MACHINE VISION-BASED TOOLS

for automotive service and repair

BY DANIEL LAU

Machine vision systems and other visual inspection methods are commonly used in the automotive industry for manufacturing, service, and repair. This article is focused on nondestructive visual testing methods for vehicle service and repair.

Introduction

Auto mechanics and vehicle owners can identify many issues through visual inspection. However, unaided visual inspections that rely on the visual acuity of the inspector may miss problem areas. Furthermore, while unaided visual inspections can often yield qualitative results, quantifying findings without advanced tools can pose significant challenges. For example, although an auto mechanic might recognize that a vehicle is misaligned during a visual inspection, without quantitative inspection tools, it's rare for them to precisely align the vehicle to meet the manufacturer's specifications.

This article focuses on the application of machine-vision systems for identifying vehicle issues and generating quantitative results, which subsequently guide prescriptive repair processes. Automotive mechanics rely on visual inspection for the following:

- **Making an initial assessment.** Technicians start with a visual inspection to get an overall understanding of the vehicle's condition and catch obvious problems such as leaking fluids or damaged parts.
- **Identifying leaks.** By visually inspecting the underside of a car, mechanics can spot leaks from the engine, transmission, brakes, or cooling system. The color and location of the fluid can indicate the source of the leak.
- **Checking wear and tear.** Components such as brake pads, belts, hoses, and tires are checked for wear and tear. Tires, for instance, are inspected for tread depth and wear patterns that might indicate alignment issues.

- **Spotting corrosion.** Rust and corrosion can compromise the structural integrity of a vehicle. Visual inspection helps in identifying areas of corrosion that need to be addressed to prevent further damage.
- **Conducting safety inspections.** Critical safety components such as seat belts, airbags, and lights are visually inspected to verify that they are functioning properly.
- **Examining the engine and exhaust system.** The engine and exhaust components are inspected for signs of damage, corrosion, or unusual deposits that might indicate underlying issues.
- **Evaluating the suspension and steering.** Visual inspection of the suspension and steering systems can reveal issues such as worn shocks, struts, or other suspension components that could affect the vehicle's handling capabilities.

Visual Inspection in Automotive Repair

Auto mechanics use visual inspection to identify a broad range of vehicle issues. Following is a short list of vehicle issues where visual inspection plays a crucial role in both identifying the problem and executing repairs: tire wear and tread depth assessment, detection of vehicle dents, and alignment evaluation. This article will discuss the application of machine vision methods by focusing on these issues and comparing typical inspection processes with and without machine vision systems.

Tire Tread Depth

In the US, the minimum legal tire tread depth is 2/32 in. (1.6 mm). This standard applies to all passenger cars, light trucks, and SUVs. The measurement should be taken in the major tread grooves of the tire and across different points along the tire's circumference to ensure accuracy, as tires can wear unevenly.

VISUAL INSPECTION CAPABILITIES AND LIMITATIONS

The 2/32-in. standard is based on the fact that tires significantly lose their ability to grip the road surface and effectively disperse water as their tread wears down. This increases the likelihood of hydroplaning and accidents, particularly in wet conditions. To easily check whether tires meet the minimum tread depth, the US has popularized the "penny test." Insert a penny into the tread groove as far as possible, with Abraham Lincoln's head facing down (Figure 1); if the top of Lincoln's head remains visible, the tire's tread depth is below the legal threshold, indicating the need for replacement.

Although the legal minimum tread depth is 2/32 in., numerous safety experts recommend replacing tires when they reach 4/32 in. (3.2 mm) of the remaining tread depth, especially for wet driving conditions—and even more so for winter driving conditions—to ensure optimal traction and safety on the road.

In much of the rest of the world, the legal minimum is 1.6 mm (approximately 2/32 in.).

Figure 1. Measuring tire tread depth with a Lincoln penny.

Figure 2. Measuring tire tread depth with a depth gauge.

The penny test is a common method for determining whether the remaining tread depth meets the minimum legal requirement. However, this method is highly dependent on the user. A more robust approach is to use a micrometer or depth gauge (shown in Figure 2).

Because tires wear unevenly, to properly assess if the remaining tread meets local legal requirements, multiple measurements should be taken at various circumferential positions around the tire and along each tread. Care must be taken to ensure that the depth gauge is properly positioned for accurate readings. Additionally, the depth gauge must be calibrated to eliminate any systemic bias that could affect the measurement results.

To determine if a measurement approach can be used to meet a specific requirement, a gauge study, specifically a Gage R&R (Repeatability and Reproducibility) study, should be conducted. A gauge study assesses the measurement system's overall performance via the following factors:

- **Repeatability (equipment variation).** This assesses whether the same operator can get consistent measurements using the same depth gauge on the same tire tread multiple times. Low repeatability suggests that the gauge itself or the measurement process introduces significant variability.
- **Reproducibility (operator variation).** This evaluates whether different operators can achieve consistent measurements using the same depth gauge on the same tire tread. High variability in this area indicates differences in how operators use the gauge or interpret its readings.
- **Overall measurement system variation.** This combines repeatability and reproducibility to assess the total variation introduced by the measurement system, encompassing both the depth gauge and the operators.

We conducted a gauge study on the use of a depth gauge for tire tread measurement and found that the operator contributed approximately 0.039 in. (1.0 mm) to the overall range of measurements for a given tread. Therefore, to ensure that the potential error introduced by the operator (the auto mechanic) does not result in tires worn beyond the legal limit being incorrectly assessed as passing, the pass-fail measurement result must be adjusted to account for this potential error (Figure 3).

To ensure a pass condition with a 95% confidence interval, where the minimum legal tread depth is 2/32 in., and considering the inherent variability in measurements, we must account for the uncertainty in the measurement process. This involves adjusting the nominal pass threshold to accommodate this measurement variability. By doing so, we can be 95% confident that the true tread depth does not fall below the minimum legal limit.

Figure 3. The impact of a visual inspection on the tread depth fail limit.

The calculation entails determining the standard deviation (σ) of a set of measurements and using the Z-score associated with a 95% confidence level. For a 95% confidence level, the Z-score is 1.96. Because the range of measurements is 0.0394 in., if we assume this range represents the total variability (six standard deviations in a normal distribution, as per the Six Sigma methodology), we can approximate the standard deviation as:

$$(1)\quad \sigma = \frac{\text{Range}}{6}$$

To ensure the measurement result meets the minimum legal tread depth with a 95% confidence interval, we adjust the threshold by adding the margin of error (MoE) to the fail criteria. The margin of error is calculated as:

$$(2)\quad \text{MoE} = Z \times \sigma$$

where

Z is the Z-score (1.96 for a 95% confidence level), and

σ is the standard deviation.

To ensure a pass condition with a 95% confidence interval, given a fail criteria of 2/32 in. and a range of measurements of 0.0394 in., the measurement result for tread depth must be at least 0.0755 in. This adjusted threshold accounts for measurement variability and ensures, with 95% confidence, that the true tread depth meets or exceeds the legal minimum tread depth.

While the above approach ensures that the tread of all tires measured with a depth gauge meets the legal minimum, the significant variance in the measurement process means that many tires with tread measurements shallower than 0.0755 in. may actually have true tread depths deeper than the legal limit of 2/32 in. This means that tires with remaining usable life might be discarded unnecessarily.

CURRENT MACHINE VISION CAPABILITIES AND OPPORTUNITIES

Much of the variability in the measurement process is a result of errors associated with visual inspection. Since the auto mechanic positions the depth gauge by eye, their visual acuity and patience are an integral part of the overall measurement process. While a depth gauge is a cost-effective tool, its use for this measurement might not be the most economically sound decision. The economic expense of discarding tires with usable life may outweigh the economic benefits of using an inexpensive depth gauge (or penny) for the assessment.

Tire tread depth can also be measured using 3D imaging approaches that incorporate structured light projection with machine vision systems. Structured light projection systems illuminate the object under inspection with a pattern of light, which can be either static or dynamic (time-varying). Machine vision systems are typically calibrated camera systems that acquire a high-fidelity image of the object under inspection. The most common method of structured light is laser line scanning. Laser line scanning is a simple form: the projected pattern is a line. In a laser line scanning system, a laser line is projected onto the surface of an object, and a machine vision camera captures the resulting image. From this image, the 3D profile of the surface can be determined. By capturing a series of profiles, the surface of an object can be reconstructed as a 3D digital model.

When measuring tread depth using a laser line scanning system, the tread depth can be calculated from the resulting 3D model. This is typically done by creating a reference surface from the tire's contact area (the part of the tire that touches the road) and using this reference surface to calculate the depth of the tread. With a sufficiently detailed 3D model, statistical variations in tread depth can be analyzed. These statistical variations in tread depth can provide valuable information regarding the safety of the vehicle. For instance, the wear pattern across the tire's surface can reveal alignment problems.

Gage R&R measures of laser line scanning systems exhibit significantly lower variances in repeatability and reproducibility compared to those associated with the use of depth gauges by operators. A typical measurement range for a laser line scanning system is 0.008 in. When compared to the earlier depth gauge results, this reduces the guard band from 0.0129 in. to 0.0026 in. (see Figure 4).

Because the resulting pass/fail limit has been reduced to 0.0651 in., compared to the earlier threshold of 0.0755 in., significantly fewer good tires will be discarded.

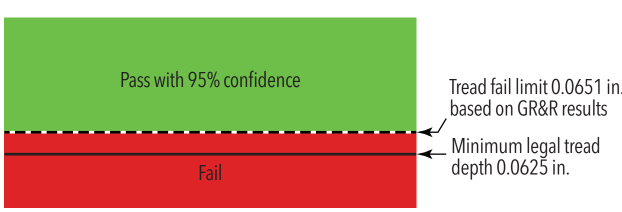

Figure 4. The impact of a machine vision system on the tread depth fail limit.

Figure 5. Laser line scanning system.

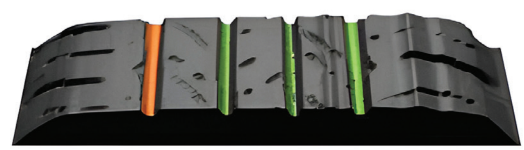

Figure 6. 3D model of a tire with tread depth measurement result.

For this application, the use of a machine vision–based 3D imaging system improves the accuracy of measurement results and reduces the economic waste associated with discarding tires that still have usable life.

Vehicle Dents

The identification and repair of dents in vehicle bodies are almost entirely reliant on visual inspection. Auto mechanics and dent repair specialists depend on their visual acuity to locate dents and determine if the repair has been successfully completed.

VISUAL INSPECTION CAPABILITIES AND LIMITATIONS

Although various techniques exist for repairing dents, we will focus on PDR (paintless dent repair) to illustrate the importance of visual inspection in the dent repair process. PDR is a popular method that typically does not require the removal of body panels or pounding out dents from the interior. Instead, the dent is pulled and pounded from the exterior of the damaged body panel. Dents in metal structures contain areas of both plastic and elastic deformation. To restore the metal to its undamaged

Figure 7. Dent repair: (a) Pulling and (b) pounding the dent.

condition, pressure must be applied precisely to the areas of deformation. Applying the right amount of pressure in the correct location is necessary to achieve a good result.

Applying the right pressure in the right direction along areas of the dent that are above the original surface can relieve the strain in these regions and cause other areas of the dent to move closer to their original, undamaged shape. Similarly, pulling areas of the dent (Figure 7) that are below the original surface has a comparable effect. By combining pressure at high points (dent pounding) with pressure at low points (dent pulling), the auto mechanic can restore the body panel surface to a close approximation of its original, undamaged state.

When repairing a dent, determining when to stop can be challenging. Specialists in dent repair often project lines onto the surface of the dent to aid in this process. By visually observing the lines, they can better estimate when the dent has been removed. Figure 8 shows how line projection is used to assess whether the dent has been removed. While this approach is an improvement over purely visual methods, the final determination of whether the dent has been removed still relies on visual inspection. Factors such as lighting conditions, object reflectance

Figure 8. Using a visual aid for determining the extent of the dent.

Figure 9. A dent repaired using PDR.

properties, inspector fatigue, and inspector visual acuity all influence the outcome. Figure 9 shows an example of a dent repaired using PDR.

CURRENT MACHINE VISION CAPABILITIES AND OPPORTUNITIES

3D imaging tools can create digital 3D models of the surface deformation of vehicle dents. These 3D models can be used to assess the extent of the damage and suggest the appropriate method of repair. Figure 10 shows an example of a 2D and 3D image of a dent on a vehicle.

When the original CAD data is available, the digital 3D model created from the 3D imaging tool can be directly compared to the CAD model. However, in most cases, CAD data is not available. In such instances, mathematical models of the object under inspection can be used to establish a reference surface against which the deformation can be measured. For the dent shown in Figure 10, the extent of the deformation was calculated from the 3D surface data using a

Figure 10. A structured light system for imaging dents.

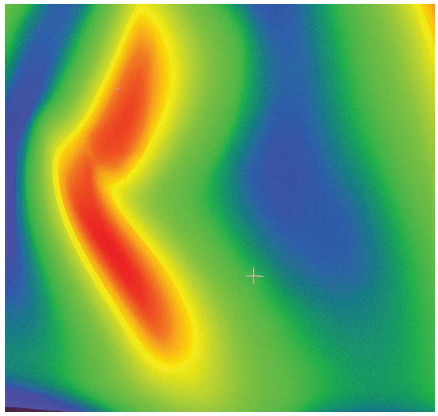

Figure 11. Deformation calculation for the dent shown in Figure 10.

reference surface that was mathematically derived directly from the data. The result is illustrated as a heat map in Figure 11.

Using the 3D data from a dent measurement, various representations can be calculated. A depth map with false color (Figure 11) can be used to identify the high points and low points of the dent, providing the auto mechanic with information to determine where to pound and where to pull on the dent. A more sophisticated approach involves using the dent depth information to calculate the dent strain (Figure 12). Relieving the dent strain is a key part of the PDR process. Deriving dent strain maps from the 3D data facilitates a digital workflow for dent repair. Figure 12 illustrates the locations of strain in a dent along with the dent depth.

3D data on a dent can also be used to generate strain maps, offering more precise guidance on where to pound or pull to restore the body panel to its original shape. Additionally, utilizing 3D data enables the identification of when the dent has been successfully repaired. This approach introduces a mathematical metric for determining dent repair, promoting better consistency among technicians and across various vehicles, taking the guesswork out of dent repair.

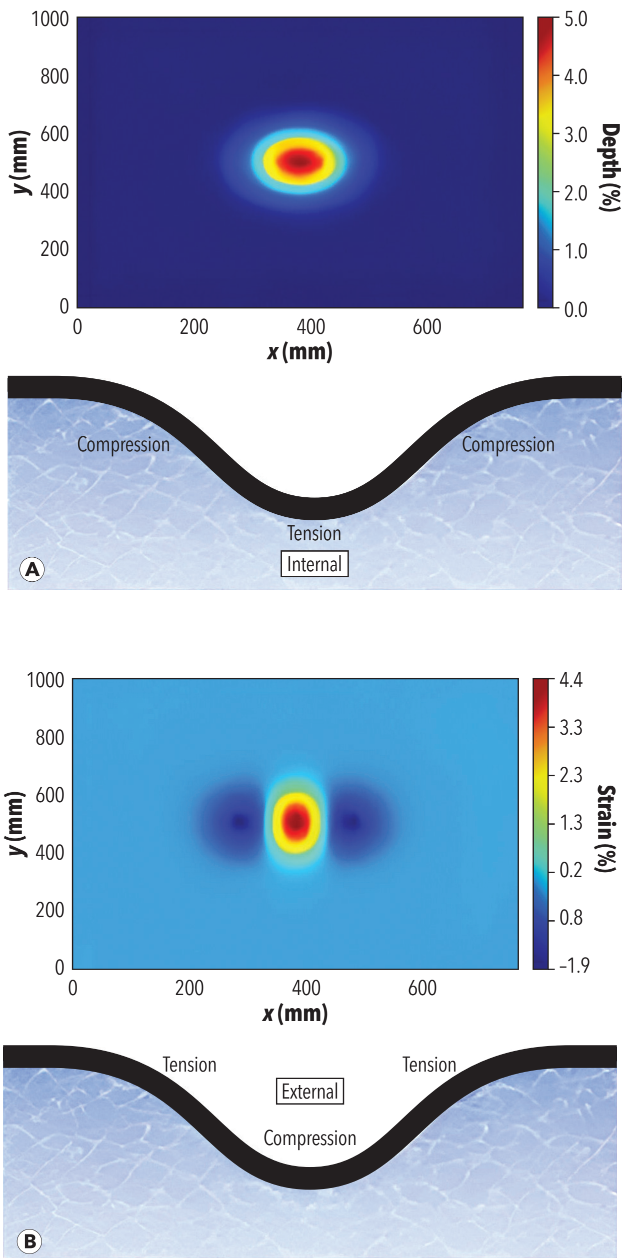

Figure 12. Locations of strain in a dent: (a) dent depth; (b) dent strain.

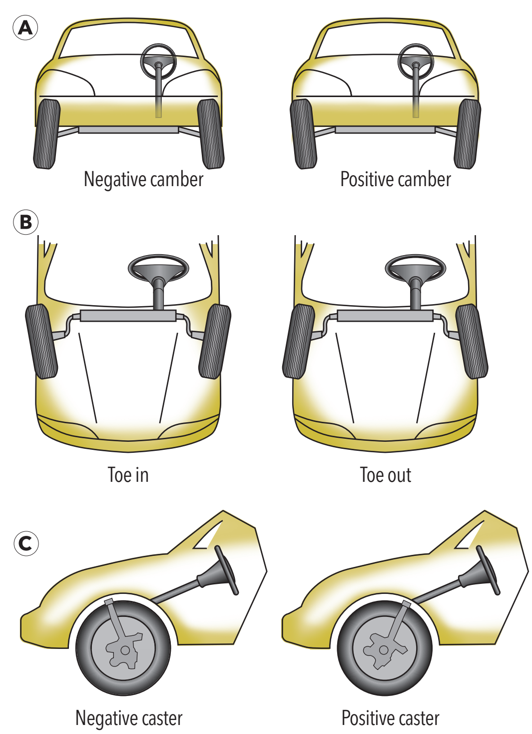

Figure 13. Vehicle alignment parameters: (a) camber; (b) toe; (c) caster.

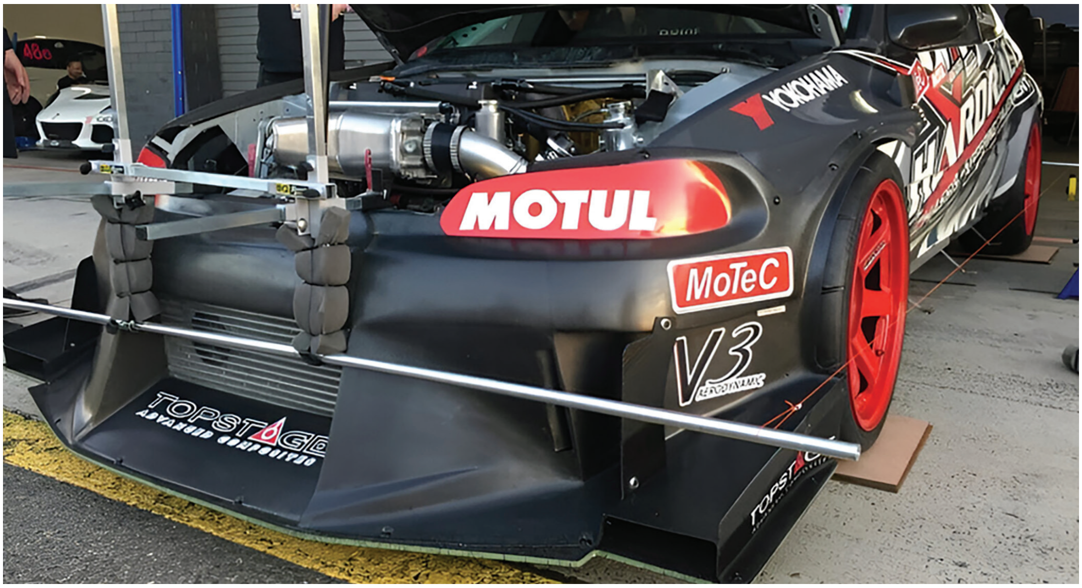

Figure 14. Visual alignment of a vehicle.

Vehicle Alignment

Safe and comfortable driving requires correct vehicle alignment. In addition to affecting safety, improperly aligned vehicles contribute to increased wear and tear. This is particularly evident in increased and uneven wear on tires. The three primary vehicle alignment parameters are camber, toe, and caster (Figure 13).

VISUAL INSPECTION CAPABILITIES AND LIMITATIONS

A well-trained auto mechanic using simple tools (Figure 14) can align a vehicle using visual methods. Following is a typical checklist used for visual inspection for alignment.

1. **Prepare the vehicle.** Ensure the vehicle is parked on a level surface. Check that the tire pressure aligns with the manufacturer's specifications. Make sure there are no heavy items in the trunk or elsewhere that could impact the vehicle's stance. The vehicle should be in a neutral position, with the steering wheel centered.
2. **Inspect the tire condition.** Look for signs of uneven tire wear. Uneven wear on the inside or outside of the tires may indicate misalignment.
3. **Check the wheel toe alignment.** The "toe" refers to the angle of the wheels relative to the vehicle's centerline. Stand in front of the vehicle and look at the front wheels. They should appear parallel to each other and aligned with the car's body. Repeat the process from behind the vehicle, checking the rear wheels.
4. **Examine the camber angle.** The camber is the tilt of the wheel. When looking at the vehicle from the front or back, the wheels should be perpendicular to the ground. A visible tilt inward (negative camber) or outward (positive camber) could indicate a problem.
5. **Observe the steering wheel position.** Sit in the driver's seat and check if the steering wheel is centered when the wheels are pointed straight ahead. A misaligned steering wheel while driving straight can indicate alignment issues.
6. **Check the suspension components.** Inspect the suspension components for any signs of wear or damage. Worn parts can affect wheel alignment. Accurate measurements of toe and camber can be achieved by establishing reference points using string and a straight pipe (Figure 14). Key alignment parameters can be measured using these reference points, a tape measure, and a level. While the cost of the alignment tools is minimal, the procedure largely relies on visual inspection and requires a well-trained mechanic.

CURRENT MACHINE VISION CAPABILITIES AND OPPORTUNITIES

Currently, there is a shortage of well-trained mechanics, and frequent turnover at automobile service and repair shops increases training costs while diminishing the productivity of mechanics employed by these businesses. For automobile service and repair shops specializing in vehicle alignment, tools are required to enable mechanics with minimal training to perform the complex task of aligning a vehicle. Machine vision–based tools (Figure 15) automate the vehicle alignment process and generate digital records.

Using machine vision-based alignment tools eliminates the error associated with visual inspection. The standard deviation for a typical machine

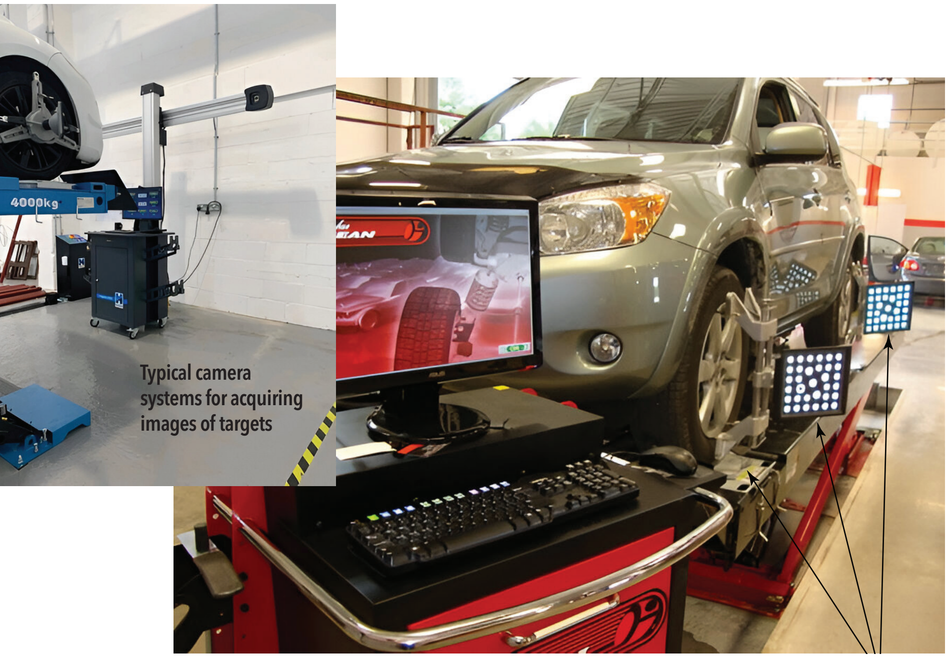

Figure 15. Tools for performing a machine vision–based alignment of a passenger vehicle.

vision–based system, for toe and camber measurements, is typically around 0.02 degrees. Achieving this level of accuracy through purely visual inspection is extremely challenging. Additionally, because the workflow is embedded in software, technician training requirements are reduced. The process is guided by the software, ensuring accurate results. Figure 16 shows results from a commercially available machine vision–based wheel alignment system.

A machine vision–based wheel alignment system calculates the orientation of the wheels by analyzing the alignment markers attached to each wheel. Typical results, along with the acceptable range for the specific vehicle under test, are shown in Figure 16. For instance, the camber specification includes a minimum of –1.75, a maximum of –0.25, and a preferred value of –1.00 (all values are in degrees).

Conclusion

For many years, automotive mechanics have relied on visual inspection to perform a variety of tasks, including tire inspection, dent repair, and wheel alignment. Visual inspection is crucial for determining whether tires need to be replaced, identifying and repairing dents and other damages in collision shops, and assessing vehicle alignment by auto mechanics. However, purely visual methods are susceptible to errors. Limitations in visual acuity, inadequate lighting, fatigue, and other human factors contribute to errors in visual inspections. These errors can range from minor, such as overlooking a small dent, to major, such as inaccurately assessing vehicle wheel alignment or tire tread depth.

Machine vision–based methods establish standard inspection and repair processes, mitigate measurement errors, reduce training requirements, and improve the overall efficiency of vehicle inspections and repairs. Today, automotive shops have access to a variety of machine vision–based tools. These tools include both 2D and 3D imaging for almost all aspects of vehicle inspection and repair that were previously done through purely visual techniques. As vehicle manufacturers continue to integrate advanced technologies into automobiles, the demand for advanced machine vision–based tools will increase. For instance, new tools are required to meet the need for calibration and repair of ADAS (Advanced Driver Assistance Systems) and other autonomous or semi-autonomous technologies. ME

AUTHOR

Daniel L. Lau, PhD: Databeam Professor and Certified Professional Engineer, Department of Electrical and Computer Engineering, University of Kentucky, Lexington, KY; dllau@uky.edu

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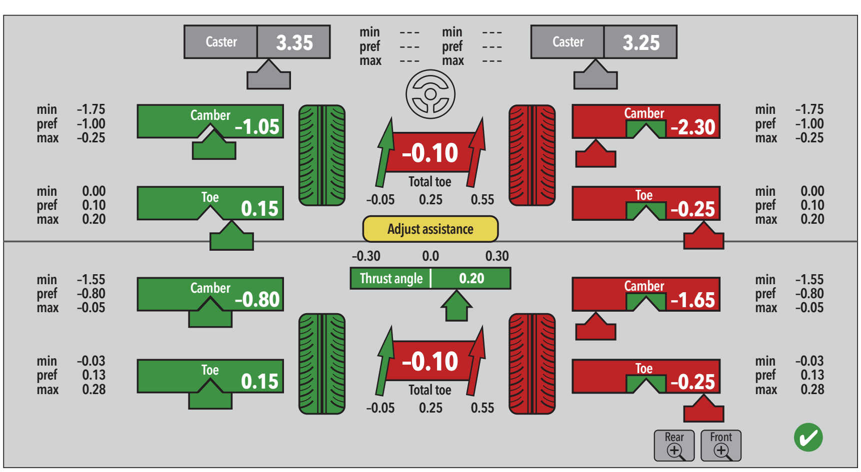

Figure 16. Typical measurement results from a machine vision-based wheel alignment system.

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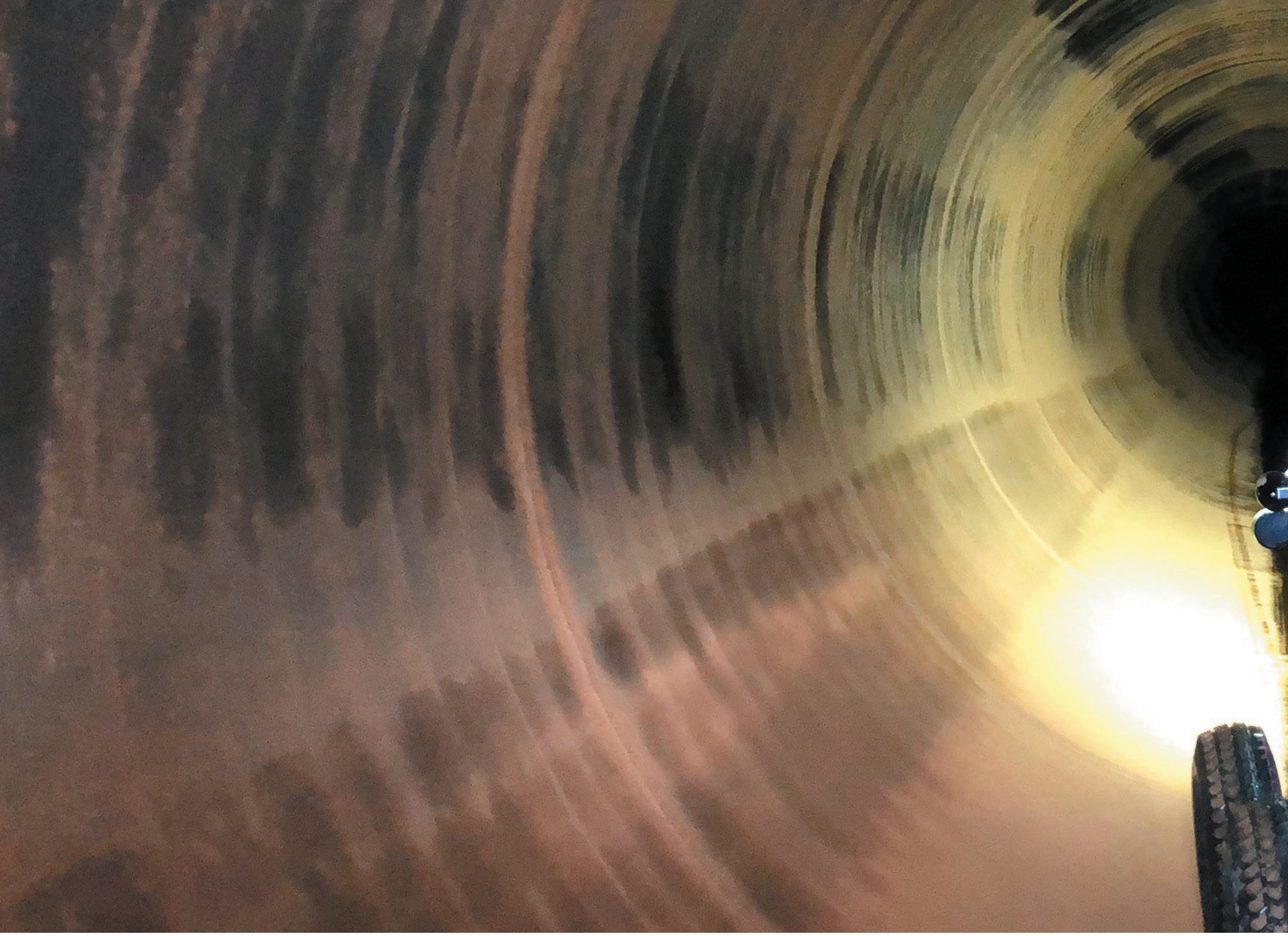

ROBOTIC CRAWLERS

BY RON KESSLER

Modern robotic crawlers provide a means of safe and effective remote data capture, reducing confined space entries, minimizing data collection times, enhancing inspection data quality, and optimizing overall inspection spend.

Introduction

Direct visual testing (VT) is a nondestructive testing method utilized for surface inspection and evaluation. The specifications of direct visual inspection are defined as placing the eye within 24 in. (600 mm) of the surface to be examined, at an angle of not less than 30°, supported by a white light source with a minimum intensity of 100 fc (1000 lux). For many industries, direct VT presents formidable challenges, as the costs to access the examination area are prohibitively expensive and