2006-01-1167

Thermal Modeling and Imaging of As-built Vehicle Components

Andreas Koschan, Priya Govindasamy, Sreenivas Sukumar, David Page, and Mongi Abidi
The University of Tennessee, Imaging, Robotics, and Intelligent Systems Lab., Knoxville, TN

David Gorsich
U.S. Army RDECOM, Tank-Automotive Research, Development and Engineering Center, Warren, MI

ABSTRACT

This paper addresses the issue of thermal modeling of vehicle components where the 3D models of the components are not traditional CAD models derived from engineering drawings but are models derived from 3D-imaging scans of existing real-world objects. A "reverse engineering" pipeline is presented that uses 3D scanners to capture the geometry of an existing object from different views and then integrates these multiple views into a single 3D surface mesh description of the object. This process requires no a priori CAD drawings of the object and thus enables modeling in situations where the original manufacturer no longer exists or soldiers have made undocumented field modifications. The paper further discusses the use of these generated 3D models to simulate thermal imaging properties of the object using the Multi Service Electro-Optic Signature (MuSES) software. Thus, given an object of interest, this paper explores, first generating a 3D model of the object and, second, analyzing the thermal signature through simulation. As a third step, this paper investigates the experimental achievability and limitations of thermal image simulation of vehicle components.

INTRODUCTION

Visual inspection and maintenance of automotive components in a vehicle can be achieved with the help of thermal images that represent the heat pattern of the components under consideration. Thermal images of automotive components taken over a period of time can be analyzed and inspected for certain abnormalities. Changes in the form, material or location of the automotive parts result in the expense of time and physical work. Simulation of thermal images of automotive parts in a virtual environment can be done for various applications ranging from fluid flow analysis to complex thermal management of components.

In the past, several approaches have been made to simulate thermal signatures of under hood and vehicle automotive parts based on computer aided design (CAD) generated meshes or meshes developed from 3D modeling tools. However, CAD models may not be available from some manufactures. CAD models that are available are not perfectly clean surface meshes and tend to be very voluminous. The use of rapid omni-tree based Cartesian mesh to reduce the volume of the mesh for vehicle thermal management is described by Srinivasan et al. [21]. Damodaran et al. [8] discuss the method of simulation to identify and resolve under hood and under vehicle thermal issues. Current major areas of thermal modeling can be grouped together under the general headings of front end, under hood, underbody, passenger compartment, brake cooling and power train applications.

Virtual simulation of thermal signatures has had or can have a great impact on the design of many automotive components and processes such as the catalytic converter, intake and exhaust ports, ducts and manifolds, engine cooling modules, and thermal conditions. Effects of substrate preheating have been compared between the thermal modeling results and the experiments carried out by Dai et al. [7], which paves a way for comparison between real thermal images and simulated thermal images. This paper explains the generation of a 3D model of the as-built component, analyzes the thermal signature through simulation and also investigates the experimental achievability and limitations of thermal image simulation of an automotive part. Figure 1 shows real and simulated thermal images of a car muffler.

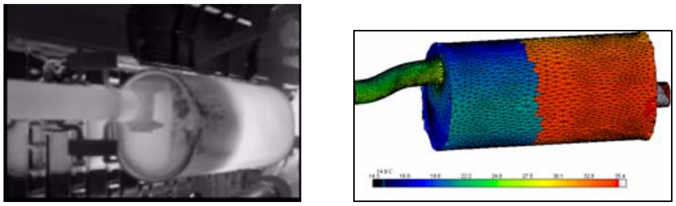

(a) (b)

Figure 1. Thermal image of muffler. a) Real thermal image of muffler captured using an infrared camera and (b) Simulated thermal image of muffler by assigning thermal properties.

Simulation of automotive parts poses several challenges where the shape and complexity of the geometry are the first and foremost to be considered. Many factors, both inside and outside the vehicle, affect the heat flow pattern of the vehicle. Real time temperature curves of automotive components can be integrated into the simulation for achieving results close to reality.

The remainder of this paper is laid out as follows. The next section reviews the theoretical background on thermal modeling and simulation. It also introduces the basic components of a thermal imaging system. The idea and the process of reverse engineering of the as-built models are described afterwards. Furthermore, this paper presents experimental results of thermal data acquisition and results of thermal modeling of vehicle components. Finally, the paper concludes with ideas for extending this research.

THERMAL MODELING AND IMAGING

THERMAL MODELING

Image synthesis involves the knowledge and understanding of the governing parameters and equations. Simulation of thermal images is achieved based on the thermal radiation properties of the object under consideration. The net heat exchange Q_{net} due to radiation between two arbitrary surfaces that are not blackbodies can be described [17] by

$$Q_{net} = A_1 F_{1-2} \sigma (T_1^4 - T_2^4) \, , \tag{1}$$

where T_1 and T_2 are the surface temperatures of the two surfaces, F_{1-2} is the fraction of energy that is emitted from surface one and absorbed at surface two both directly and by reflection, A_1 is area, and σ is the Stefan-Boltzmann constant.

The radiation phenomenon is a nonlinear process because the thermal energy emitted due to radiation is proportional to the fourth power of absolute temperature. To compute the radiation heat transfer between two surfaces, it is necessary to introduce the concept of radiation view factor or configuration factor or shape factor [16]. View factor is the estimation of the quantity of rays that are cast from each element in the model, which is used in calculating radiation. The greater number of view factors estimated, the higher is the computation time depending on the number of elements in the model. A view factor F_{ij} is defined as the fraction of thermal energy that leaves the surface *i* and is incident on the surface *j.* The view factor can be defined as

$$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j}{\pi R^2} dA_i dA_j \, , \tag{2}$$

where A_i and A_j are the areas of the surfaces *i* and *j,* respectively, θ_i and θ_j are the angles between the position-dependent normal vectors to surfaces *i* and *j* and a line of length R connecting the points of evaluation of the normal.

Similarly, for F_{ij} it can be modeled as Equation 2 and hence it follows that

$$A_i F_{ij} = A_j F_{ji} \, . \tag{3}$$

The above equation is known as the reciprocity relation of view factors. This relation is used to compute view factors from the other known view factors and reduces the number of view factors to be calculated. The basic assumptions used in deriving Equation 1 are:

A) The two surfaces are diffusively emitting and reflecting.

B) The two surfaces are isothermal.

For an enclosure of *N* surfaces, it holds

$$\sum_{j=1}^{N} F_{ij} = 1 \, . \tag{4}$$

The radiosity solution produces finite number of view factor equations or a linear system that must be solved. The computation of view factors is a complex task and can be done in different ways. Different methods for view factor calculation are discussed in [4] and [20].

REQUIREMENTS OF SIMULATION

The simulation of thermal images in a virtual environment requires the incorporation of conditions and thermal properties from the real time system in order to obtain good results. The knowledge of the simulation type and the identification of the best component for analysis, the material and thermal properties, and the use of optimal geometry are required prior to simulation. The knowledge of these properties aids obtaining a better thermal signature prediction of the component under consideration and also helps in fine-tuning of the simulation environment for improved results.

Geometry of components

The geometry of the model under consideration is an essential requirement for thermal modeling. Geometry is often composed of vertices, curves, surfaces and solids as described by a CAD or solid modeling package. The most commonly applied geometry is a 3D surface mesh description of the component considered for thermal modeling. The 3D mesh could result from CAD or from other 3D modeling tools or could also be generated by reverse engineering. The process of creating a thermal mesh is a complex task, which requires modeling expertise and advanced tools. The 3D mesh of the component under consideration should be complete without holes or missing elements for thermal signature modeling. The meshing should also have a uniform aspect ratio and uniform normal vectors to avoid the directional effects of heat flow.

The time required for simulation is directly proportional to the resolution of the mesh. A 3D mesh geometry with 100,000 elements consumes, for example, more time for simulation than a mesh with 10,000 elements. Voluminous meshes not only increase the size of the model but also increase the time needed for the simulation. In such cases, the thermal solution is not obtained for each and every element, which further increases the time for simulation. The CAD models are usually voluminous [21], or complex, and hence reduction of the mesh size is a necessary step. The CAD mesh often contains holes and needs to be cleaned before using it for thermal simulation of under hood and under vehicle components. CAD models are not readily available from the manufacturers with very detailed information of the interiors. This imposes the generation of 3D model meshes from other sources. As-built automotive components can be modeled using the concept of reverse engineering, which will be discussed in more detail later. In simple terms it can be defined as the generation of 3D meshes by laser scanning the model and reconstruction from that scan.

Parameters for thermal modeling

In the simulation of vehicle components, the thermal modeling requires the knowledge of certain parameters like the environmental conditions surrounding the vehicle, temperature curves of the components with respect to time, the materials of the component surfaces and their emissivities. This subsection discusses in detail these parameters and the assignment of properties.

a) *Environmental conditions* – Environmental parameters like the wind direction, humidity, solar radiance, and the cloud cover determine the starting ambience of the vehicle. These parameters initiate the necessary heating up of the engine components when the vehicle is first started and also aid in simulating thermal images of automotive components for a particular day or for a particular period of time.

b) *Temperature curves* – Simulations of automotive components have not received much recognition though they have been in use for several years [8]. This lack of recognition is mainly due to the non-capability of providing actual temperature variations with respect to time for the component under study. Exact prediction of temperature variations would be an important improvement to the model. Consider, for example, the exhaust system components in a vehicle. The surface temperature of the exhaust system components such as the manifolds, connecting pipes, catalytic converter, muffler etc., varies between 785 K and 925 K, when the engine is operating at its maximum capacity [21]. There is no flow of coolant fluid in real time, but however there occurs heat loss due to conduction, radiation and convection. These conditions slightly reduce the outside temperature and should be taken into account when assigning temperature curves. In order to achieve this assignment, improvement steps for measuring the temperature variations are necessary. One approach to this requirement is to measure the temperature variations with a digital data logging infrared thermometer, which works similar to an infrared imaging device, and measures the temperature values with respect to time.

c) *Definition of properties* – The assignment of properties for the parts plays an important role in the thermal modeling of the components. Some of the parameters needed for the model building are discussed below along with their importance and role in the thermal infrared prediction. The parameters assigned are the *type of material*, the *thickness of material*, and the *surface condition*.

Based on the type of material assigned, the numerical solution calculates the net energy incident on the element or part. The emissivity of the surface material plays an important role in the radiation of heat. The knowledge of the material used for manufacturing the components gives the thermal conductivity and the emissivity of the material, which in turn results in improved simulation.

The thickness value is used to determine the capacitance of the part. It has no effect on the geometry used. The surface properties and paint code values are used to apply a surface emissivity value to the thermal calculations carried out. This value is used to know how much heat is reflected from the part and how much is absorbed and emitted by the part.

d) *Effects of fluids* – The systems in the engine compartment are forced to be at an acceptable temperature with the help of fluid flow. In general, the fluid flow in a heat engine is caused by active pressure sources that produce forced flow and passive pressure sources that produce natural flow [14, 15]. The heat flow in and out of the system is mainly coupled with the fluid flow. The convective heat transfer coefficient defines the heat transfer due to convection. It represents the thermal resistance of relatively stagnant layer of fluid between a heat transfer surface and the fluid medium. The fluid flow effects can be modeled either in a simulation or they are assumed to be virtually present by carefully designing the temperature curves such that the effects of fluid flow and the heat conduction or convection are also modeled.

THERMAL IMAGING

Thermal imaging devices are a combination of optics, detectors and signal processing units, which detect the thermal infrared radiation emitted by the objects in the scene without the use of artificial illumination [5]. Figure 2 illustrates the basic components of a thermal imaging device. The thermal imaging system views the target or the scene through the infrared detecting lens system which is focused on a detector array and then processed through the signal processing unit, which is finally displayed as a temperature pattern on the display system. There are two main types of thermal imagers: namely cooled thermal cameras and uncooled thermal cameras.

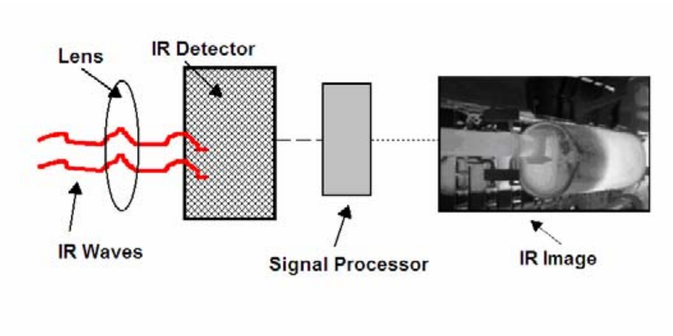


Figure 2. Basic components of a thermal imaging system.

Uncooled cameras are the most common type of thermal imaging device. The infrared-detector elements are contained in a unit that operates at room temperature. This type of system is completely quiet, activates immediately and has a built-in battery. Cryogenically cooled cameras are more expensive and more susceptible to damage from rugged use. These systems have the elements sealed inside a container that cools them below zero degrees Celsius. The advantage of such a system is the very high resolution and sensitivity that results from cooling the elements. Cryogenically cooled systems can "see" a difference as small as 0.1° C from more than 300 m away.

In thermal imaging systems [18, 22], the lens collects the energy from a spot on the target and focuses it on the surface of the infrared detector. The focused light is scanned by a phased array of infrared-detector elements. The detector elements create a detailed temperature pattern called a *thermogram*. The thermogram created by the detector elements is translated into electric impulses. The impulses are sent to a signal-processing unit, a circuit board with a dedicated chip that translates the information from the elements into data for the display. The combination of these impulses from each element creates the image.

The thermal image formed in this way represents the heat signature of the automotive component under consideration. Calibration of the thermal imaging system can significantly improve the results [1, 9, 10, 23, 24]. The thermal images are used as basis for thermal modeling, from which thermal properties and surrounding conditions are extracted and used.

REVERSE ENGINEERING OF AS-BUILT VEHICLE COMPONENTS

Computer aided design in combination with computer aided manufacturing has changed many engineering disciplines since the 1980’s. A designer can quickly manufacture a real world tangible object from a conceptual CAD description. What if the CAD description is not readily available for an obsolete object? In this context, reverse engineering (RE) plays a significant role as the ability to create rapid prototypes from existing components [2]. The RE pipeline begins with the product and works through the design process in the opposite direction to arrive at a product definition. In doing so, it uncovers as much information as possible about the design ideas that were used to produce that particular component. Here design ideas indicate the shape and topology of the surfaces used in the manufacturing process and not the functionality. The challenge that is addressed in this paper is the extent of automation that can be achieved with laser-based range scanners and their appropriateness to thermal modeling and simulation in the automotive industry.

The conventional approach to reverse engineering the CAD description of a mechanical component has been the use of coordinate measuring machines (CMM). CMMs though accurate are tedious and require a probe in contact with the object. They do not provide the flexibility for rapid non-contact digitization. Thus, laser range scanners are applied here to generate 3D CAD models from real-world objects. Integrating multiple view range images allows reconstructing a 3D model of an object of interest.

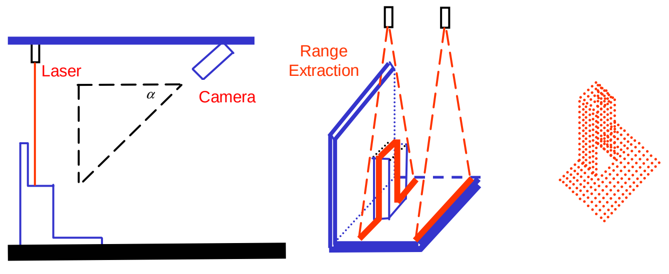
Figure 3 illustrates the employed laser scanning system for reverse engineering automotive parts at the University of Tennessee. The setup consists of a high speed sub-millimeter accurate range sensor (IVP Ranger SC-386 MAPP 2200). The Ranger consists of a special 512 x 512 pixel camera that is specifically tailored with supporting electronics to integrate image processing functions onto a single parallel-architecture chip. The calibrated sensor [13] detects the sheet-of-light laser incident on the target object and outputs the range (distance) perpendicular to the motion direction from the light source.

Figure 3. Laser scanning equipment for reverse engineering of as-built automotive parts.

The Ranger uses an active triangulation scheme for 3D data collection where the scene is illuminated from one direction and viewed from another. The arrangement of the system is such that the camera and the laser are mounted relative to the proposed target area to form a triangle where the camera, laser, and target are each corners of the triangle (see Figure 4(a)). The angle where the laser forms a corner is typically a right angle such that the laser stripe projects along one side of the triangle. The angle, α, at the camera corner is usually 30-60 degrees. The baseline distance B between the camera and the laser specifies the right triangle completely. The triangulation geometry specifies the range (distance) as a function of sensor offset position s, focal length of the camera f, baseline distance B, and the angle α as shown in Equation 5.

$$r(s) = B\frac{f\tan\alpha - s}{f + s\tan\alpha}. \qquad (5)$$

The laser line (profile of r) conveys surface cues about the object. The digitization of the underlying surface is achieved by accumulating such surface profiles. Thus, a single scan will only contain information about the object as viewed by the camera at the present position. The side of the object occluded from the camera does not appear in the data. One solution to overcome this problem is to acquire data from multiple view points. The challenge now shifts to the automatic integration of these views into the CAD model (polygonal mesh representation) of the object. This task is approached as a two step paradigm. First the multi-view datasets are aligned to a global co-ordinate frame. This process also called as surface registration involves matching surfaces that have common (similar) geometric information. According to Horn et al. [11], given three or more pairs of non-coplanar corresponding 3D points between views, the unknown rigid transformation of rotation and translation has a closed form solution. The registration problem can therefore be approached as a point matching problem.



(a) (b) (c)

Figure 4. Principle behind active triangulation. (a) Range sensor and the laser separated on a common motion platform. (b) Laser scanning and range extraction. (c) Profile accumulation.

The most popular registration algorithm is the Iterative Closest Point (ICP) algorithm [3]. The implementation of ICP in Rapidform (a reverse modeler software package) is used for the task of surface registration. The software allows initializing the ICP algorithm by manual point selection.

The three pairs of corresponding points so picked are iteratively refined up to a particular threshold before merging the two point clouds. This process is repeated till all the surfaces have been covered that make up the object to the desired level of detail. Then the polygonal surface is reconstructed from the point cloud output based on the organization of the points using [12]. The block diagram in Figure 5 summarizes this procedure of digitizing real world objects using laser scanners.

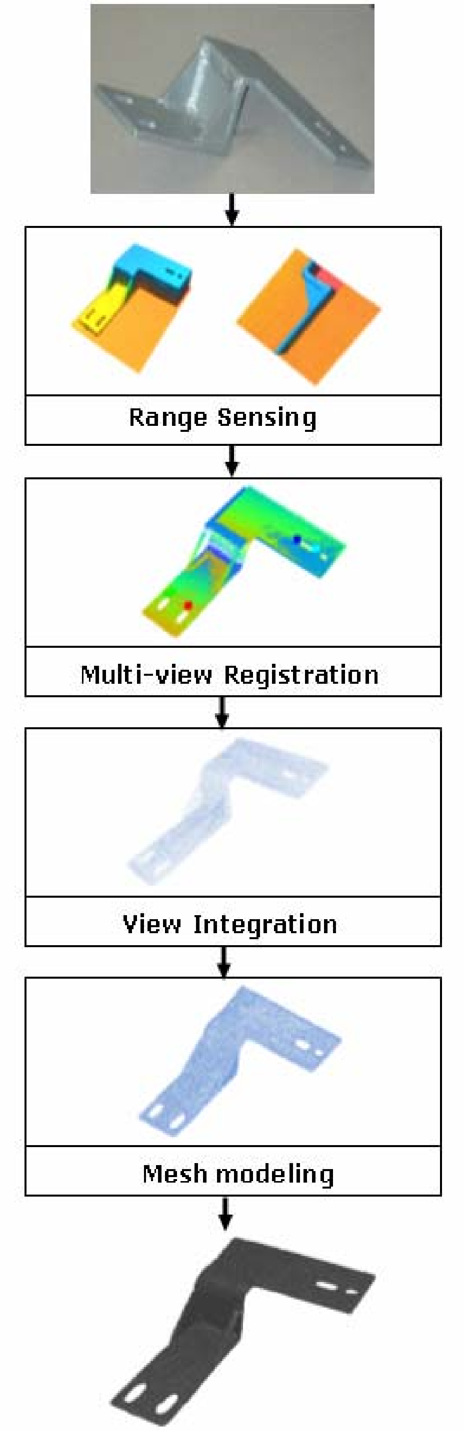
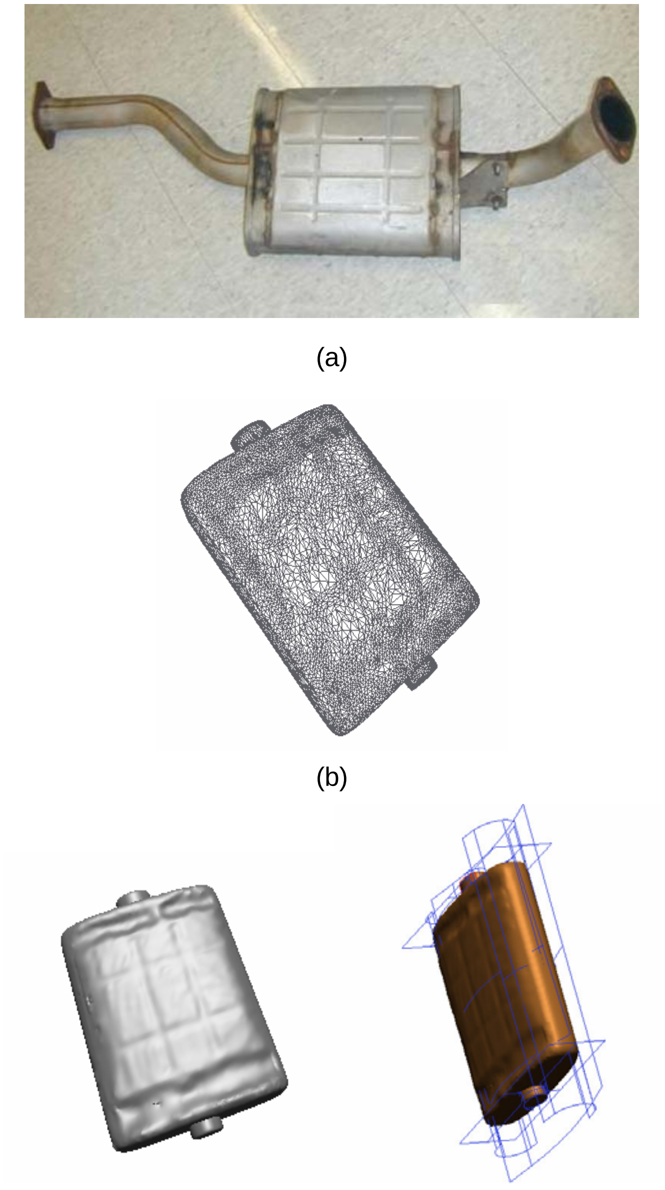


Figure 5. Reverse engineering using laser-range scanners.

EXPERIMENTAL RESULTS

The results for the procedures described earlier are presented here. First our reverse engineering pipeline is demonstrated on a muffler dismantled from a car. This muffler is used for our thermal analysis and simulations. Figure 6 shows a photograph of the muffler along with its reverse engineered model. Rapidform software is applied for creating a surface-based prototype as an extension of creating polygonal mesh models to aid manufacturing. Note that in this implementation, the emphasis has been on the geometric aspect of reverse engineering and not on the functionality of mechanical components.



(a)

(b)

(c) (d)

Figure 6. Reverse engineering a muffler dismantled from a car. (a) Photograph of the muffler. (b) The multi-view fused wire frame model after surface reconstruction of the point cloud. (c) Mesh rendering of the CAD model. (d) Rapid prototype of the muffler after surface analysis and interpretation.

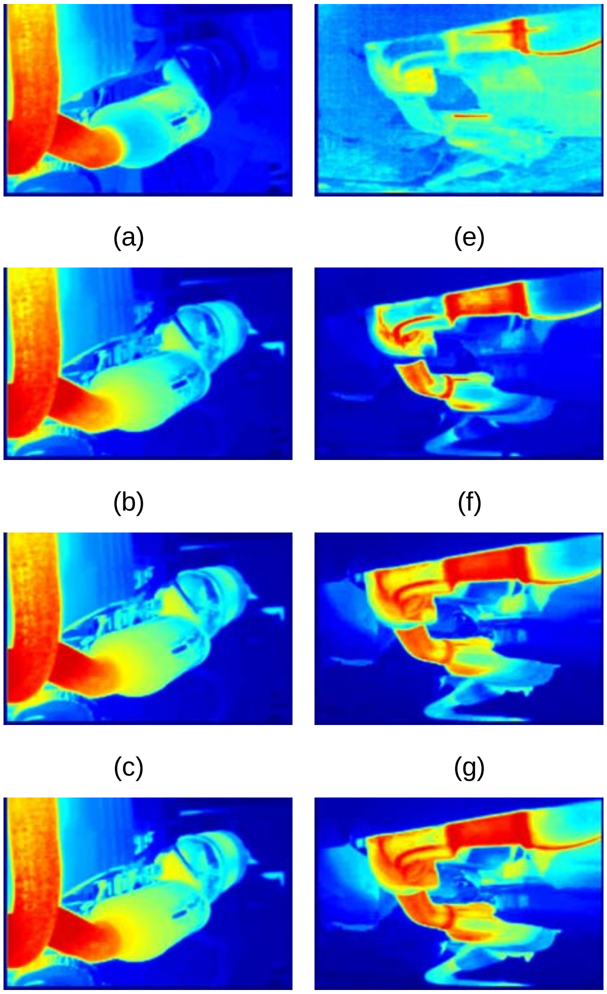
Next the thermal properties and the real thermal images of the as-built components are obtained as a basis for thermal simulation. The setup for data capture is shown in Figure 7. An Indigo Omega thermal camera, an uncooled thermal camera, was used to acquire a sequence of thermal images over a period of time, with the vehicles Dodge RAM 3500 van and Ford Taurus running during the entire capture time. The camera was mounted on a tripod and the system was adjusted to focus the under vehicle chassis. The real thermal image sequences from the camera were recorded continuously as a video sequence using a laptop equipped with a frame grabber card. The results shown here include sections showing the catalytic converter and the muffler of the Dodge van (Figure 8 (a)). Additional the exhaust manifold pipes and the catalytic converter of the Ford Taurus vehicle as shown in Figure 8 (b).

Figure 7. Setup for thermal data acquisition. The setup includes two uncooled infrared cameras, an infrared thermometer and a laptop for controlling the devices.

(a) (b)

Figure 8. Visual images of Section I. (a) Dodge van section involving the catalytic converter and the muffler. (b) Ford car section involving the exhaust manifold pipes and catalytic converter.

The vehicle used for data acquisition was started at time 0 and left running until the entire sequence of 50 minutes was imaged. The starting room temperature was 30 degree Celsius. The video file was then edited and frames extracted from the video are presented here. The grayscale images were color coded for enhanced visualization. The sequence of images shown in Figures 9 (a - h) are color coded thermal image sequences of section I of the Dodge van and Ford car, when the engine was started at time zero with an interval of two minutes. As seen from the images for the Dodge Van, the pipe from the exhaust manifold is at higher temperature and is represented by red and the catalytic converter is in turquoise and represents less temperature value in the temperature scale. The muffler is even colder and is shown in dark blue which represents cold in the color scale. The changes in temperature can be seen over the catalytic converter surface for the Ford car. The exhaust manifold pipes are at higher temperature and they appear red due to the color scale used. The variation in temperature can be seen in the color coded images in Figure 9 (a –h) where the varying colors represent the change in temperature. The color scale used spans from blue, representing regions that are cold and red, representing regions that are hot.



(a) (e)

(b) (f)

(c) (g)

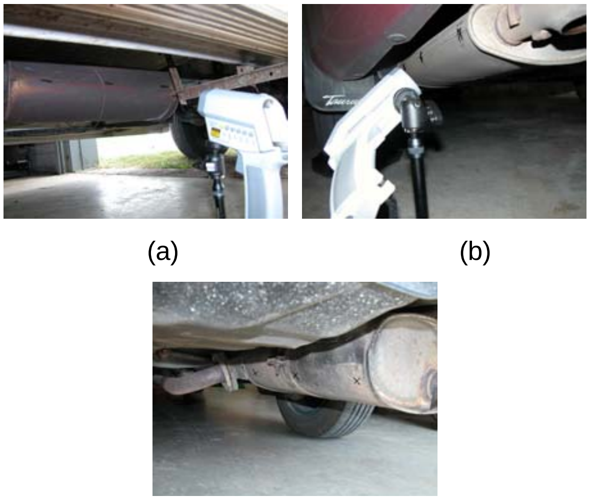
(d) (h)

Figure 9. Thermal image sequences of Section I of Dodge Van and Ford Car. (a – d) Color coded thermal images of Dodge Van with an interval of two minutes. (e –h) Color coded thermal images of Ford Car with an interval of two minutes.

The temperature curves of the as-built components were measured using a Raytek infrared thermometer [19]. The thermometer measures the amount of infrared energy emitted by a target object and calculates the temperature of that object’s surface. It is essential for better simulation results to provide the exact temperature values or curves of the automotive parts under consideration. Up to date, the temperature curves used for simulation are based on assumptions [21], hence this necessitates the measurement of temperature over a period of time for improved thermal modeling. The thermometer when connected to the computer continuously records the temperature values of a particular automotive part over a period of time that can be specified using the interactive software. The data can be exported as text files and are used a temperature curves for simulation.

The geometry and the corresponding temperature curve of the automotive component vary for different models of the automobile. It is necessary for the simulation of thermal images to have the CAD model of the automotive component and the temperature curve of that component for a particular type of vehicle. The point of measurement of the Dodge RAM 3500 van muffler is shown in the Figure 10 (a). The muffler actually varies in temperature along its surface. The assumption here is that the part of the muffler closet to the catalytic converter receives more heat and the other end is at a lower temperature compared to the front end. The middle part of the muffler has significant temperature variation and is higher than the front and the rear end surface of the muffler. The temperature of the muffler was 24.0 degree Celsius when the vehicle was started. The room temperature was 25.0 degree Celsius.

The muffler geometry varies between cars from different manufacturers. The Ford Taurus muffler surface temperatures, shown in Figure 10(b), and the Toyota Corolla muffler surface temperatures, shown in Figure 10(c), were measured to illustrate different temperature curves of different mufflers. The muffler surface was divided into three regions namely the front region, the side closer to the catalytic converter, middle region and the rear region, the side closer to the tail pipe. Similarly, the Dodge RAM muffler was divided into three regions and the temperature curve was measured. The resulting temperature graphs are shown in Figures 11 (a, b and c).

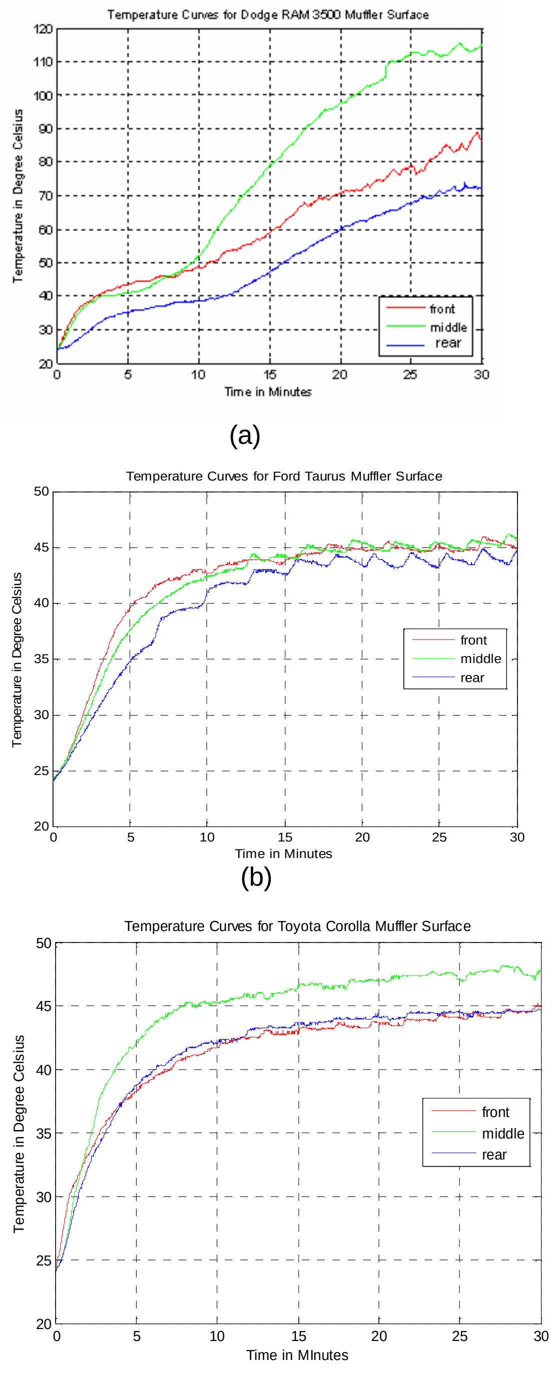


(a) (b)

(c)

Figure 10. Muffler with the point of measurement highlighted. (a) Muffler of Dodge RAM 3500 Van. (b) Muffler of Ford Taurus. (c) Muffler of Toyota Corolla.

It can be inferred from the graphs in Figure 9 that the muffler surface temperature is not identical for all cars. The geometry of the mufflers is different (see Figure 10) and the engine capacity varies between the three vehicles selected for experimentation. The Toyota Corolla has an inline, four cylinder engine, the Ford Taurus has a V6 engine, and the Dodge RAM has a V8 engine. The pipe diameters in the exhaust systems vary from model to model, and the mufflers are made of different materials.



(a)

(b)

(c)

Figure 11. Temperature curves of (a) Dodge RAM 3500 van muffler, (b) Ford Taurus, and (c) Toyota Corolla (front end, middle and rear end) for a period of 30 minutes.

With all the required prior data, the next step is the thermal modeling of the as-built automotive part, in this case the muffler of a car. Since the entire under vehicle chassis has not been reconstructed using reverse engineering, a synthetic under vehicle chassis is generated with the software Rhino 3D, and the reverse engineered muffler is appended to the chassis. The geometry is meshed into polygons suitable for thermal modeling and is imported into the software Multi-Service Electro Optic Signature (MuSES). The thermal and boundary properties were assigned to the model used.

MuSES applies the hemi-cube method to calculate the view factors as described in [6]. The basic algorithm begins by discretizing the surface of the hemicube into a set of M uniform sub patches which will be called pixels. Each pixel defines a particular direction and angle from the receiving patch's centroid. Thus each pixel contributes a specific delta-view factor value to the overall view factor between two surfaces if the pixel is covered by the projection of the transmitting surface onto the discretized hemicube. Each pixel in the rendered image is assigned a weight such that summing up the weights for all the pixels corresponding to the same thermal node yields the view factor from the thermal node at the viewing point to the thermal node scanned in the image. MuSES assumes that the geometry has been previously meshed for finite element use by choosing the centroid of each element as the points at which view factors are computed.

The simulation was carried out for a period of 15 minutes. The original input model used for simulation is shown in Figure 12. The result of simulation is shown in Figures 13 (a – d). The muffler is close to reality and the exhaust system component is at higher temperature, which is represented as white. The color scale is adjusted in such a way that the muffler variation is clearly seen. Similarly, the other automotive components can be reversed engineered and the thermal modeling of such automotive components can be achieved. The simulation can be more close to reality by incorporating the exact temperature predictions of the exhaust system or the internal heat transfer solutions.

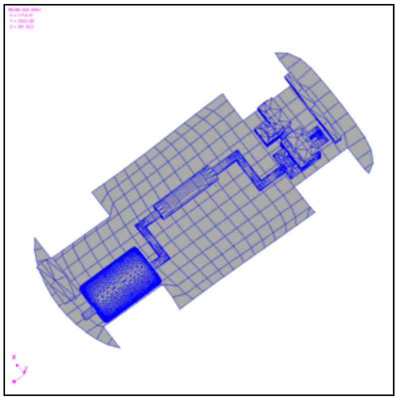
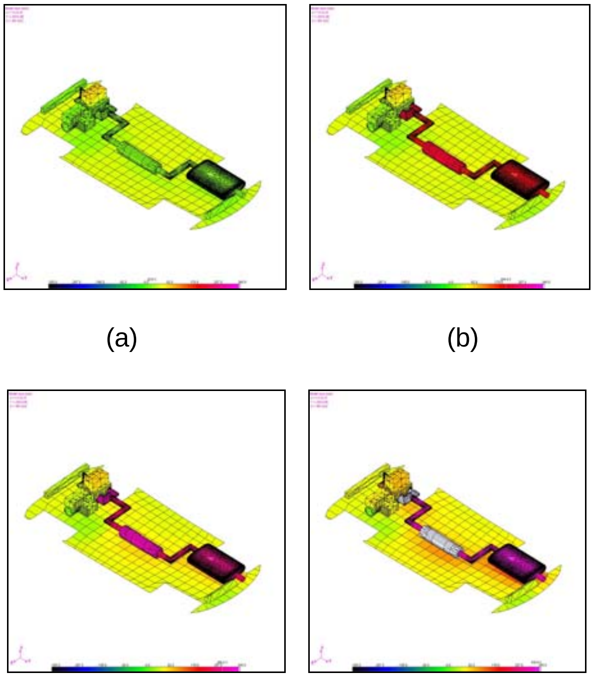


Figure 12. Synthetic CAD model of the car under body with the scanned muffler.



(a) (b)

(c) (d)

Figure 13. Simulated thermal model of the under vehicle chassis with reverse engineered muffler model. (a) Simulation result at time 0. (b) Simulation result at 5 minutes. (c) Simulation result at 10 minutes and (d) simulation result at 15 minutes.

Simulated thermal images are virtually synthesized to represent the real scene. Comparison between real and thermal images involves the complete knowledge of the internal and external processes that affect the temperature changes of the automotive part under consideration. There are some practical issues, like estimating environmental parameters, material properties, and insulation in order to compare the two types of images. The best system to compare is the exhaust system of a vehicle with the simulated exhaust system. The engine components are maintained at a certain temperature with the help of the coolant fluid, whereas the exhaust system is not internally forced to cool with the help of any coolant. The exhaust gas heats up the exhaust components as it passes through them. Commercial exhaust gas temperature monitors are available that can be used to measure the temperature changes with respect to time. Comparison of real and simulated thermal images is possible in the real sense only when all the details about the components are known and depends on the availability of similar CAD model.

CONCLUSION

The 3D model of the as-built automotive component was efficiently generated applying reverse engineering, which avoids most of the problems associated with the CAD meshes. Real time temperature curves and images were obtained to assist in thermal modeling. The simulated thermal model had the same heat pattern as the real muffler. Virtual simulation to reality can be achieved by comparing the real scene to the simulated thermal images. However, comparison of simulated thermal images with real time images poses several challenges all of which have to be overcome to achieve the objective of comparison. As discussed earlier, the geometry of the model used for simulation plays an important role in the final result of simulation. The model used should be an exact replica of the automotive components so that the visual comparison will be better. The temperature and thermal properties play an equally important role. The software should also be flexible enough to model the heat flow properties and the conduction and convection parameters.

ACKNOWLEDGMENTS

This work is supported by the DOD/RDECOM/NAC/ARC Program under grant W56HZV-04-2-0001 and by the University Research Program in Robotics under grant DOE-DE-FG52-2004NA25589.

REFERENCES

1. P. Bajscy and S. Saha, “A new thermal infrared camera calibration approach using wireless MEMS sensors,” Proceedings of *the Communication Networks and Distributed Systems Modeling and Simulation Conference*, San Diego, 2004.
2. F. Bernardini, C.L. Bajaj, J. Chen, and D.R. Schikore, “Automatic reconstruction of 3D CAD models from digital scans,” *International Journal of Computational Geometry and Applications*, **9**, pp. 327-369, 1999.
3. P.J. Besl and N.D. McKay, “A method for registration of 3D shapes,” *IEEE Trans. Pattern Analysis and Machine Intelligence*, **14**, pp. 239-256, 1992.
4. J. C. Chai, J. P. Moder, and K. C. Karki, “A Procedure for View Factor Calculation using the Finite-Volume Method,” *Numerical Heat Transfer*, Part B, **40**, pp. 23-35, 2001.
5. P. Chevrette, “Calibration of thermal imagers,” Proceedings of *SPIE*, **661**, pp. 372-382, 1986.
6. A. R. Curran, K. R. Johnson, and E. A. Marttila, “Automated radiation modeling for vehicle thermal management,” Proceedings of *SAE International Congress and Exposition*, Detroit, Michigan, 1995.
7. K. Dai, X-X. Li, and L. L. Shaw, “Comparisons between thermal modeling and experiments: effects of substrate preheating,” *Rapid Prototyping Journal,* **10**, pp. 24-34, 2004.
8. V. Damodaran and S. Kaushik, “Simulation to identify and resolve under hood/ under vehicle thermal issues,” Journal Articles by FLUENT Users, pp. 1-4, 2000.
9. D. P. Dewitt, G. D. Nutter, and T. J. Love, “*Theory and Practice of Radiation Thermometry,*” A Wiley Inter Science Publication, 1988.
10. N.P Fox, T. R. Prior, and E. Theocharous, “Radiometric calibration of infrared detectors and thermal imaging systems,” Proceedings of *SPIE*, **2474**, pp. 229-237, 1995.

11. B. Horn, H. Hilden, and S. Negahdaripour, "Closed-form solution of absolute orientation using orthonormal matrices," *Journal of the Optical Society of America*, **5**, pp. 1127-1135, 1998.
12. H. Hoppe, T. DeRose, T. Duchamp, J. McDonald, and W. Suetzle, "Surface reconstruction from unorganized points," Proceedings of *ACM SIGGRAPH*, pp. 71-78, 1992.
13. Integrated Vision Products, "*MAPP 2500 Ranger User Manual*," Integrated Vision Products, Sweden, 2000.
14. K. Johnson, A. Curran, D. Less, D. Levanen, and E. Marttila, "MuSES: A new heat and signature management design tool for virtual prototyping," Proceedings of *Ninth Annual Ground Target Modeling and Validation Conference*, Houghton, Michigan, 1998.
15. K. Johnson, A. Curran, D. Less, D. Levanen, and E. Marttila, "MuSES: A new heat and signature management design tool for virtual prototyping (a follow-on)," Proceedings of *Tenth Annual Ground Target Modeling and Validation Conference*, Houghton, Michigan, 1999.
16. S. P. Ketkar, "*Numerical Thermal Analysis,*" ASME Press, New York, 1999.
17. J. H. Lienhard IV and J. H. Lienhard V, "*A Heat Transfer Textbook*," 3rd Edition, Phlogiston Press, Cambridge, Massachusetts, 2004.
18. T. J. Quinn, "*Monographs in Physical Measurement: Temperature*," Academic Press, New York, 1983.
19. Raytek Non Contact Temperature Measurement http://www.raytek.com
20. D. Schmidt, "Techniques for Ensuring Simulation Success," Proceedings of *35th Australian Foundry Institute Conference*, Adelaide, Australia, 2004.
21. K. Srinivasan, Z. J. Wang, W. Yuan, and R. Sun, "Vehicle thermal management simulation using a rapid omni-tree based adaptive Cartesian mesh generation methodology," Proceedings of *HTFED2004,* Charlotte, North Carolina, 2004.
22. I.J. Spiro, *"Selected Papers on Radiometry,"* SPIE Milestone Series, **MS14**, The International Society for Optical Engineering, USA, 1990.
23. Z. Xiao, "A hot calibration load for measuring and controlling temperature," *International Journal of Infrared and Millimeter Waves,* **21**, pp. 1141-1151, 2000.
24. Z. Xiao, "Brightness temperature emitted by radiometer calibration load at millimeter wave band," *International Journal of Infrared and Millimeter Waves,* **22**, pp. 553-569, 2001.