Innovations Deserving
Exploratory Analysis Programs

Transit IDEA Program

Handheld Wheel Flaw Detection Device: Noncontact Electronic Wheel Gauge (NEWG)

Final Report for
Transit IDEA Project 72

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ABSTRACT

International Electronic Machines (IEM) proposed the development of a handheld, self-contained Noncontact Electronic Wheel Gauge (NEWG) to address limitations in current-art methods for measuring and tracking relevant aspects of transit wheels. Stage 1 demonstrated the feasibility of this approach, and IEM proceeded to Stage 2.

During Stage 2, IEM built upon the specifications and concepts determined in Stage 1 and produced a complete prototype design for the NEWG. During the same period, IEM also modeled and tested the algorithms and software needed for calibration, data acquisition, and processing. IEM then constructed a prototype and tested it, refining physical designs, producing methods for proper use and pose feedback, creating a custom multiplexer for data acquisition, and determining control and user interface design. IEM presented the results of the Stage 2 work to the Transportation Research Board (TRB) at a Washington meeting.

Overall, the Stage 2 work was successful and the NEWG is clearly both technologically practical and needed by the industry. IEM identified specific aspects of the gauge, including dealing with specular reflections, calibration/measurement accuracy improvement, and verification of diameter measurement that would be important development aspects in the final design.

KEYWORDS

Noncontact measurement, transit, wheel measurement, 3D metrology, handheld gauge

EXECUTIVE SUMMARY

As current-art solutions to complete wheel measurement and maintenance have proven inadequate, International Electronic Machines (IEM) proposed the development of a handheld, self-contained Noncontact Electronic Wheel Gauge (NEWG), deriving from IEM's prior work with both handheld wheel gauges and noncontact metrology. During Stage 1, IEM completed initial work on the NEWG and determined that it was feasible and practical to create such a device that would meet all industry requirements. Accordingly, IEM proceeded to Stage 2, in which a prototype would be constructed and tested.

Work performed in Stage 2 took place in five separate tasks:

- *Task 6: Design Prototype Noncontact Electronic Wheel Gauge*
- *Task 7: Instantiate and Test Selected Algorithms*
- *Task 8: Test Prototype and Refine Design*
- *Task 9: Final Test and Demonstration*
- *Task 10: Project Management and Reporting*

During Stage 2, IEM used the specifications, theoretical work, and component selections from Stage 1 in designing a prototype NEWG. This included the design of a core optical frame (for support and the maintenance of precise relationships between the optical components), concepts for pose indication during use, an exterior casing and mounting for all components including display screen, and basic external controls.

IEM also performed extensive modeling and testing of algorithms for accurate measurement of the wheel parameters. These were initially derived from IEM's prior profilometer and rail-based wheel gauge software, but then generalized for overall measurement and refined for this particular application. In addition, IEM had to develop sophisticated calibration approaches because of the variability of the key component designs. This work also included additional components of the measurement software that took advantage of the multiple lines projected, and multiple images acquired, to produce much more accurate measurements.

With the basic design and software completed, IEM was able to construct an initial prototype and test it to first verify general performance and then determine what changes or adjustments needed to be made to the software or hardware for the final prototype. The overall capability of measurement was demonstrated in the laboratory, as was the performance of all subsystems. Additional modifications for final calibration were determined based on the actual performance of the prototype. A revised design was developed that incorporated several possible indicators of pose feedback for the user.

IEM also developed a custom multiplexer board to allow high-speed, simultaneous image acquisition from the two separate cameras, when it became clear that the cameras and selected image processor were not capable of this on their own. Other issues were traced to the software drivers used for the cameras, and new drivers were explored.

IEM presented the work on the NEWG to the TCRP J-4 panel at a meeting in Washington. The work was met with considerable interest and from this meeting additional contacts in key areas were made.

Overall, the Stage 2 work proved the practicality and effectiveness of the Noncontact Electronic Wheel Gauge as described here and in prior reports. There is direct industry interest in the NEWG and IEM intends to continue development of the NEWG into a product for use in rail and potentially other industries. IEM determined three key areas—specular reflection causing image glare, refinement of calibration and measurement calculation, and improvement of diameter calculation methods—which bear further research and development work to reach the full performance levels in the specifications. It should be noted that even without these key areas, the NEWG still exceeds all existing gauges in its accuracy of measurement, at under one one-hundredth of an inch.

1. NEED FOR A NONCONTACT ELECTRONIC WHEEL GAUGE

OVERVIEW

Transit vehicles have specific needs and concerns in wheel maintenance and measurement that differ in some ways from those of standard freight. Wheel condition affects both *ride quality* and *safety* and must be carefully monitored. While the profile of a wheel is of interest to either type of rail, for the purposes of transit agencies the *diameter* measurement of the wheel is paramount (especially in certain types of drive systems, where mismatched diameter wheels can cause severe damage). In addition, transit authorities have frequently mentioned the desire to obtain the *flange angle*, which is an even more critical aspect of the wheel for transit purposes than it is for freight rail due to the type of rail, angle of turns, and repetition of routes followed by transit agencies.

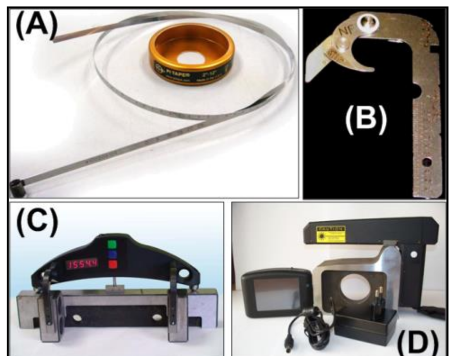

FIGURE 1 (A) "Pi Tape" for wheel diameter measurement; (B) AAR finger gauge for measuring wheel dimensions; (C) Riftek diameter gauge; (D) Riftek wheel profilometer.

PROBLEMS ASSOCIATED WITH CURRENT PRACTICE

The American Public Transit Association (APTA) describes basic measurement/ maintenance requirements (*1*), but aside from a few general descriptions such as the use of a "pi tape" and reference to "specialized gauges," *there are no absolute requirements prescribing the equipment to be used*. Figure 1 illustrates some current-art devices in use. The use of the pi tape in the field, however, requires the wheel to be jacked up off the rail. The finger gauges have been shown to be of variable accuracy as used, cannot supply diameter or flange angle, and both devices suffer from multiple chances for human error. The Riftek gauges reduce human error, but are expensive, relatively delicate instruments. In addition, all of these devices share the limitation that *they must be applied physically* in a very precise manner to the wheel to assure accurate measurement. This requires the operator to kneel or bend, and insert his/her entire hand into the wheel area, which *may be a very tight space*—especially for *transit* vehicles.

Overall, the problems associated with current practice in wheel measurement may be summarized as follows:

- **Economic.** The errors or deficiencies in current-art lead to several problems/limitations:
  - *Predictive maintenance approaches are essentially excluded from use*, as the variation in hand-measurement is generally greater than the rate of wear between individual measurements. Multiple studies have shown that using predictive maintenance techniques can reduce maintenance costs by 50% or more.
  - *Inaccurate measurements lead to unnecessary loss of service metal*. IEM studies at Class 1 railroads showed that standard practice of rounding and truing led to the loss of an extra 1/16th of an inch of service metal per true; given the tolerances and wheel designs present in transit cars, the conservation of service metal may be even more important.
  - *Necessity of redundant measurements.* In order to verify the need for wheel truing, it is usually necessary to take additional wheel measurements prior to truing. This can take 20 minutes per vehicle or possibly more, and thus for every three redundant measurements there is a loss of at least one work hour. If each wheel has only one redundant measurement per year (and IEM's research indicates this is an extremely conservative estimate), then a transit agency with approximately 9,000 wheels (a median number for large transit agencies—very large transit authorities such as NYC may handle five times that) is losing at least 3,000 man-hours on redundant measurements.
- *Safety*. Current practice leads to a significant number of accidents caused by wheels that were unfit for service, but which would not have been in service if properly measured in the prior inspection period. The cost of such accidents is millions of dollars annually. Inspectors are also prone to minor injuries during inspection, having to bend, stoop, reach, and twist, and put hands into locations

where there are potentially sharp edges and so on. While most such injuries are insignificant on a daily basis, over the long term and tens of thousands of wheels the cost becomes appreciable.

- *Environmental*. Improperly maintained wheels significantly reduce ride quality and increase local noise pollution. Similarly, such wheels increase the effort required to pull the train, causing the waste of significant amounts of energy, which means extra emissions in the air (even electrical-based transit systems obtain their power ultimately from polluting primary sources).

2. SOLUTION: PORTABLE NONCONTACT ELECTRONIC WHEEL GAUGE

IEM'S APPROACH

IEM performed Stage 1 of the development of a Noncontact Electronic Wheel Gauge (NEWG) which, when completely developed, would offer the *functionality of diameter gauge and profilometer in a single, noncontact, one-hand operable package* that will be lighter, much faster, more affordable, and vastly more versatile than any other device currently on the market. IEM's Stage 1 work demonstrated the feasibility and practicality of developing a NEWG offering multiple unique features, including:

- **Portable, integrated, easy-to-use unit—**no cables or other ancillary components.
- **High-accuracy, single-action measurement** of all aspects of a wheel.
- **Take measurements of wheel from any accessible angle—**bottom, side, top.
- **Work with any size wheel for rail transit, freight, or high-speed rail.**
- **Visible, audible, and tactile feedback** on successful measurement.
- **Automatically compares measurements to updatable table** of standard re-true/ condemn limits and alerts if action needed.
- **Stores all data onboard until downloaded** (assures no loss of data).
- **Transmit data wirelessly or through wired connection** to central data collection.
- **Multiple other applications**
  - ***Can be configured to measure many other objects*** in field of view—rail, brake components, etc.
- **Increase safety, comfort,** and **efficiency,** and **reduce costs.**

BASIC PRINCIPLES OF NEWG OPERATION

The *core concept* behind the Noncontact Electronic Wheel Gauge is simple: create a *portable, hand-usable version of our in-ground measurement systems*. Those systems, in turn, were created based on one of the oldest measurement principles, triangulation. IEM's unique innovations were in applying three-dimensional (3D) laser-based triangulation, also called laser-based metrology, to railroad components. IEM's patents 5,636,026 and 6,768,551 directly describe and address this process, which was originally invented and patented in more broad terms by IEM staff. The 3D laser triangulation scanner is an active scanner that uses laser light to probe the environment. In operation, structured light (curved or straight sheets of light that can produce points, lines, circles, etc. when projected on a surface) is directed at the object to be measured.

In Figure 2, a single point is projected onto the object to illustrate the concept. It can be shown mathematically that for every point of the object on which the laser point falls, there is a unique location in the field of view of the imaging device where the image of the point will be recorded. Further, if the object is moved by *DZ*, the image of the point in the image plane is moved by *DZ.* Thus in its simplest form a point triangulation gauge can be used to measure distance or displacement. This technique is called triangulation because the laser dot, the camera and the laser emitter form a triangle. The length of one side of the triangle, the distance between the camera and the laser emitter is known. The angle of the laser emitter with respect to the imaging axis is also known. The angle of the camera axis can be determined by looking at the location of the laser dot in the camera's field of view. These three pieces of information fully determine the shape and size of the triangle and gives the location of the laser dot of the triangle. In most cases a laser line, projected as a sheet of light from the laser instead of a single laser dot, is swept across the

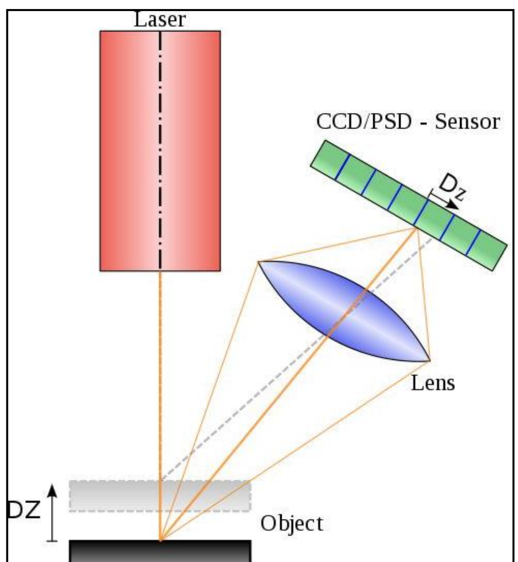

FIGURE 2 Basic principle of 3D Structured Light metrology (advanced triangulation).

object to speed up the acquisition process, enabling a 3D dimensionally correct model of the object to be generated.

Advantages of NEWG Approach

The major known competitor product, the Calipri gauge, involves a measurement head connected to a large, shoulder-slung processor/datalogger unit. This is a design IEM used for our first portable electronic wheel gauge, and the connection proved to be the single greatest point of failure in the entire system. IEM, therefore, sees it as essential that the NEWG performs all functions in a single unit, requiring neither contact with the wheel or the operator placing his/her hands in the wheel space, and do this with a single placement and measurement of the device. *To achieve this, IEM intends to use one of the other most well-established means of disambiguating image data:* stereo image measurement.

The combination of triangulation and stereo measurement allows the NEWG to accurately, quickly, and reliably determine all relevant wheel measurements with little-to-no additional information.

IEM's Criteria for a Portable Noncontact Electronic Wheel Gauge

IEM's Portable Wheel Flaw Detection Gauge must offer more performance than any current-art device while overcoming their shortcomings. Therefore, it should:

- **Feature single-unit construction**. No connected controller/datalogger units.
- **Obtain all needed measurements in a single pass**. Diameter, flange angle, and other measurements should not require any additional passes. One wheel, one use.
- **Store all measurements on board for wired or wireless transfer when feasible**. The use of the NEWG should not be dependent on maintaining a physical or wireless connection during measurement.
- **Require minimal special training to use**.
- **Survive all rail yard environmental conditions**.
- **Provide a user-friendly interface**.

- **Be highly reliable**.

3. SUMMARY OF STAGE 1 WORK

Work performed in Stage 1 was divided between five separate tasks:

- *Task 1: Capabilities and Requirements Specification*
- *Task 2: Model System Performance and Capabilities*
- *Task 3: Determine Needed Algorithmic Approach*
- *Task 4: Produce Base Component Performance Specifications*
- *Task 5: Select System Components*

During Stage 1, IEM determined performance specifications for the NEWG, including measurement, environmental, and physical capabilities. IEM modeled the system extensively and determined what performance could be expected, as well as the core methods for measurement that would be used for the NEWG.

IEM then determined the core algorithmic approaches needed to perform the selected methods. This included determining number of laser lines and orientations for best analysis, and determining both theoretical and experimental values of error to be expected from handheld operation of the NEWG in the field. It was shown that normal use of the NEWG should not produce accelerations/movement that would be significant to the collection of the desired images. IEM also determined a basic solution to achieving mil-scale accuracy with the imagery available.

With these aspects of the NEWG project completed, IEM was able to create detailed requirement specifications for the key components of the NEWG, including the cameras and lasers. IEM was then able to research and select components that met or exceeded all of these key specifications. Initial modeling was also done on physical designs for the NEWG itself and testing began on the selected components.

Overall, the Stage 1 work demonstrated that it was both feasible and practical to create the NEWG as described. All of the physical components were available and the tolerances desired were shown to be achievable, and IEM determined the algorithmic approaches to be used to achieve real-time measurements with such a device. Based on these results, IEM moved forward with Stage 2 of the NEWG project.

4. RESULTS OF WORK

Overview

In Stage 2 of the NEWG project, the work was also divided up into five separate tasks. These tasks were:

- *Task 6: Design Prototype Noncontact Electronic Wheel Gauge*
- *Task 7: Instantiate and Test Selected Algorithms*
- *Task 8: Test Prototype and Refine Design*
- *Task 9: Final Test and Demonstration*
- *Task 10: Project Management and Reporting*

The work performed on all of these tasks is detailed below.

Task 6: Design Prototype Noncontact Electronic Wheel Gauge

In this task, IEM began the work of designing the initial prototype of the NEWG, based on the specifications developed previously (Appendix A). This prototype was intended to test the actual workings of the selected components in the configurations required by the real system, although it was not expected to be a complete or finalized version. Developing such a design requires multiple iterations to arrive at a functional, reliable, rugged, and usable device.

The prototype design was based on the single-unit-with-handles design shown in the Stage 1 report, and reproduced here as Figure 3. The advantage of this basic design is that it is reasonably compact and easy to use overall. It is expected a final physical design will be determined after real-world testing with actual railcars.

The key mechanical component to the NEWG design is the *optical frame*—the core supporting component that serves as the mounting substrate for the optical components (lasers and cameras) and assures that all these components remain in proper alignment with each other. IEM therefore first modeled (Figure 4) the optical frame, including the selected imaging and laser line generators as components.

FIGURE 3 Conceptual design for NEWG (CG model).

The optical frame seen in Figure 4 is a single piece of rigid polymer, with sockets specifically tailored to the laser and camera components. Once these components are fixed in the sockets and calibrated, the frame will maintain their relative positions.

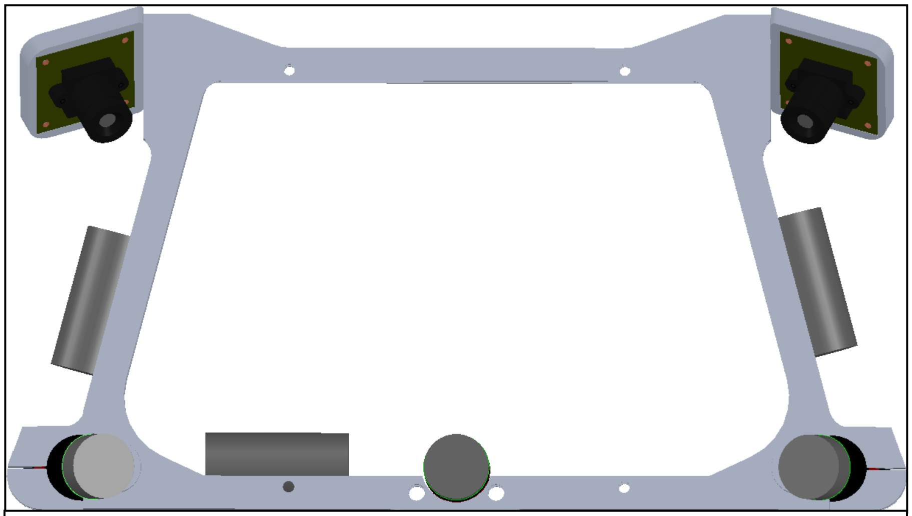

FIGURE 4 Model of optical frame with components.

Once IEM had obtained all of the selected components and had assured ourselves of their basic functionality, IEM manufactured a prototype of the optical frame and installed these components on it, as shown in Figure 5. Figure 5 also shows the display screen and part of the data processing framework.

The screen was placed on the interior surface of the prototype for several reasons. It is actually better protected on the interior rather than on the exterior of the unit, and the

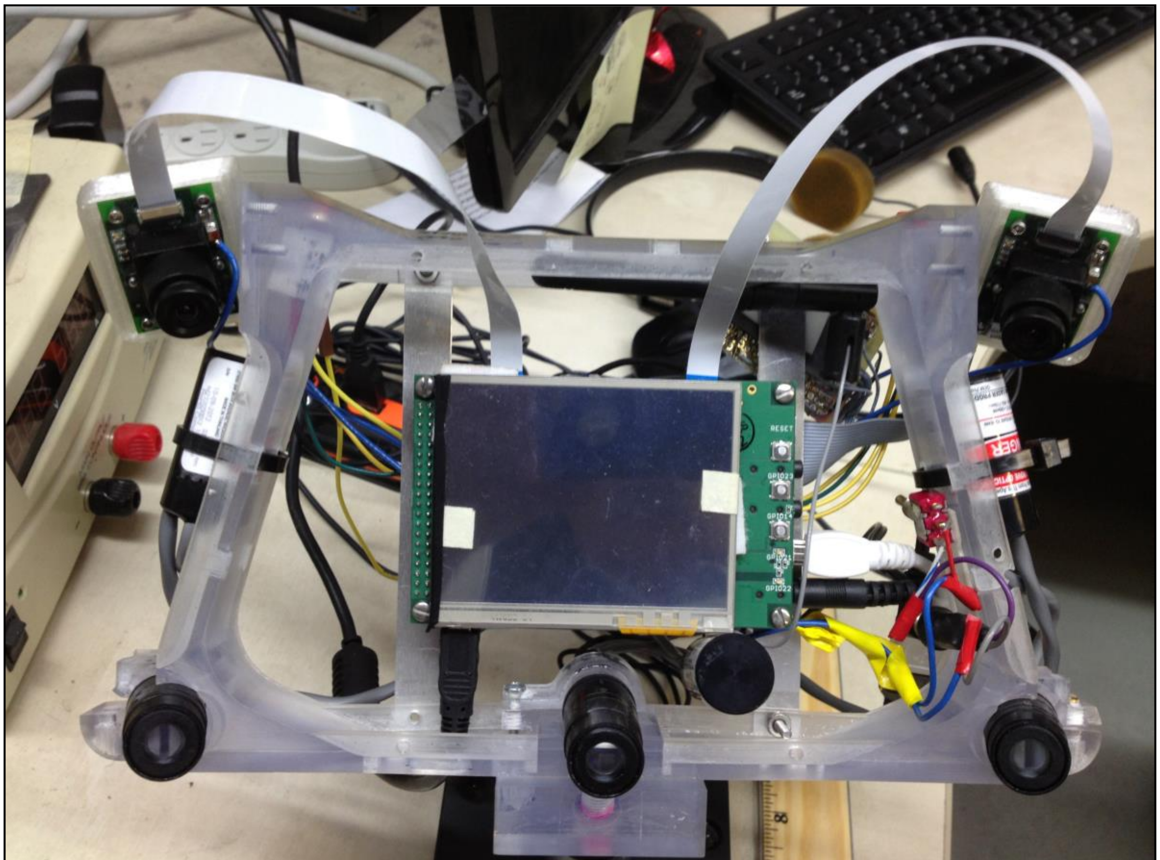

FIGURE 5 Prototype optical frame with all components installed.

screen itself is not needed for taking measurements. A separate interface was to be used for that. Given the design of the overall frame, it would actually be easier to hold and operate the screen-based menus from this position, as well.

When the NEWG is in use, the images must be taken within a reasonably close approximation of face-on to the wheel—not tilted too much in any direction—or the resulting images will be too distorted to be useful. This was discussed in the Stage 1 report, as was the ability to sense this pose information, and whether it was feasible for a human being to meet the needed stability (it was).

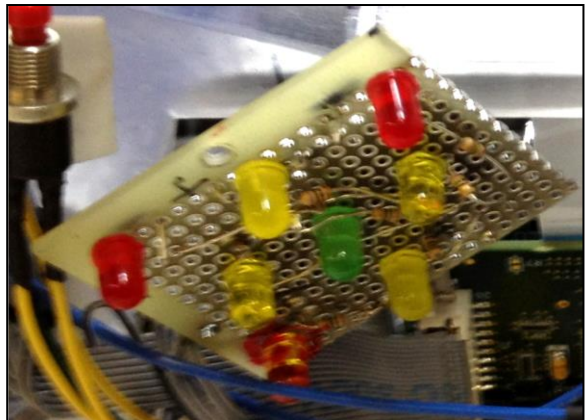

FIGURE 6 Prototype pose indicator array.

It was thus important to provide some means for the NEWG to guide the user to properly hold the unit and pass it across the wheel. IEM examined several possible interface methods, and for the initial prototype settled on a matrix of light-emitting diodes (LEDs) that would indicate departure from acceptable (a few degrees) in any direction. Figure 6 shows the breadboard prototype for this, mounted on the back of the frame seen in Figure 5. The top rear corner of the unit should be reasonably consistently visible to the user. In the final design, two such indicators would be expected, one on each side, as which side the user will be holding will vary depending on which side of the train they are on.

The optical frame and other components must of course be contained within an enclosure that provides further support, structure for mounting the other components, and protection for all operating components. Figure 7 shows the prototype enclosure manufactured for the initial development and testing.

With the structure completed and all components acquired and installed, IEM was ready for testing the general operation of the prototype (and, following the completion of Task 7, for testing its actual measurement capabilities).

Task 7: Instantiate and Test Selected Algorithms

The algorithms for measuring the dimensions of the target wheel depend strongly on the pattern selected. Based on modeling and tests of various patterns, IEM eventually selected a three-laser pattern with the two side components projecting a horizontal (cross-wheel) three-line set, and the central component projecting a vertical (along wheel face) three-line set. The three sets of lines would provide both measurement data and additional

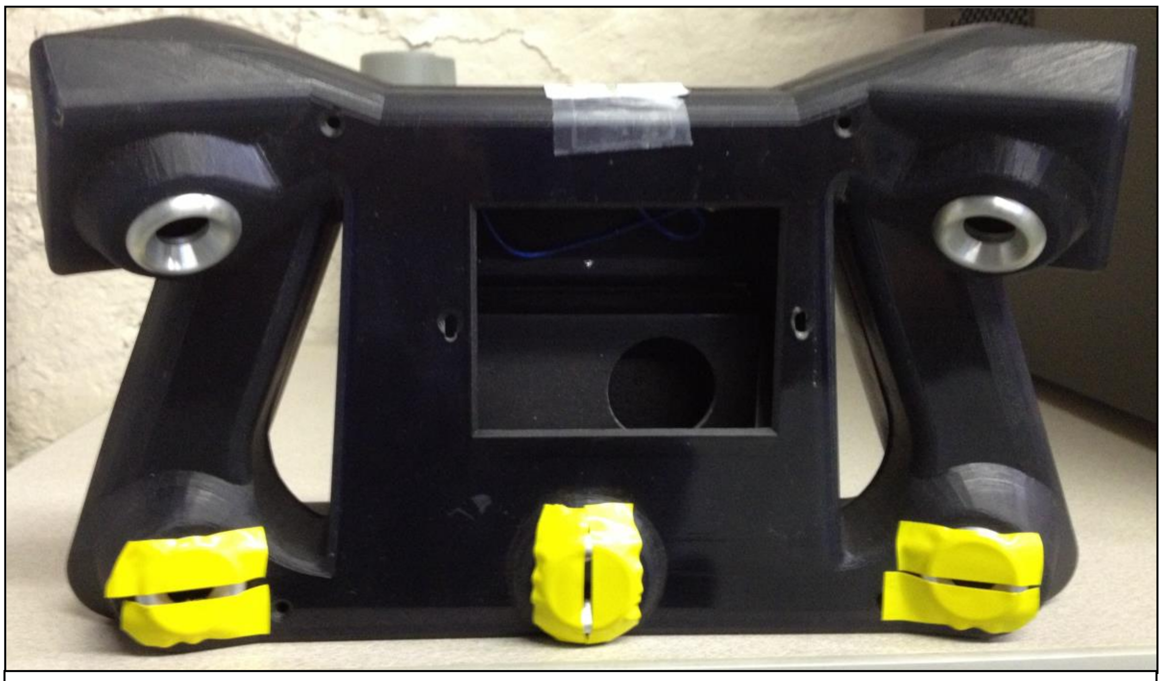

FIGURE 7 Enclosure for prototype NEWG.

range and pose information through the precise spacing, intersection, and divergence of the different sets of lines.

At the expected 30 fps (frames per second) data speed, multiple usable frames would be expected to be taken as the NEWG was passed by the wheel. Figure 8 shows a series of such frames, all of which provide sufficient data for wheel measurement. This would allow the NEWG to perform multiple measurements of the wheel in a single pass, and average those to reduce error and increase precision.

It is also worth emphasizing that the combination of the three-line based pattern and the multiple images has a very powerful effect on the measurement. Each image pair of images provides three independent measurements of the key features. Thus, the total number of measurements provided by, for example, five image pairs, is 3x5 or fifteen measurements. Averaging multiple measurements increases overall accuracy by the

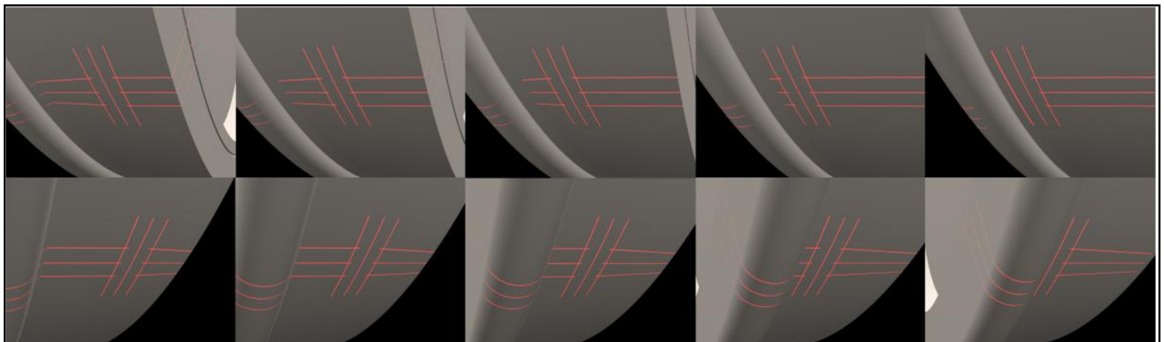

FIGURE 8 Sequence of modeled images taken by a single pass across the wheel.

square root of the number of measurements, so in this case the accuracy of measurement is increased by nearly four times; measurement accuracy increases by at least three times with only three image pairs. This allows the NEWG to reach the high accuracy levels demanded by transit agencies.

IEM developed software that was able to verify that images were acceptable—not too distant, not too tilted in one axis or another, and complete with respect to the ability to provide good measurements of all target parameters, as well as algorithms and software to specifically compensate for variation within the previously determined acceptable limits (±5 degrees) and then to compute from the visible lines the actual profiles of the target wheel. Figure 9 shows a "nominal" image pair based on these guidelines.

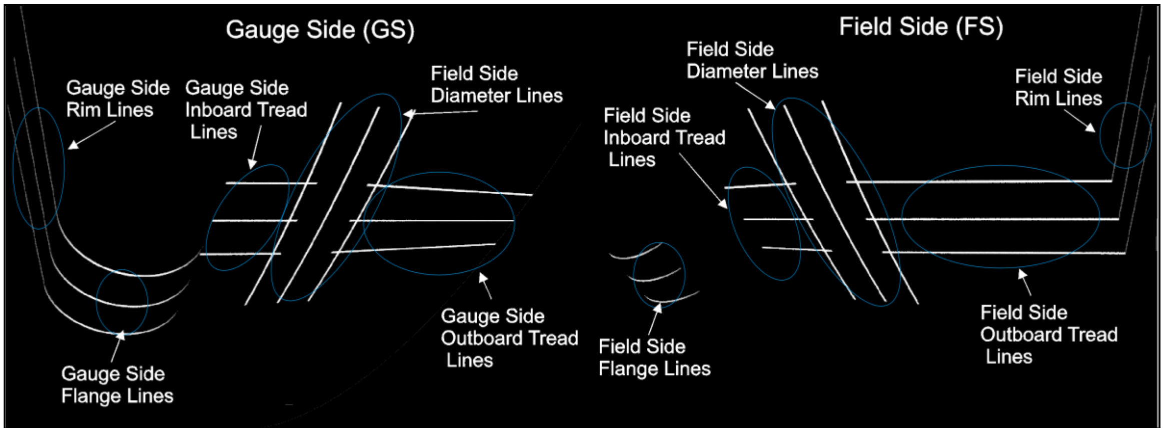

FIGURE 9 Nominal image pair for NEWG profile analysis.

For the main software components, development required considerably more extensive work. The key performance requirement for NEWG was the ability to accurately measure all relevant parameters of a transit (or, potentially, freight) wheel in a single pass. As mentioned earlier, this was based on IEM's prior work on wheel measurement, and as the approach in question was an image-based measurement one, the starting point was IEM's MATLAB-based code for our in-ground wheel systems. This had to be examined in detail and revised.

The major reason for revisions and updates was the discovery of unexpected assumptions or defaults that rendered it difficult or impossible to transfer to a different application. In the early development of the code, in-ground operation was assumed, and it turned out that a number of convenient assumptions with respect to orientation, alignment of hardware, and other aspects of the system were built into the original rail-based wheel gauge code. IEM had to remove these assumptions and replace them with fully functional code that allowed for all possible changes in the distances, angles, and equipment involved.

Following this translation, IEM had to "port" the software from MATLAB to OpenCV code, as MATLAB code is not reasonable to run on a miniature high-speed measurement device. This, itself, proved somewhat challenging, as MATLAB (being a specialized modeling/prototyping tool for engineering and scientific software) has numerous easily used function calls that do not exist in OpenCV—and which are quite nontrivial functions. IEM had to create these functions during the "port" process.

Calibration of the overall system was the next requirement. It too was significantly challenging, not because of basic conceptual issues, but because of real-world limitations. The cameras available for the NEWG's operation are very small, low in power, high in resolution, and so on, but in order to achieve many of these things they have been minimized in other areas. The cameras and their lenses are merely fastened to a circuit board via screw mountings, which may be tightened in varying degrees. This means that their alignment—in any axis—may be off by an unknown amount, and likely by more than is accounted for in standard calibration approaches.

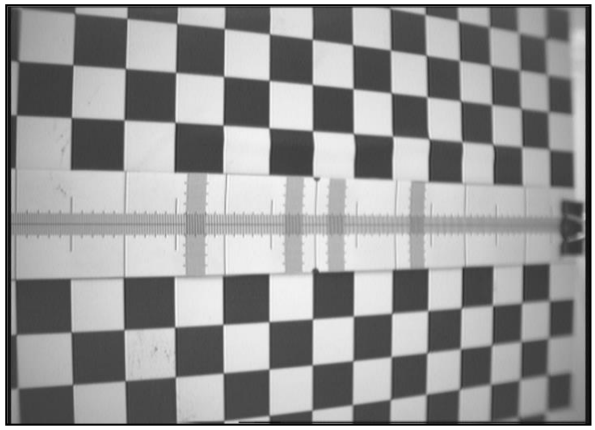

FIGURE 10 View of calibration target from one NEWG camera.

Examination of the units showed that the lenses available for these cameras (and any other likely candidates) were considerably lower in quality than those used on larger and more expensive cameras. IEM therefore had to create software to quantify the precise characteristics of each camera-lens subsystem before any actual calibration software could be written and tested.

Major challenges to the calibration itself lay in the fact that this application involved wide fields of view with significant barrel distortion, operating at very close range. IEM was, however, able to devise a calibration image and pattern specifically tailored for this type of optical design, as seen in Figure 10.

As actual calibration was tested, however, it emerged that there was another significant issue that had been previously unnoticed in the design; specifically, that the two cameras were mounted so as to point along converging lines in the direction of the target. While the actual measurements to be derived are not, technically, stereo vision measurement, the calibration of the cameras to allow the disparate images to be properly mapped for the NEWG's operation is equivalent to stereo camera calibration and alignment, and it turned out that the most available calibration suites all incorporated the assumption that the two stereo cameras were mounted with parallel axes, not inward-looking. IEM had to devise a more general calibration method and find software compatible with this method.

All software was tested with synthetic imagery generated by POVRAY and tailored to present a realistic profile of a railroad wheel under all conditions.

TASK 8: TEST PROTOTYPE AND REFINE DESIGN

General Results

With the prototype constructed and basic software available, IEM began tests of the initial prototype. Figure 11 shows the original prototype in the process of acquiring images from an actual railroad wheel as part of the testing.

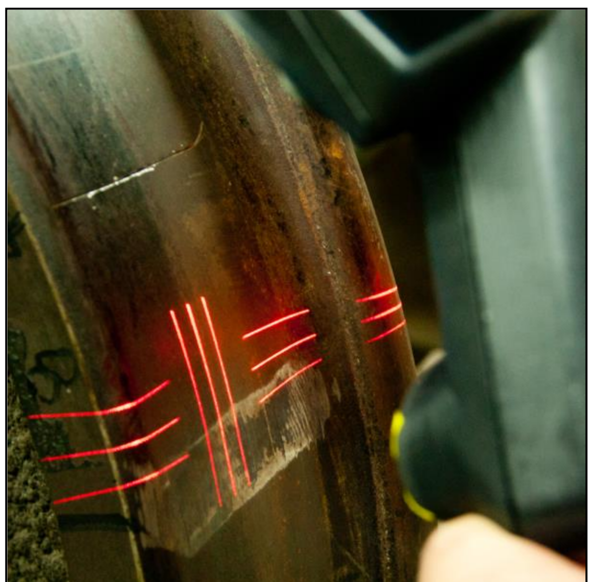

FIGURE 11 Initial laser and camera tests.

During this initial testing, one of the things that became apparent was that the data acquisition for the cameras had some problems maintaining synchronization. It was not possible to directly synchronize the two cameras together, so the selected video card was instructed to trigger frame acquisition simultaneously in each camera then process them sequentially. The card could handle a real-time processing rate of 60 fps, so 30 fps effective between both cameras was possible, and quite acceptable.

However, the triggering turned out to not be as accurate as needed (since the two images must be acquired at the same precise moment if they are to produce accurate measurements). To address this, IEM designed and constructed a custom multiplexing (MUX) board for the cameras. The MUX board would acquire the frames, order them sequentially, and send them as a single stream to the video processing board.

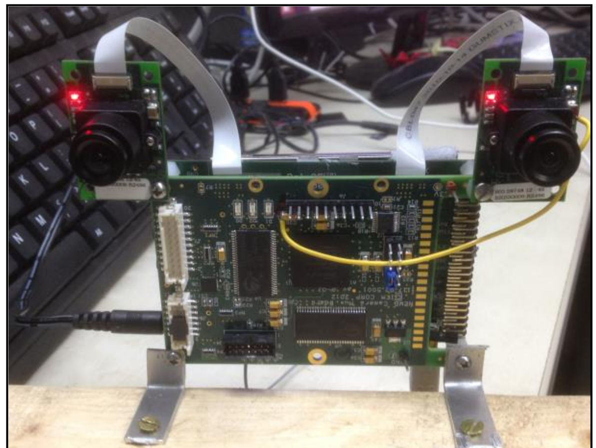

FIGURE 12 MUX board undergoing testing.

Shown in Figure 12 connected to two active cameras, the MUX board functioned well. There were, however, issues with the actual acquisition of the images; it was eventually found that the unit would take approximately 16 images in sequence that were well-timed, and then lose timing precipitously after that point. Considerable effort was dedicated to diagnosing this problem.

At first the MUX board—being a new design and untested—was suspected; then the cameras or the software. Finally, however, it was determined that the camera drivers themselves were to blame, consuming a vastly greater proportion of system resources and providing less control than was expected. Such problems often appear in “open source” software. However, IEM has located two other alternative drivers and has begun work to incorporate these rather than the prior drivers.

Other evaluation of the physical design and performance of the NEWG was performed during this time. IEM determined that a number of improvements were to be made in the design:

- **Due to variations in the camera design**, the mounting pockets for the cameras turned out to be slightly “off” and require some redesign. This also necessitated some modification of the laser mounts.
- **Laser power modules** need a better means to secure them to the frame.

- **Board stack alignment** must be properly controlled. This is crucial as the board stack includes the 3-axis accelerometer and must be properly aligned when mounted so as to provide accurate feedback.
- **Improved cable routing** with strain relief; the cables used for such small electronics can be very sensitive to twist or pull.

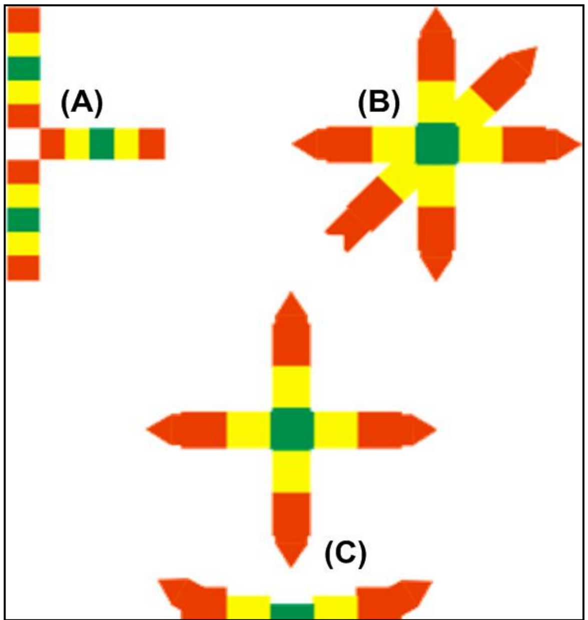

FIGURE 13 Possible indicator designs for proper pose adjustment.

In addition, for the final prototype it was clear that a number of other improvements should be made, including:

- **Include calibration mounting**. To properly calibrate the gauge requires that it be held rigidly in a known pose. Providing a usable calibration mount—possibly a ¼ in. tapped hole in the frame—will allow this to be done easily, conveniently, and reliably.
- **Determine mounting location and configuration of Pose feedback LED display**. Figure 13 shows several possible configurations for pose feedback indicators. All of these indicators are intended to convey the idea of three separate aspects of proper pose: tilted incorrectly toward or away from the plane of the wheel, toward or away from the face of the wheel, and rotated with respect to the tread line.


FIGURE 13 Applique version of Figure 14A design on prototype casing.

Figure 13A is intended to be applied at a corner of the gauge, such that the three lines of lights each lie along one axis of the gauge. This is made more easily understandable in Figure 14, which shows an appliqué version of this design on the corner of the prototype casing. However, this has the disadvantage of possibly being difficult to read in use and also being more difficult to read for the "rotation" issue.

Figure 13B is compact, easily placed on the rearward portion of the gauge, and shows a three-dimensional axis, but it also still somewhat difficult to determine what this means with respect to gauge rotation.

Figure 13C is the current front-runner design, with two obvious axes of motion corresponding to alignment with the plane and face of the wheel, and a curved indicator corresponding to the tilt or rotation of the gauge with respect to the wheel.

- **Control placement and activation.** The most useful and appropriate positions of the key controls—on/off, laser activation, etc.—were still being examined during this time. Feedback from potential users was expected to resolve some of these issues.
- **Manufacture laser aperture slit fixtures.** The prototype used carefully applied tape for the slits, but a proper manufactured aperture was necessary for the final design.

During this same period, IEM began developing a screen-based user interface for the NEWG. There is of course a "user interface" in the overall operation of the gauge for taking readings, that consists of the pose indicator (whatever design may be chosen), the trigger switch for taking readings, and any tactile/acoustic feedback mechanisms.

The main user interface is presented on the screen, and in the current design is based strongly on IEM's handheld wheel profile system, which also uses visual menus for control and setup. Figure 15 shows examples of the type of menus expected.

The main menu (Figure 15A) permits sign-in (for both security and tracking purposes), operation, definition capability (as there may be a need to customize the units and their operational focus), and access to utilities. Utilities (Figure 15B) include uploading and downloading data and recalling particular entries for display. Operations (Figure 15C) allow selection of wheel types, car definitions (for proper car-to-wheel correspondence), wheel selection, and actual measurement triggers. The Select Wheel menu (Figure 15D) shows an example of a menu allowing the user to input data.

From the above it should be clear that there may be other menus, or expansions of the menus, made available. Depending on the needs and assumptions of the customer, there could also be fewer (e.g., one could imagine designing the unit such that any updates on things such as wheel type would be performed automatically during recharging, and therefore there would be no need for separate menu items for these functions).

In any event, IEM also projected possible data views for a scanned wheel's profile. As IEM has developed multiple wheel-measuring systems over the past several years we have considerable experience with the presentation of such data to users. For the preliminary work, IEM again decided to use an approach similar to that used by our portable wheel profilometers, which shows a sketched profile of the wheel combined with notations on the specific dimensions of the wheel. Figure 16 shows an example of the type of image expected. Note that as this is taken from IEM's profilometer as an

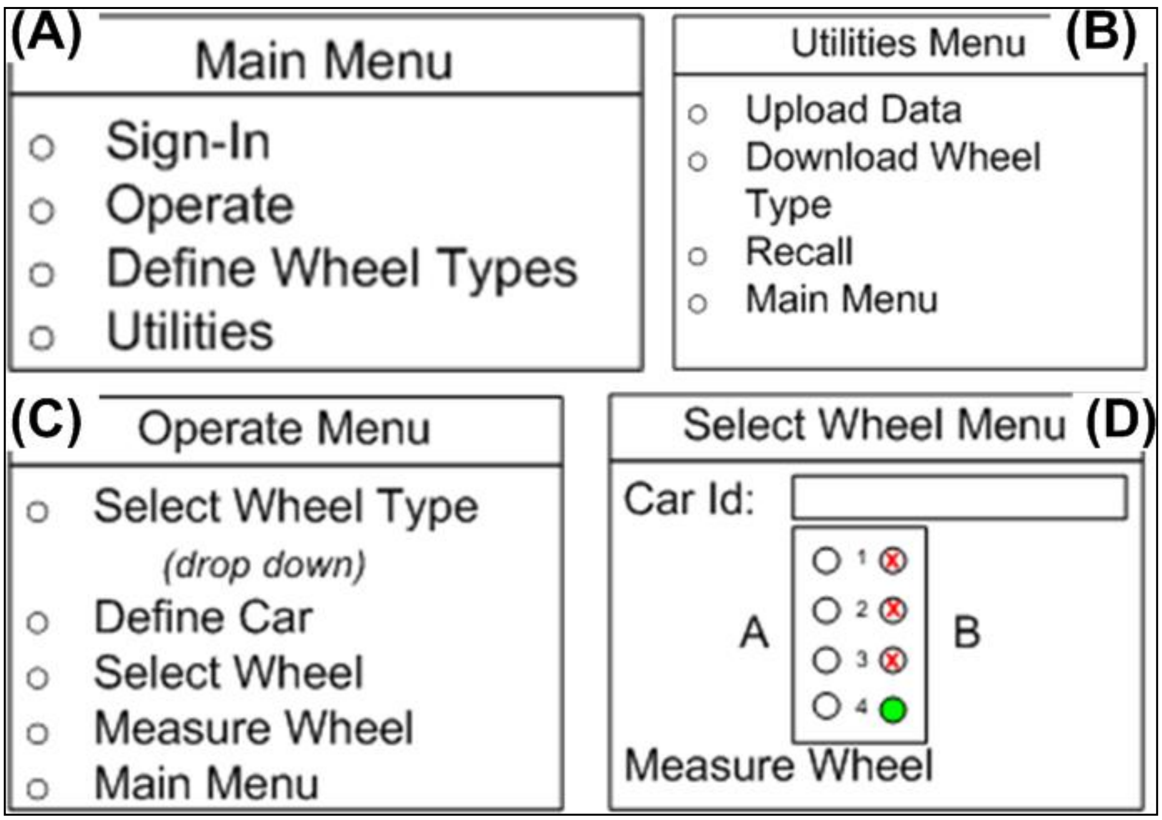

FIGURE 15 Prototype GUI menus for the NEWG. (A) Main menu; (B) Utilities menu; (C) Operations menu; (D) Wheel selection menu.

example, it does not include diameter, which would be very prominent in the actual display for transit use.

As the screen on the NEWG will be quite small, IEM is exploring alternative displays that will convey the key information and be easy to read under all circumstances.

Meeting and Presentation

IEM also scheduled a meeting and presentation to TRB TCRP J-4 panel of the progress made and projected for the NEWG. This presentation was made on September 18, 2013, at TRB in Washington, D.C. At the meeting, IEM presented an

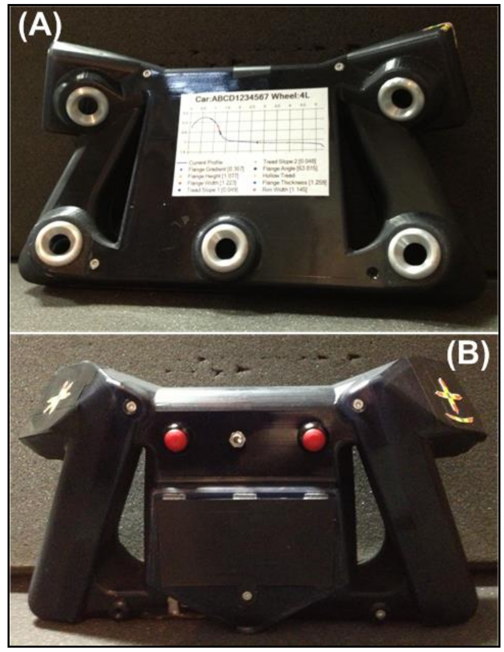

FIGURE 17 Mockup of completed NEWG unit.

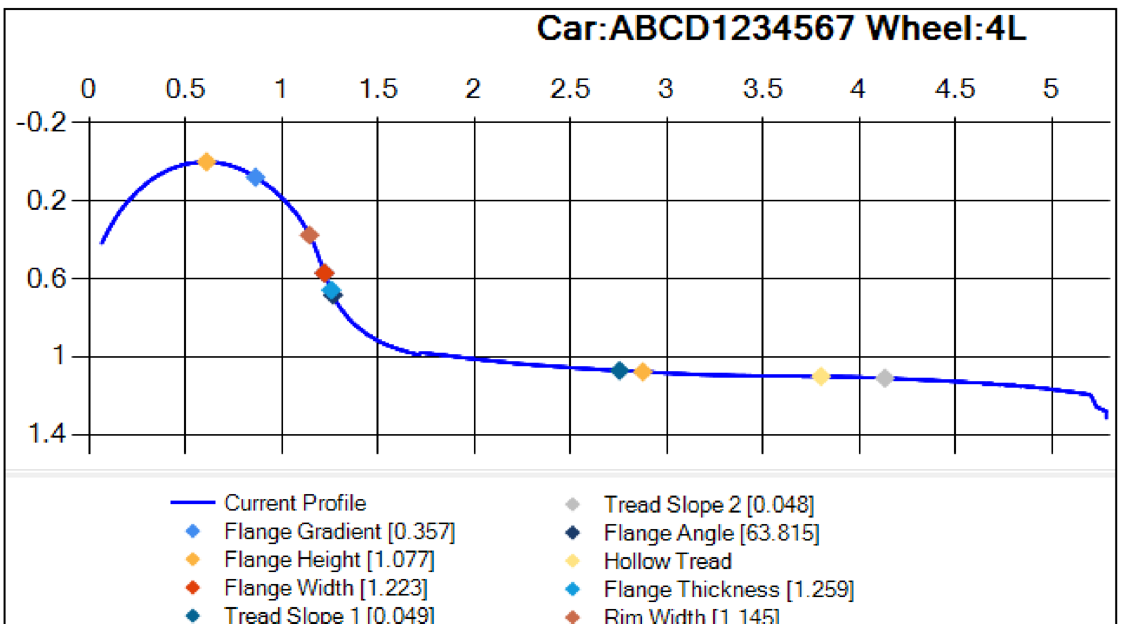

FIGURE 16 Example of profile display.

overview of the project, a mockup of the current design concept (shown in Figure 17). The final design is not quite settled at this point (see Task 9), so the mockup was viewed as the best way to present the then-current vision for the NEWG design.

There was generally positive feedback from the attendees of the meeting. One substantive question, or rather two related questions that were raised, however, had to do with the safety of operation of the NEWG unit. It was observed that as the screen (in the current design) is on the "inside" of the gauge, both cameras and lasers are facing the operator during use. The attendees naturally questioned whether this was safe. Could the lasers be accidentally triggered, and did they pose a safety hazard either to the operator, or to others?

The short answer to both questions is "no." To detail further:

- **There is no way in which the lasers could be accidentally triggered by the operator while using the screen menus**. The activation of the lasers currently is a dual-protected function; the user must first select "Measure Wheel" in order to arm the lasers, and then press the "measurement" button to trigger the actual use of the lasers. Any other menu setting of the device *cannot* trigger the lasers because they are not armed.
- **In addition, the system is designed to only activate the lasers if the gauge is held in particular orientations**, neither of which are likely orientations for the gauge to be held while the user is attempting to use the menu screen. Thus, it is extremely unlikely that the lasers could be activated when a user is looking at the screen, and in fact the only way this could happen would require a *deliberate* sequence of events by the user to activate the lasers under those conditions. *It could not be done accidentally*.
- **Even if the lasers *were* activated, they pose no danger to either the operator or any other persons in the area.** The lasers are 7 mW units but the power of the laser beam is spread over a 60 degree fan and this disperses the effective intensity of the light to well below the safety threshold. The only way to potentially damage one's eyes with these devices would be to put one's eye directly into one of the laser projection ports on the NEWG at point blank range.

- **Again, this would require a very deliberate act** on the part of the operator, and the lasers themselves would not activate unless the operator had also undertaken another quite deliberate sequence of actions to arm and trigger the lasers.
- **Finally, the lasers also shut down automatically** after projecting for long enough to acquire the needed images, which is only a second or so.

This presentation also led to IEM correspondence with Paul Messina of Port Authority Trans-Hudson (PATH), which is moving forward (see Task 9). Overall, TRB expressed satisfaction with the work performed on the NEWG development.

Key Research Areas Remaining

The overall testing of the prototype unit showed that the basic functionality of the NEWG was present and working as theory had predicted. There were, however, a few areas seen that will require additional work to bring the NEWG to a fully deployable device meeting all specifications.

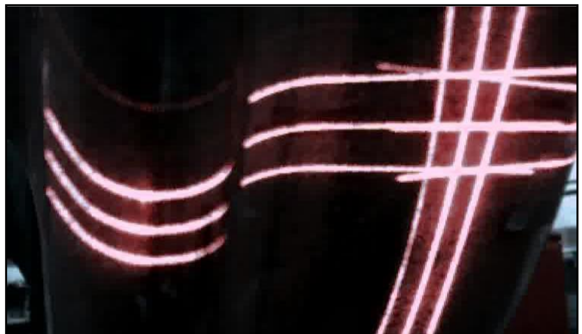

FIGURE 18 Actual NEWG image of wheel.

The first is a technical issue involving the imagery gathered by the NEWG unit. Figure 18 is a good image taken by the NEWG of one of IEM's test railroad wheels. An image of this quality provides all the data necessary for accurate, reliable measurement of the wheels.

However, depending on the exact condition of the wheel and the precise angle at which the NEWG is held, there are situations in which the wheel can specularly reflect the laser light directly back to the camera, resulting in significant glare or bloom in the image. This naturally washes out key details near the reflection site and could significantly impact the accuracy of the measurements.

Because of this*, one area of research for the final design will be to determine how to address these situations.* The NEWG should either be able to somehow eliminate the reflections directly from the image, or should be able to guide the user into holding the

NEWG in a manner that minimizes the unwanted reflections. Eliminating these reflections through design alone may have significant impacts on the precise size and shape of the unit; these are of course critical areas in deployability and usability.

Related to this is the need for a refinement of the calibration and final computation process. IEM has performed the initial work of creating a general calibration of the system that takes into account that the cameras are not parallel but face inward towards a selected point, but more work needs to be done to refine this approach, make it “bulletproof,” and instantiate it in a simple, reliable method that can be performed without complex operations that in themselves increase the chances for an improperly performed calibration. The calibration directly affects the measurement accuracy. As discussed earlier, even a very small change in angle can result in a significant change in measurement, so the calibration of the gauge must be done to extremely precise levels in order to reach the desired measurement accuracy of approximately two mils (0.002 in.).

It is important to note that even now, the *accuracy of the NEWG exceeds that of any available gauge* at better than ten mils (most gauges are only accurate to approximately 1/16th or about 63 mils, and even IEM’s in-ground rail-based wheel gauge can only reach roughly 15 mils in accuracy). The additional refinements to be researched will bring this down to the 2-mil accuracy needed for the transit industry.

Also related to this is a need to verify and assure the reliable accuracy of the diameter measurement. The major challenge of diameter measurement under the current design is simply that the NEWG can only “see” a relatively small section of the wheel at a time. It is easy to compute an accurate diameter if one has, say, half of the circle encoded, and of course impossible to do so from a single point on the circle. The current design can image the diameter lines along an arc of perhaps 8 inches, something around 1/30th of a circle. This means that precision becomes much more important; the arcs themselves provide sufficient data to measure the circumference, and thus diameter, but the accuracy of this measurement could be affected by local variations in the surface.

Task 9: Final Test and Demonstration

As of this writing, the actual final tests/demonstrations have not yet occurred. IEM has worked with New Jersey Transit (NJT) in development of concepts for the

NEWG in conjunction with our ongoing support for IEM Profilometers used by NJT. Based on their experiences with the profilometer, NJT maintenance staff has provided IEM with critical feedback on specific design elements for NEWG. IEM has discussed plans for demonstrating NEWG to NJT and for setting up a test plan for them to use the device in actual practice and provide us with critical feedback on the performance of the device. IEM is now finalizing the design of the NEWG and plans to schedule the tests/ demonstrations with NJT before the end of 2013.

In addition, IEM is currently in talks with PATH safety engineer Paul Messina, who attended the original TCRP presentation. At the meeting, Mr. Messina mentioned that at a meeting with the Southeastern Pennsylvania Transportation Authority the prior week the issue of poor wheel measurements had been a major topic. PATH has significant wheel issues due to many tight turns on their route, which produce uneven and notable wear above that expected due to mileage alone. Because of this PATH has considerable interest in the NEWG technology and IEM's other measurement systems, including our current version of the rail-based wheel gauge that was originally developed with assistance by TRB many years ago.

IEM therefore anticipates additional work and demonstrations in the relatively short term.

Task 10: Project Management and Reporting

During this period, IEM's primary point of contact (POC) at TRB, Harvey Berlin, finally retired after many years of service. Mr. Berlin's replacement, Jon Williams, notified IEM of this change and became the new primary POC. IEM updated Mr. Williams on the then-current status, arranged the meeting discussed earlier, and performed the presentation.

This final report is of course a component of the work performed under this task.

IEM made a Poster Presentation concerning TRANSIT-72 at the 93rd Annual Meeting of the Transportation Research Board in January 2014.

5. CONCLUSIONS

The Stage 2 work has shown that the Noncontact Electronic Wheel Gauge is completely feasible, and with recent contacts it has been demonstrated to be something of relevant interest to the transit industry. While a final prototype is still in development, all of the key technological aspects—specific camera selections, mounting, laser selection, calibration, image acquisition and processing, actual measurement, and interface/data presentation—have been directly addressed and tested.

IEM has identified three specific, related areas—addressing reflective glare in images, assuring proper calibration and imaging precision, and assuring the accuracy of diameter measurement in specific—that will require additional research work to address. The basic principles and overall performance of the NEWG have been demonstrated, but in these specific areas there are key elements, especially in the imaging analysis using the particular stereo-equivalent pairs of images, which are innovative and unique and require further investigation and refinement to reach the specified levels of performance.

The development of the NEWG is therefore a success and IEM believes that finalizing a production design and moving forward to marketing and distribution is the obvious next step. It should also be noted that the basic technology of the NEWG is capable of performing accurate measurements of multiple other targets and objects including rail.

REFERENCE

1. *Recommended Practice for Truck Systems Periodic Inspection and Maintenance*, APTA RT-RP-VIM-019-03, American Public Transportation Association, Washington, D.C., 2003, 19 pp.

APPENDIX A. STAGE 1 SPECIFICATIONS FOR NONCONTACT ELECTRONIC WHEEL GAUGE (NEWG)

Parameter	Description	Specification/ Requirement	Notes
Environmental			
Temperature range	Range of temperatures over which NEWG is usable	-40°F to +110°F (usable range) -50°F to +120°F (survival range)	Covers temperature range in most of North America
Precipitation	What degree of precipitation is tolerable by NEWG?	Light drizzle or snow	It is assumed the unit will not be used in pouring rain or very heavy snow as this would also interfere with measurement taking in other ways
Time of day	When can NEWG be used?	24/7	Railroads operate essentially year-round at all hours. NEWG must match this requirement.
Illumination	What lighting conditions are required to use NEWG?	Any lighting	The NEWG provides its own illumination (eye-safe lasers) and all feedback is from self-illuminated sources.
Measurements	What can NEWG measure?	Diameter, flange angle, full wheel profile (rim thickness, rim height, etc.)	NEWG should provide all the capabilities of a standard wheel gauge as well as the ones specifically demanded by transit
Accuracy	To what accuracy can NEWG measure the target parameters?	0.002 inches (2 mils) individual measurement; 0.005 inches (5 mils) over entire profile	One mil of wear equates to, roughly, 10,000 miles of use
Repeatability	How closely do repeated measurements of the same wheel agree?	0.001 inches (1 mil)	Good repeatability is necessary to achieve useful measurements.
Wheel surface quality	In what condition do the wheels have to be for measurement?	Any condition (clean and shining, grease, dirt, rust, etc.)	The point of NEWG is to reduce time and effort for wheel inspection; any requirement to "prepare" the surface of the wheel directly opposes this goal.
Operator requirements			
Required to operate	What capabilities does the user need to operate NEWG?	One-handed operation; must have good vision	Vision needed to read feedback on small panel.

Motion tolerance	What motions can NEWG tolerate while in use?	Any normal hand-arm motions	It is assumed that a hand-operated unit will never follow precise lines; there will be vibration, tilt, etc., and NEWG must account for that
User feedback	How does NEWG let the user know key information about its operation?	Multicolored LED indicators, LCD screen, possible auditory/tactile feedback	Initial prototype will focus on LEDs and screen; other options to be added in final development.
Controls	What controls will be needed to operate NEWG?	Minimal key controls with "trigger" button for readings	Analogous to the minimal control interface developed for our current electronic wheel gauge.
Technical/Operational			
Size/weight	How big will NEWG be?	<2lbs.	Exact dimensions not yet known. The unit will have to fit between the wheel and rail and/or other obstructions. Minimal size is determined by the minimal separation of lasers and cameras, and the thickness of these units.
Battery charging	How is the battery kept charged?	External contact or inductive charge stand	External contact charging is easiest, but such contacts can become damaged, dirty, etc.; inductive charging is less efficient but requires no physical contact between battery circuitry and charging mechanism.
Communications	How does NEWG communicate data to main systems?	Wireless – probably WiFi or Bluetooth based	IEM uses a similar mechanism for our profilometers to communicate with base stations
Self-diagnostics	Can NEWG tell if something is wrong with it?	Detect dirty lenses/windows. May be able to detect other faults such as damaged LEDs, etc.	NEWG has to have some self-diagnostic capability in order to make sure it is properly maintained.
Calibration	How is NEWG calibrated?	Initial calibration done prior to shipping; recalibration with supplied object/target	The manufacturing and testing of the NEWG units will culminate in calibration of the new units. Calibration should be verified in-house at least once per year using a supplied target. Ideally any adjustments will be able to be done using

			software; major misadjustments may require returning the NEWG unit to IEM.
Ruggedness	What can NEWG withstand?	Minimum is survival of repeated impacts onto hard surface from 3 feet	Will test in multiple scenarios.
Applications	What applications can NEWG be used for?	Wheel measurement (Transit and freight), track measurements, disk brake measurements, track frog measurements	The handheld laser metrology approach offers significant potential in applications to many other measurement problems.

APPENDIX B. RESPONSE TO TRB COMMENTS ON DRAFT REPORT

Reviewers

Recommended Option for Distribution			
Reviewer #	**Name**	*Do Not Distribute*	*NTIS, TOPS and J-4 Panel*
1	Fred Gilliam		✓
2	Frank Lonyai		✓
3	Jon Fayos		✓
4	Greg Cook		✓

Comments

Reviewer #1: Page 10 the other two software providers should have a similar description paragraph as the other four providers. One of the providers that did not receive a description has a superior software than most, if not all that did receive a paragraph. The report is pretty technical and will not be read by most people, Techies will love it perhaps.

IEM Response: *IEM has carefully reviewed the draft report that and can find no references to software providers as referenced in this comment. Perhaps this was a review of a different report?*

Reviewer #2: It is a well-written and balanced approach to a complex technical issue. They made good progress.

IEM Response: No response required

Reviewer #3: This project has resulted in a successful prototype demonstration for what looks to be a significant improvement of devices currently used in the industry

IEM Response: No response required

Reviewer #4: Great Safety enhancement. It was good to see the report finalized after seeing a presentation on the device.

IEM Response: No response required

APPENDIX C. RESPONSE TO COMMENTS FROM NJ TRANSIT

Comments from Dak Murthy, Director of Quality at NJ Transit

“It is promising to note that this Noncontact Electronic Wheel Gauge (NEWG) is capable of measuring wheel diameter, flange angle, full wheel profile (rim thickness, rim height, etc.). As a suggestion for improvement, it will help immensely if the tool has voice commands and can be converted into go-no go gage. It will be nice if the tool can be expanded into Wheel measurement (Transit and freight), track measurements, disk brake measurements, track frog measurements etc.”

IEM Response: IEM appreciates the suggestions from Mr. Murthy. While we hope we can achieve his ideal for voice commands and multiple uses, we want to emphasize this is but a prototype model that demonstrates the capability of the system.