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Application Note | **Case Study** | Technology Primer | White Paper

Machine Vision Aids Earthquake Retrofit Studies

In seismically active regions such as Italy most new buildings are built to resist earthquakes, but many older buildings are not. To find a balance between the cost and the effectiveness of retrofitting older buildings, the European Center for Training and Research in Earthquake Engineering (EUCENTRE) conducted tests on scale model buildings mounted on shake tables that simulated earthquakes. EUCENTRE turned to machine vision to find a quick and accurate method of monitoring the building's movements during tests.

As recent events in Haiti and Argentina have highlighted, many urban buildings in seismically active regions worldwide are in need of reinforcement to resist earthquake damage. One challenge facing earthquake retrofit activities is finding a balance between the cost and the effectiveness of the methods to be used. As part of its efforts to verify the efficiency and accuracy of new Italian regulations for the seismic assessment and repair to existing buildings, the European Centre for Training and Research in Earthquake Engineering (EUCENTRE, Pavia, Italy) used machine vision as a no-contact measurement system.

The organization conducted tests using 1:2 scale model buildings representative of Italian construction methods in the 50s and 60s (reinforced concrete frame with masonry infills) and mounted on a shake table that could simulate minor, moderate, and severe earthquakes with longitudinal excitation. In order to understand the structure's response to earthquake movement, researchers needed to measure both how the building moved as well as to measure any structural deformation that occurred. Damage-related measurements of interest included floor displacements and rotations, inter-story drifts, and shear deformation of infill panels as well as curvatures of critical structural elements. level excitation and time-frequency analysis to monitor the dynamic modes evolution and the damage progress through the test campaign. Results are presented in terms of modal frequencies, and shapes.

Classical Methods Have Limits

The classical methods for making such measurements utilize strain gauges, displacement transducers, and accelerometers. Strain gauges attach to structural elements such as the steel bars in the center of concrete castings and change resistance as they deform. Displacement transducers connect between two points in the structure and measure the relative displacement between those points. Coupled transducers allow determination of curvature in the deformation. Accelerometers monitor the movement of individual points within the structure; integrating the signal can provide a measure of displacement, as well.

While these instruments can provide highly precise real-time measurements of building flexure and movement, they have their drawbacks. For one, these devices must be rigidly attached to the structure in order to make measurements. In the case of strain gauges, this requires attaching the gauge to the steel bar before pouring the concrete to construct the building. For displacement transducers this requires bolting both transducer ends to structural elements. Another drawback is that strain gauges and displacement transducers only measure local displacement along a single axis, requiring researchers to choose carefully the mounting location and orientation of these instruments. In the case of strain gauges, this placement cannot be changed later; it is sealed in concrete.

Accelerometers allow greater positioning flexibility because they can be mounted anywhere, needing only one anchor point, and can be moved with relative ease. Unfortunately they cannot directly measure displacement and the signal integration needed to obtain displacement introduces errors and uncertainties into the results.

All these instrumentation methods have the additional drawback that they require wiring to bring their signals to a data acquisition system, increasing the installation effort and cost. This cost adds to the cost of the instruments themselves, with the result that researchers must often make a tradeoff between the number of measurement sites and the cost to acquire and install the instruments.

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Vision Simplifies Measurement

As a part of its retrofit research, EUCENTRE evaluated an advanced optical system for making non-contact measurements of building seismic response. This optical method promised several important benefits, the first of which was the ease with which the measurement sites could be prepared. Rather than installing gauges and other instruments, researchers simply attach reflective markers to key points on the structure and make their measurements with a machine vision system.

The vision system that EUCENTER developed consisted of as many as ten stand-alone image acquisition and analysis units with a common electrical trigger to synchronize data acquisition. Each unit included one or two Teledyne DALSA Pantera cameras with 2352x1728 resolution and 120 frame/second acquisition speed, a PC with two RAID-0 300 GB hard disk drives, and an Xcelera X64 frame grabber connected into the PC's 4x PCIExpress socket. All units connected to a network that provided remote system control and database storage capability.

To provide complete monitoring of building motion during excitation, unit cameras imaged key points within the building's structure, including the base of support columns and the junctures of the floors and ceilings with the support columns (Figure 1). A pattern of reflective markers within each field of view provided the analysis system with measurement points that it could use to calculate both motion and distortion within the structure. Each pattern allowed the determination of local effects and correlation of data among the synchronized units allowed the determination of global effects.

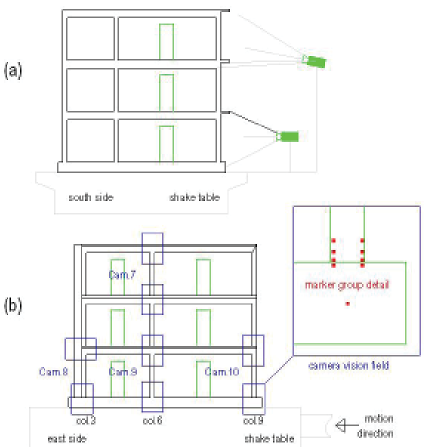

Figure 1 – East side cameras (a), cameras vision fields and marker group detail (b). The EUCENTRE vision system monitored reflective markers placed at critical column bases and junctions with the floors and ceiling in the model structure, using the pattern to monitor displacement, rotation, and distortion of the building element.

One of the challenges the vision system needed to overcome was the effect of environmental illumination. The greater the contrast between the marker and the background, the faster and more reliably the vision system could identify the markers and measure their position. In some configurations, however, the environmental illumination could wash out marker visibility (Figure 2a). To resolve this problem, the researchers mounted infra-red filters in the cameras to eliminate ambient light from the image and used infra-red lamps to ensure controlled illumination of the markers. The result was a significant increase in marker visibility (Figure 2b) and, thus, enhanced measurement speed and accuracy.

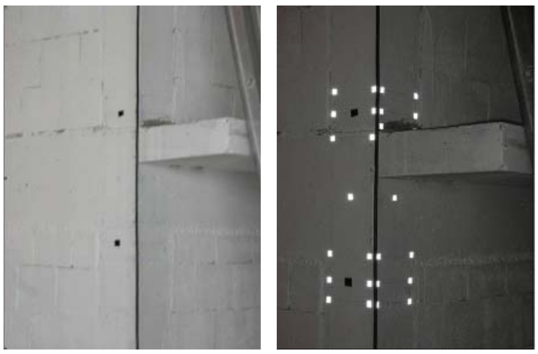

Figure 2a & b ***Reflector markers placed on the structure (left) and highlighted (right)***
Environmental lighting could wash out the reflective marker images (a) but the use of IR illumination and in-camera filters provided significant contrast enhancement (b).

High Precision and Accuracy

The image analysis system identified markers within an image by looking for "blobs" - groups of contiguous pixels having the same color. Having identified a blob, the analysis software then determined the blob's center by examining transitions in the color's intensity within the blob (Figure 3). This centroid determination had a theoretical precision of 0.02 sub-pixels, which corresponded to a measurement precision on the order of 0.01 mm. To create the mapping from pixels to real-world placement, the researchers used a pinhole-camera model and geometric analysis of the camera and marker placements.

The host CPU's processing power limited the number of markers that a unit could work with. Within that limit, however, the cameras and analysis units could identify markers on the structure anywhere within their field of view and calculate their absolute coordinates at a frequency of

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60 Hz. For finer time resolution, the system could work with any 2M-pixel rectangular area within the field of view at a frequency and achieve a measurement speed of 120 Hz. These speeds were more than adequate to measure the typical vibration frequencies of building seismic responses.

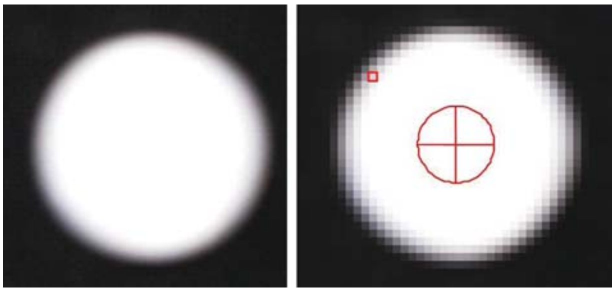

***Figure 3* – Blob centroid detection**
The vision system used blob analysis to detect markers within the image, then used color gradient to determine the blob centroid to sub-pixel precision.

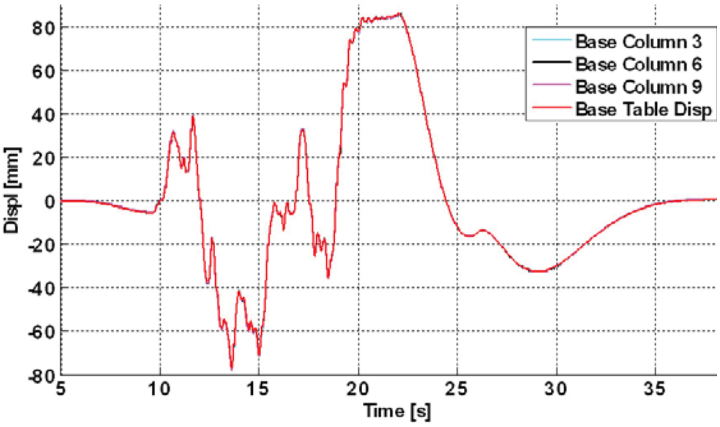

***Figure 4* – Comparison between table motion and cameras results.**
A comparison of the vision-determined column-base displacement with the shake table's known motion shows an exact match.

In order to test the accuracy of this innovative optical measurement system, EUCENTRE compared the movement results for the bases of the building's support columns against the known movement of the shake table to which they were attached. Under low acceleration conditions, the column bases should undergo simple rigid translation, so that their movements should correspond to the table's movement. As shown in Figure 4, the results were a nearly perfect match.

Machine vision has thus added an important new tool to earthquake retrofit evaluation. Because it relies simply on the placement of markers, optical instrumentation is relatively quick and inexpensive to install. Further, measurement sites are readily modified and augmented, allowing researchers to explore unanticipated regions of interest that may arise during testing. The high performance of modern high-definition digital cameras and image processing systems provides speed, precision, and accuracy comparable to traditional methods. The result is that machine vision provides a relatively low-cost, easy-to-install method for the measurement and analysis of structural motion.

www.teledynedalsa.com

Americas
Boston, USA
+1 978-670-2000
sales.americas@teledynedalsa.com

Europe
Munich, Germany
+49 8142-46770
sales.europe@teledynedalsa.com

Asia Pacific
Tokyo, Japan
+81 3-5960-6353
sales.asia@teledynedalsa.com

Shanghai, China
+86 21-3368-0027
sales.asia@teledynedalsa.com

Teledyne DALSA has its corporate offices in Waterloo, Canada