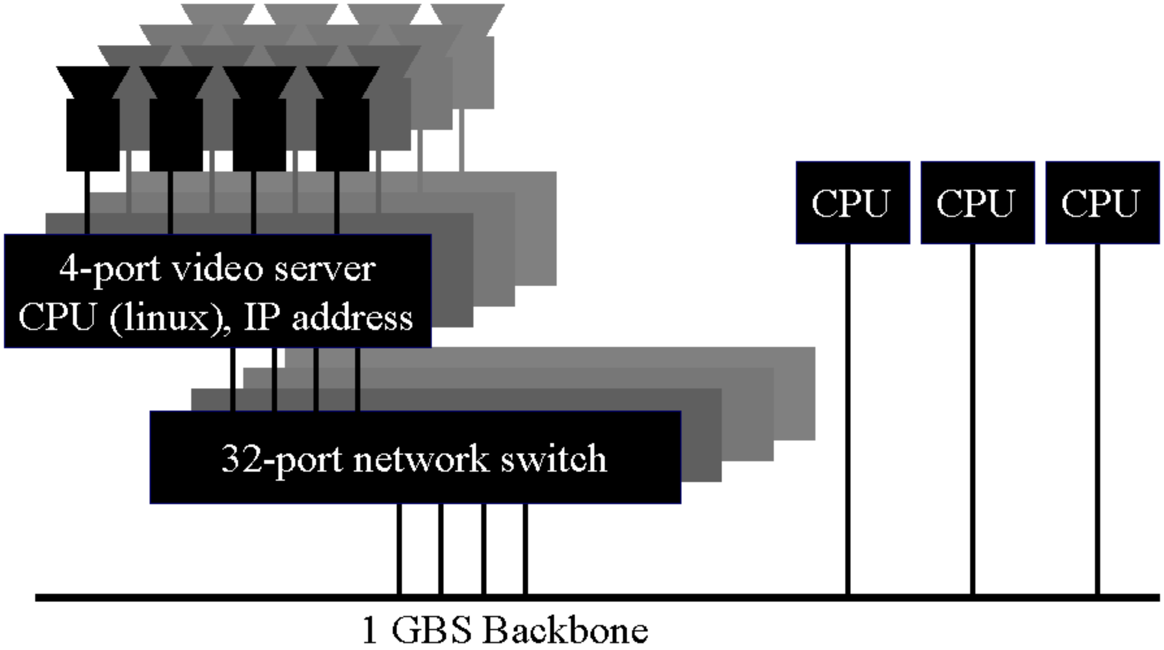

Figure 7. The network camera configuration. Each camera is assigned an IP address and connected to a high speed network backbone. The images can then be transferred to any number of computers, which are connected to the same network.

connected directly to a computer network. As a result, large numbers of cameras can be controlled using standard network devices, such as hubs and switches (see Figure 7). With this design the cameras can be triggered simultaneously and quickly read out, but is difficult to control acquisition rate of each camera (i.e., the number of frames per second). For the bed-of-cameras design this was not a problem because only one instantaneous set of images was taken per vehicle.

The new linear camera array configuration (which is overall much simpler and far less expensive) is not compatible with network camera approach. The new camera configuration (shown in Figure 8) uses an interconnected array of firewire cameras. Firewire cameras consist of a standard CCD imaging chip integrated with a digitizer and a high speed (80 Mbyte/sec) IEEE 1394 communications protocol interface. The high-speed interface enables the system to collect images at 30 frames per second and up to 12 firewire cameras can be connected to a single PC. By connecting multiple PCs together with a synchronization board (i.e., repeating the setup shown in Figure 8) the system can be configured to control an arbitrary number of cameras.

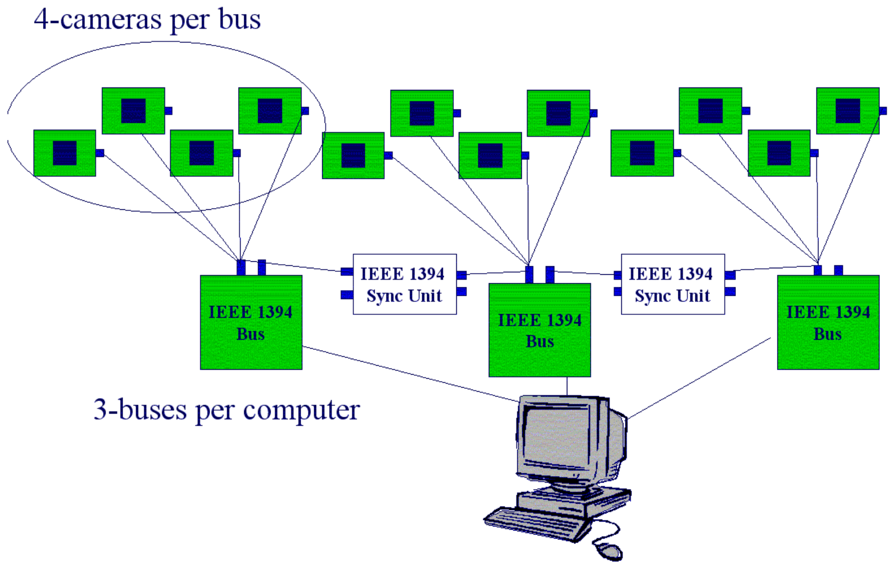

Figure 8. The engineering prototype image acquisition system will use Firewire (IEEE 1394) cameras. Each computer can support 12 cameras.

2.4 Mosaic generation. The mosaic generation system is responsible for building a composite image from a collection of video frames, which have been stored in memory by the image acquisition system. The mosaic generation program works in several steps. First, a column of images from linear camera array of is collected, calibrated, rectified and stitched together to form five row mosaics. Each row mosaic is an instantaneous view of the undercarriage from a different viewing angle (looking towards the front, back, left, right and straight up).

Next, using the optic flow technique shown in Figure 9, the program estimates the translation and rotation of the vehicle between acquisitions of two image columns. This is done by (i) finding a set of approximately 10-20 common feature points that were captured by two cameras at two times, (ii) computing a displacement vector for each feature point, and (iii) using the rigid body constraints and a least squares method to solve for the translation and rotation of the vehicle. The program finds the coordinates $(X,Y,Z)_{ij}$ by triangulating the i'th feature point at times j=1,2. The displacement vector $\Delta_i(1,2)$ for the i'th feature point is found by taking the vector difference of the two triangulated positions, i.e.,

$$\Delta_i(1,2) = [(X_{i2} - X_{i1}), (Y_{i2} - Y_{i1}), (Z_{i2} - Z_{i1})]$$

Because the vehicle is a rigid body the set of displacement vectors Δ_i i=0,1,2,… provide enough information for the program to solve for the translation and rotation of the vehicle from time 1 to time 2. If the vehicle moves in the horizontal plane there are five rigid body parameters -- two translation parameters, two parameters that fix the center of rotation, and one parameter that describes the amount of rotation. Recalling that the principal rays are perpendicular to the plane

of motion, the … the principal rays
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Once the posi … are joined together
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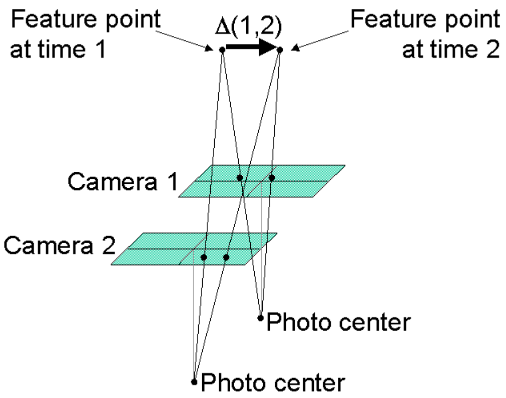

Figure 9. The displacement vector Δ(1,2) is estimated by observing a feature point is in two cameras at two times.

We are investigating two mosaic algorithms. One is based on the *Parallel-Perspective Stereo Mosaic* methodology (see Appendix C for more details). The other is based on the *Adaptive Window* approach (see Appendix B for more details).

A key feature of this system is its ability to capture a full view of the undercarriage from multiple viewpoints. As shown in Figure 10, this is done by building separate mosaics using the back looking, front looking, left looking, right looking and center looking sections of the full field-of-view of each image. Thus, if an object were occluded in one view, it would likely be visible in another view. This is a remarkable result, which will significantly enhance the capabilities of the proposed system.

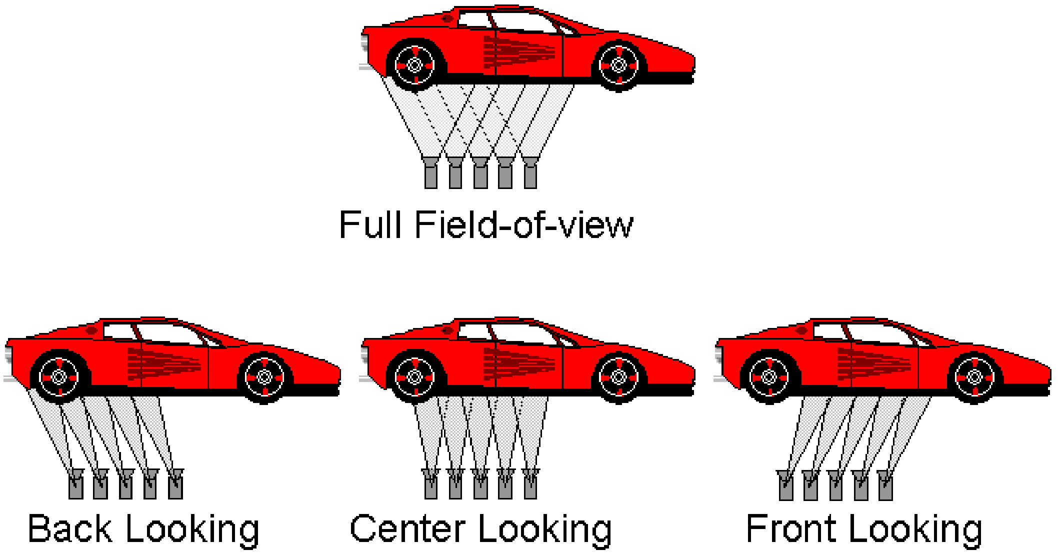

Figure 10. A diagram (not to scale) showing how multiple perspective view mosaics are formed from overlapping wide field-of-view images by taking slices from the back looking, center looking and front looking sections of the full field-of-view.

2.5 Multiple Perspective View Graphical User Interface. The purpose of the graphical user interface (GUI) is to provide a simple intuitive means for the operator to view and understand the output of the data processing system. Figure 11 shows a sample screen from the GUI. On the right-hand side of the display a center full view mosaic is displayed. This view gives the operator a complete view of the undercarriage. The operator can roam around the full view mosaic using a cursor. The current position of the cursor is indicated with a roaming window, which has a red border. When the operator selects an area for inspection, she/he clicks a button on the mouse, and the roaming window becomes an inspection window, and its border color changes from red to blue. When an inspection window is selected, the program retrieves the five perspective views of the undercarriage and displays them on the left-hand side of the display. These five views give the operator the ability to look around occluding objects. The operator also has the ability to retrieve an original image of any part of the undercarriage by clicking a button on the mouse. When an original image is requested the GUI marks the area with a window with a green border and displays the original image chip in the upper-left corner of the display. The GUI runs in real-time and is written in tcl/tk, a machine-independent graphic language.

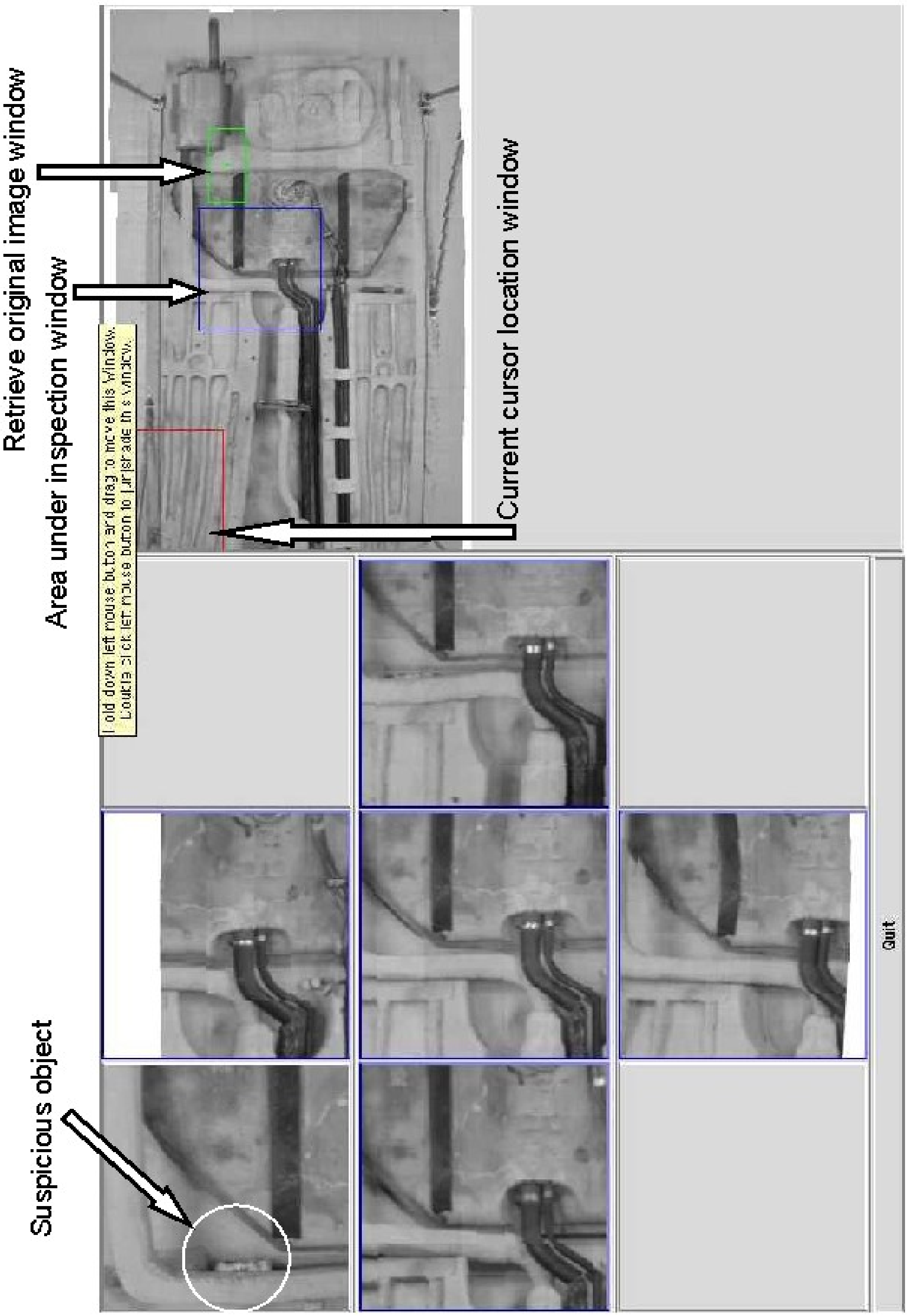

Figure 11. A sample GUI screen. A full view of the undercarriage is displayed on the right side of the display. The current cursor location is outlined in red. The area selected for inspection is outlined in blue. The five perspective views of the inspection area are shown on the left-hand side of the display. An original image chip showing a suspicious object is shown in the upper-left corner.

3 Experimental results

To help test the mosaic algorithms for the linear array design a full undercarriage mockup was built from car parts and Styrofoam and the camera rig was reconfigured to simulate the linear camera array design. This new setup, which is shown in Figures 12-15, more accurately reflects the depth changes and color of an actual undercarriage. We test the performance of the system under the following conditions:

- Working with this new model we were able to generate complete sets of images by moving the camera rig over the mockup. Variation is the vehicle’s speed was simulated by increasing and decreasing the distance the camera rig moved between exposures, and variations in the vehicle’s direction was simulated by rotating the mockup below the camera rig.

- Straight line motion, Figure 16. The camera rig was moved in a direction parallel to the mockup and images were taken at equally spaced intervals. This simulated constant speed, straight line motion of the vehicle over the system.

- Driving at an angle, Figure 17. The camera rig was moved at an angle to the mockup and images were taken at equally spaced intervals. This simulated constant speed, angled motion of the vehicle over the system.

- Straight line motion with variable speed including backing up, Figure 18. The camera rig was moved in a direction parallel to the mockup and the images were taken at irregularly spaced intervals, which included backing up the rig between exposures. This simulated variable speed (including backing up) straight line motion over the vehicle. Also included is a mosaic generated by stitching together image slices without regard to matching. This simulated the results that a conventional scanner arraignment.

- Turning motion, Figure 19. The camera rig was moved in a direction parallel to the mockup and the images were taken at irregular intervals (without backing up). In addition, the mockup was rotated under the camera rig. This simulated turning motion of the vehicle.

These tests clearly demonstrated the ability of the system to reconstruct the undercarriage of a vehicle under a wide variety of conditions. During Phase-II we will integrate the rigid body constraints (discussed above), which will further improve the accuracy and robustness of the system.

4. Towards a Phase-II engineering prototype

The advantage of the linear array concept design proposed by ACTI and UMass over similar systems currently on the market is the ability of our system to account for the motion of the vehicle in the mosaic generation process.

Recent work has focused on specifying algorithms that will improve the quality of the under vehicle mosaic images, and understanding the relationship between the engineering prototype design and the quality of the mosaics. The algorithm design effort continues to focus on adapting the geo-registered mosaic methodology developed for the UMass environmental monitoring program to the problem of under vehicle inspection. These start-of-the art algorithms will simultaneously solve for the motion of the vehicle while creating geometrically correct mosaics.

The initial stages of prototype development have focused on categorizing the relationship between the mechanical design (camera placement, lens field-of-view, and image capture rate), the vehicle motion, and the algorithm performance (measured in terms of geometric accuracy, reliability, and the ability to visualize the vehicle underside in 3D).

In a series of experiments we studied the relationship between camera configuration, mosaic quality, and simplicity of the design. Of particular interest is the relationship between lens field-of-view (FOV), optical path (the mean distance between the undercarriage and the cameras), and the spacing between cameras. In principal, increasing the lens FOV increases the stereo effect (ability to see around objects). However, increasing the lens FOV also increases the perspective distortion, which decreases the reliability of the mosaic system. In one recent study, we determined that the mosaic algorithm produces consistently reliable results if the lens field-of-view (FOV) between 30 and 45 degrees, with a cameras separation between by 3 and 6 inches.

We have begun designing an engineering UVIS prototype. The system, which may be installed in a driveway or laid directly on the road, will consist of a linear array of approximately 30 cameras and support equipment, such as a license plate reader and scale. At regular time intervals, the camera array is triggered and the images are stored in memory. After the car passes over the device, a stereoscopic set of five mosaics is formed. Each mosaic image is equivalent to an image that views the vehicle for a different viewpoint – from the left, right, front, rear and straight up. These mosaics are displayed with a graphical user interface that allows the operator to view any part of the vehicle from five different viewpoints. Thus, enabling the operator to look around occluding objects such as pipes and mufflers.

Figure 12. A picture of the undercarriage mockup built from car parts as well as Styrofoam and cardboard pieces

Figure 13. A close-up picture showing the 3D structure of the mockup parts. Notice the suspicious item under the tailpipe near the lower right corner.

Figure 14. A view of the laboratory prototype with the linear camera rig.

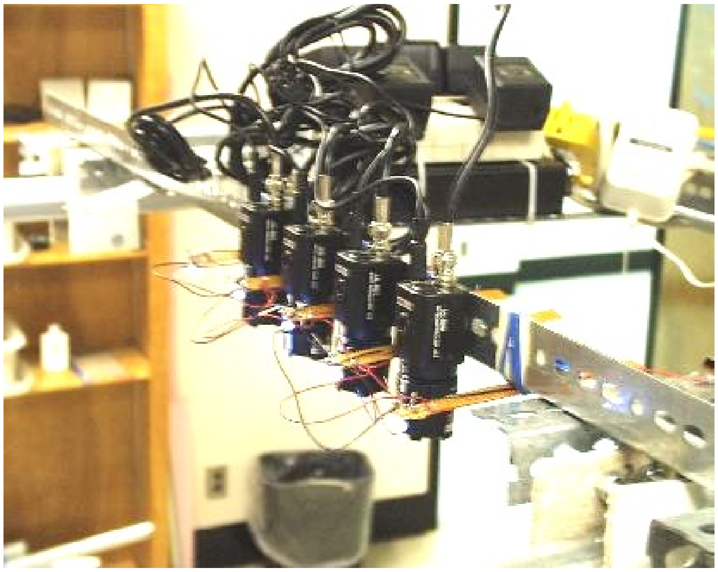

Figure 15. A close-up of the cameras showing the linear array and the LED lights placed around the cameras to even the lighting on the mockup.

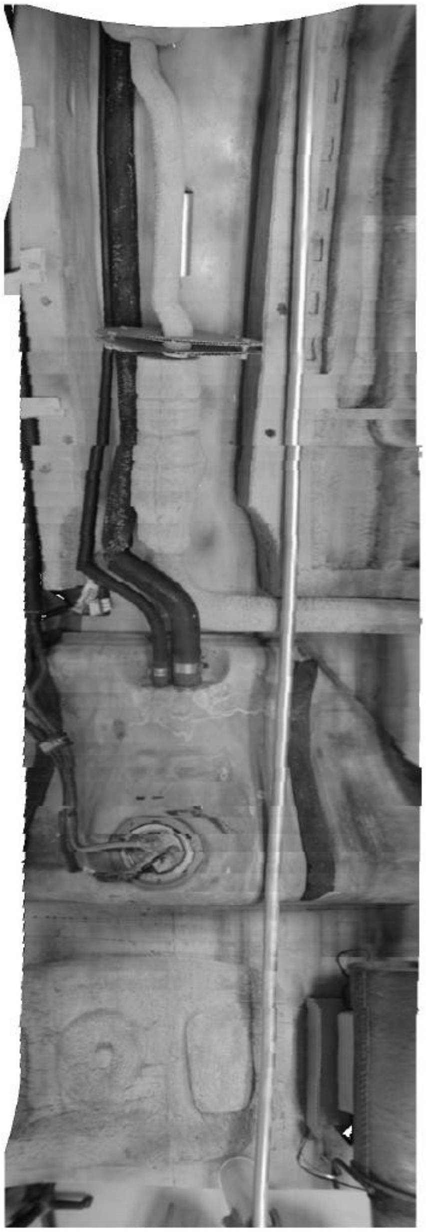

Figure 16. A straight line motion test. The mosaic is made from one camera moving down the length of the mockup in a straight line at constant speed. The straight piece of PVC pipe was laid on the mockup to test the ability of the system to reconstruct straight objects.

Figure 17. Angled straight line motion test. The mosaic is made from one camera moving down the length of the mockup at a fixed angle at constant speed. The straight piece of PVC pipe was laid on the mockup to test the ability of the system to reconstruct straight objects.

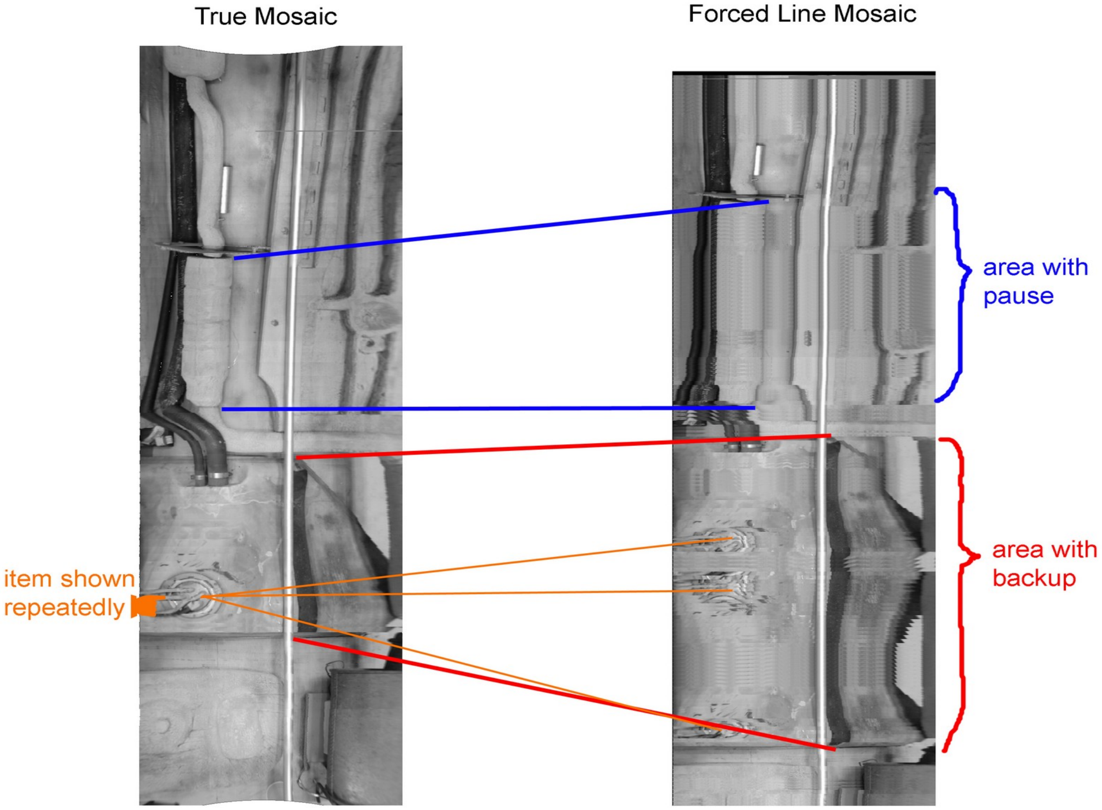

Figure 18. Variable speed test. The mosaic is made from one camera moving down the length of the mockup along a straight line at variable speed including backing up. The mosaic on the left was made using the UMass mosaic system. The mosaic on the right was made by stitching together consecutive slices from each image. The straight piece of PVC pipe was laid on the mockup to test the ability of the system to reconstruct straight objects.

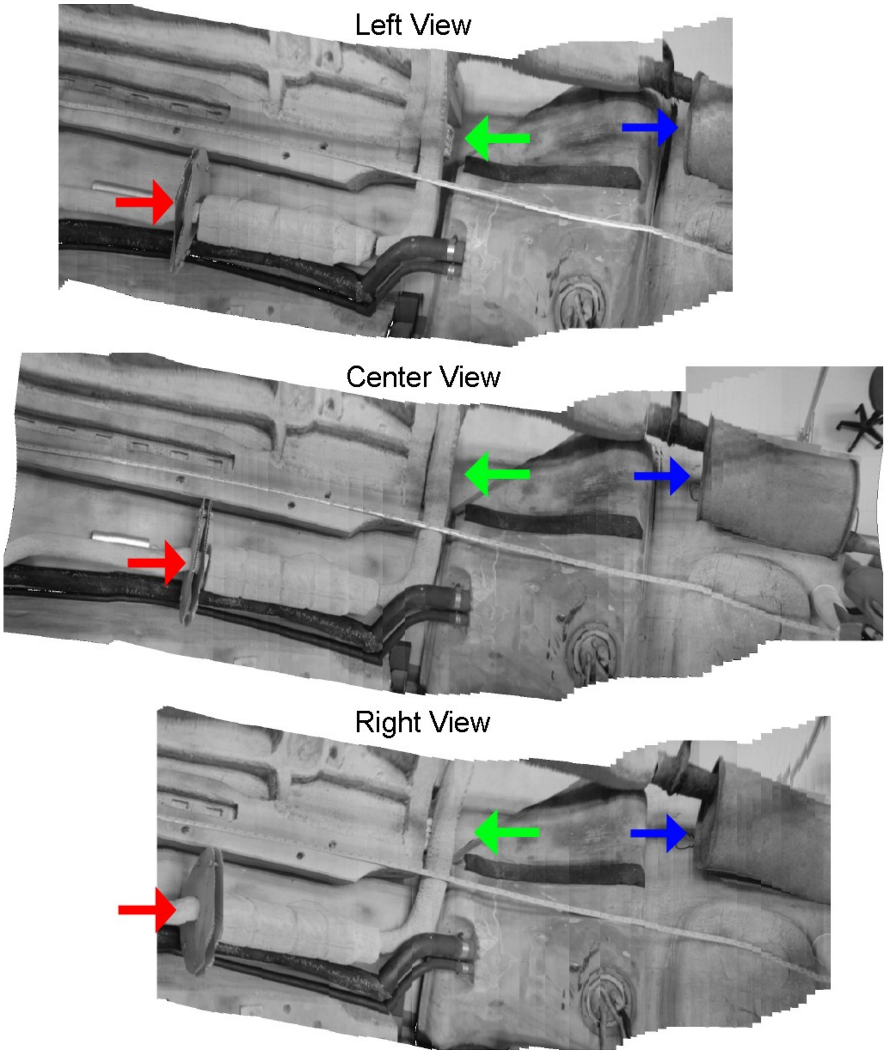

Figure 19. Curved motion test. Three mosaics (left view, center view and right view) are made from one camera moving at variable speed (without backing up) while the mockup is turned. The straight piece of PVC pipe was laid on the mockup to test the ability of the system to reconstruct straight objects. The arrows point to occluded objects that become visible when viewed from different angles.