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OPTICAL (CAMERA-BASED) TECHNOLOGY FOR SEISMIC RISK ASSESEMENT

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ABSTRACT
Optical (camera-based) technologies can greatly assist in risk assessment. Potential applications are identified in this paper. Several field application examples are described, largely encompassing the areas of civil infrastructure monitoring. Since optical (camera-based) systems can be particularly powerful for monitoring both local and global movements within a scene or environment, natural hazards such as earthquakes are an important application area for these new technologies. It is observed that concepts from the methodology applied to general civil infrastructure systems are readily applied to other types of natural or man-made hazards. First, a clear definition of seismic risk assessment is provided. Subsequently, two important fields where cameras may be useful in seismic risk assessment are described. Specifically, the context of (i) early warning systems and (ii) post-earthquake assessment are addressed. An example of using the optical record from a series of large shake table tests is provided and the comparison with other methods dicussed.

INTRODUCTION
The overall performance of buildings, bridges, and other infrastructure subjected to earthquake motions has dramatically improved over the years, largely due to an increased understanding of the behavior of primary structural systems. However, although the structure may perform fairly well, other (nonstructural) hazards due to imposed earthquake motions may result in building closure and/or lead to other dangerous hazards. Specific examples include the breakage of pipes or elements within the pipe network, which may result in water or other fluid leakage throughout the building, rendering the structure temporarily unusable. The application of a network of sensors that is able to detect such a situation has the potential for reducing any subsequent damage by activating shut-off valves in the fluid supply. Sensors that detect hazardous situations, such as gas leaks or dangerous chemicals that have spilled can also be used to warn people from entering a hazardous area.

A particularly promising device for use in these situations is an optical (camera-based) sensor. Optical sensors can be of great potential when monitoring movement of all different types of systems. In this paper, the term optical sensor is used to denote any type of image-based sensor [e.g. video cameras, charged-couple-device (CCD) cameras, infrared or other cameras]. Due to the readily available high-speed computational platforms today, a huge amount of data can be processed in near-real time. These computational advantages, combined with an increased availability of high quality optical sensors have promoted their usage in many practical field applications. Common field examples broadly might be categorized as either observation or surveillance. The most pervasive example of the former is transportation or traffic observation while the most common example of the later is surveillance in public buildings. However, optical sensors are advantageous beyond inspection or surveillance applications. A particularly promising application is field monitoring. For example, their non-intrusive nature may be beneficial for monitoring certain systems critical to the infrastructure, such as pipe(s) or networks of pipes, electrical systems, or other service system equipment. Perhaps the simplest example is an optical sensor that has detected a broken pipe. This information may be used to close an upstream valve to prevent further fluid leakage and subsequent damage to the area. An important life-threatening example is an area containing hazardous substances. These areas can be monitored if, for instance, there is potential that dangerous chemicals may spill. After identifying such a hazardous situation, the affected area may then be isolated in order to prevent humans from entering this hazardous section.

Since optical sensors capable of capture rates of more than 30 frames per second are available at reasonable prices, the proposed monitoring system can be installed permanently in several rooms of a building at relatively low cost, compared to the overall cost of the structure. With such an infrastructure, an additional safety system can be provided that is capable of reducing or eliminating the types of hazards described previously.

In this paper, ideas are presented for using optical sensors to reduce earthquake hazards (particularly secondary hazards) by increasing our assessment ability. However, the methods described are not restricted to this particular application area. The concept holds for any type of application where movement is imposed upon structures. Initially, an overview of optical sensors used in various field applications is provided. Subsequently, selection of optical sensors that reasonably meet the requirements for monitoring structural (and nonstructural) movements and techniques for evaluating optical data are discussed. A precise definition of risk assessment is provided and examples from past earthquakes are described where deployment of these systems would have been extremely beneficial. Finally, challenges related to implementing optical sensors and computer vision algorithms in this application area are discussed.

FIELD APPLICATION EXAMPLES

The increased speed and resolution, combined with dramatically decreasing cost of optical sensors in recent years has resulted in an increased usage of these systems in practical field applications. Some of these are observing public areas for security reasons, monitoring traffic or bridges, inspecting sensitive systems, or detecting changes in the environment over time.

To enhance security in public buildings optical sensors may be used. For instance, surveillance cameras are installed to monitor the pass through of people. Face recognition software is then able to identify runaway teenagers or suspects in criminal activities [1].

Another application is monitoring traffic on a surface road or highway. This can aid in detecting unauthorized use of a roadway or to recognize special traffic situations, such as excessive congestion. Several publications are available describing vehicle tracking in the field [2] [3] [4]). The RoadWatch project described by Beymer et al. [5] uses one camera to track multiple cars at once. Vision algorithms implemented in this project allow for tracking only parts of a vehicle to avoid occlusion problems. This enables the system to count the number of vehicles on a highway and detect volume and location of traffic congestions.

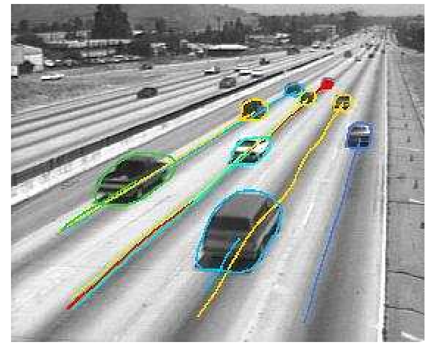


Figure 1. Cars tracked by RoadWatch (image courtesy of David Beymer [5]).

Figure 1 shows an example of several cars being tracked by this system.

Similarly, optical sensors are used to monitor bridge structures [6]. In this example project, streamed digital video images provide a mechanism to monitor the traffic moving over critical areas of the bridge. The optical sensors are combined with other types of measurement devices such as accelerometers, mechanical displacement and force transducers, each strategically located on the structure. With the optical sensors it is easy to identify heavy trucks that are traveling over the structure and measure their velocities. The bottom half of Figure 2 illustrates the synchronization of images and vibration data used to identify the

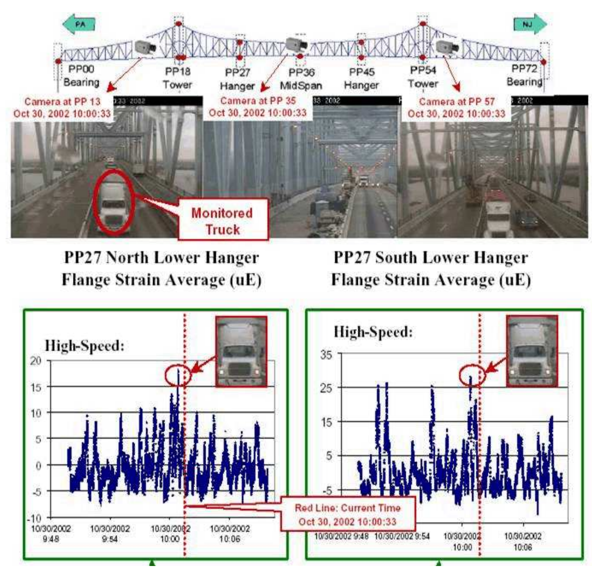


Figure 2. Bridge monitoring using cameras and conventional sensors (Commodore Barry Bridge, monitoring system by Aktan et al. [6]) (Schematic courtesy of E. Aktan).

Figure 3. Growing ice at the shore highlighted by an edge detection algorithm (image courtesy of USGS [16]).

response of a heavy truck crossing the bridge.

Optical sensors may also be used in areas such as inspection of various train and railway related systems [7]. Applications exist that inspect the rail profile [8], [9], rail gap [10], contact wire positions [11], or wear [12]. Additionally, the train itself may be inspected or monitored. Applications include the inspection of the wheels or the thickness of the brake pads. During operation, optical sensors can detect locking wheels or overheating brake systems. To observe the maximum occupancy inside a train, optical sensors have also been used to count the number of passengers [13] [14] [15].

For environmental monitoring changes in the shorelines and costal bluffs can be observed, based on images collected from continuously streaming cameras monitoring for example the water-beach interface [16]. In this example, a system was developed that is able to monitor breaking waves, alongshore currents, rip currents, and beach-face profiling, especially in stormy weather. Figure 3 illustrates an example of image data captured during a cold winter season, where the red line outlines the ice-shoreline interface.

CAPTURING SYSTEM

Based on the dominant range of frequencies of movement generated during earthquakes and satisfying optimal sampling rates (i.e. to ensure aliasing of images does not occur), data aquisition rates of at least 30 frames per second are necessary. Ideally, higher frequencies (i.e. greater than 60 frames per second) are desirable to allow for differentiation of acquired movement data to obtain velocities and accelerations. In addition, the optical sensors and associated processing system should be capable of capturing image data at high resolutions. Given only these specifications, there are hundreds of optical sensors available. However, given other desirable attributes, such as low cost, small size, high shock rating, readily available and compatible interfaces (such as IEEE firewire or USB-2 interfaces), the selection greatly reduces. Other limiting factors for the overall system include interface transfer hardware (e.g. PC-specific hardware such as the PCI bus, hard drives, interface cards, etc.). Any of these elements may have the potential for limiting the system bandwidth and subsequently the capture rate.

The current implementation uses Basler A301fc cameras for capturing. These cameras have a resolution of 658×494 at a color depth of 8 bits. The frame rate of this camera type is 80 f/s. Accordingly, the data rate produced by this camera is 24.8 MB/s. Running full resolution at the highest speed of these cameras may challenge the computer system. Every component of such a system needs to be designed to be able to fulfill the bandwidth requirements. Figure 4 shows all involved components along with the data rate produced by one camera and the maximal bandwidth of that component. First, the data is transfered to main memory using firewire. The firewire bus with its maximal transfer rate of 400 Mbit/s (that is 50 MB/s) has sufficient bandwidth available. Since the data has be transmitted to the hard drives using the SCSI bus, it has to cross the memory bus and PCI bus for a second time. This consequently doubles the data rate needed in this type of application for these two buses. With the bandwidths of the memory bus and the PCI bus being 30033 MB/s respectively 80 MB/s this is no limiting factor for this application. Also, the SCSI bus being able to transfer data at speeds of up to 320 MB/s is able to cope with the amount of data produced by the camera.

A limitation may be the hard drive. Usually, hard drives have a very high transfer rate of 60 MB/s or even more nowadays. Unfortunately, these devices can reach this rate only while reading. Being aware of the high bandwidth needs of this application the capturing computer system is equipped with quite fast Seagate ST336752LW SCSI hard drives. Benchmark tests showed that the transfer rate while writing an AVI stream to these devices is only at about 27 MB/s. This is just enough for storing the images captured by the camera. Overall, every component has a bandwidth that is sufficiently high enough to transfer the capturing data from the camera to the hard drives. Consequently, a computer system equipped with devices similar to the ones described here with repsect to speed is able to capture at the full frame rate of the camera.

TECHNIQUES FOR INTERPRETING OPTICAL DATA

Optical sensor networks within a building can greatly aid in monitoring sensitive systems. At any given time, a single sensor may be used to observe multiple systems or system components simultaneously. This may provide a pre-event inventory of a particular structure or room, including both occupancy statistics as well as details regarding the interior infrastructure.

According to the Federal Emergency Management Agency [17] condition assessment of nonstructural components within a building after an earthquake event is performed by visually inspecting one to three samples of a particular component. This de-

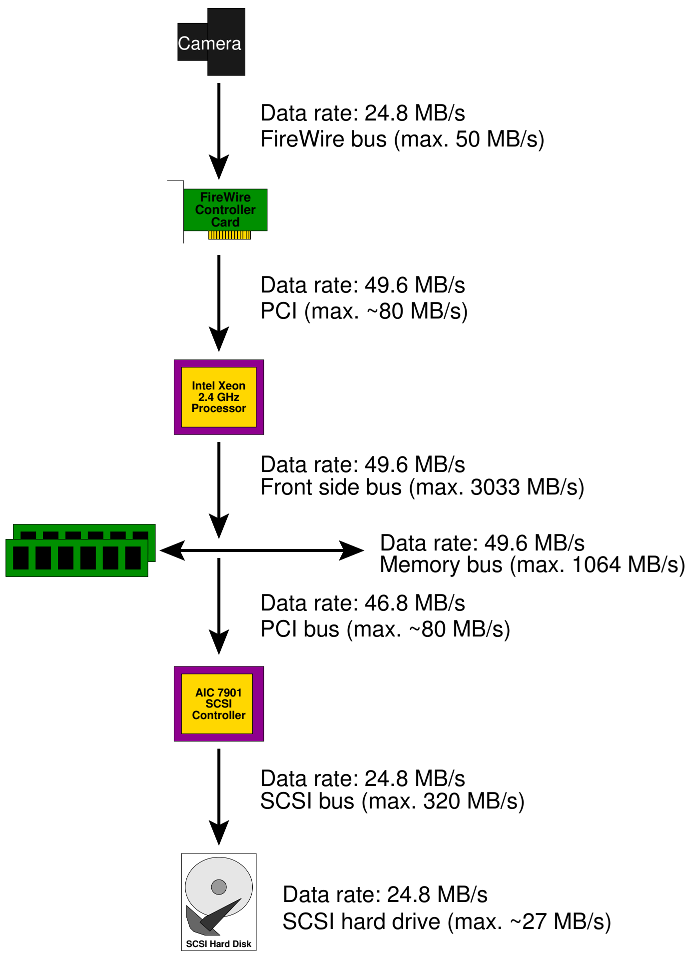


Figure 4. Data flow inside the computer system during capturing.

pends on the availability of detailed drawings of the component and its attachment. This, of course, does not take into account the pre-earthquake condition of the component. Using optical sensors the performance of the component or any other building equipment can be monitored throughout the duration of an earthquake event and any time before or after that event.

Figure 5 shows a series of sequential images captured by an optical sensor. In this example, a retail store is reconstructed on a shake table and the contents of the scene observed. During simulated earthquake motions, a heavy box falls from one of the shelves and rolls onto the floor. These changes in the environment can be detected and highlighted. In this case, rectangles show object movement over time, annotated with a vector indicating the primary direction of movement. Computer vision techniques allow one to track various objects using a set of image sequences. This may include large objects undergoing significant positional changes, as well as other types of nonstructural elements such as networks of pipes or suspended lights. Other elements falling from furniture inside the monitored room can be tracked as well. This facilitates the detection of hazardous situations if it is known what types of elements are present in the environment. Clearly, a pre-calibration of the environment is required.

In contrast to Figure 5, Figure 6 depicts a reduced field of view of an environment. The optical sensor is directed towards a portion of a shelf where several glass containers, which may contain potentially hazardous chemicals, are resting. During shaking, one of the containers topples and spills some of its contents. The monitored container is circled in the images. The upper images show single shots of the captured video stream. To track the container an edge detection algorithm has been used, resulting in images such as the ones shown in Figure 6(b). For this purpose, the algorithm introduced by Canny [18] provides the best results. It can be seen that the edges of the monitored container can be extracted in order to track the target object and identify it toppling.

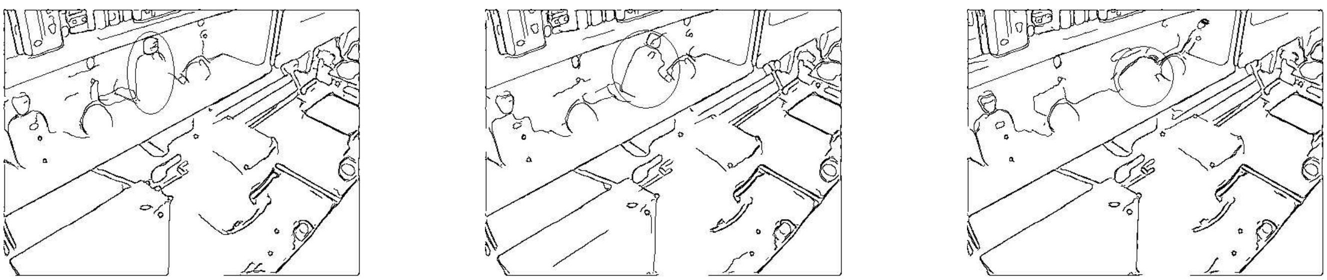
If at least two cameras are present and located in the same area, a three-dimensional model can be computed from the images if no occlusion occurs. This, of course, assumes that the optical sensors are synchronized and every sensor takes an image at exactly the same time or that precise time stamps are available allowing for image synchronization. Ideally, more than two cameras should be used. Using intelligent edge detection algorithms, objects in the scene can be identified and tracked when they move. Since one can compute a three-dimensional model of the scene, it is also possible to track the objects while measuring the absolute movement at the same time. This requires that a reference distance in the scene is known for each of the three dimensions. If optical sensors with higher frame rates are used, differentiation and signal processing allow the calculation of velocity and acceleration of objects in the scene.

RISK ASSESSMENT

Many definitions are available to quantify the term risk assessment. Generally, risk is defined as the uncertainty of a specific occurrence times the consequence resulting from this occurrence. Uncertainty must be determined for each risk individually. This can be done using mathematical models based on probability estimates. Consequence is most often defined as the financial measure of the effect of the occurrence. One must distinguish between risks that affect people and risks that affect only material (objects). Financial consequence affecting material (objects) may be fairly challenging to estimate, whereas risk associated with people, such as fatalities, may be defined with a greater level of certainty. With people being involved, one can precisely define risk as the hazard severity level times the likelihood of occurrence times the number of persons exposed to the risk [19].

Figure 5. Object tracking and detection from digital streamline images taken during shake table experiments. Current position shown in solid red, tracked (previous) position shown in dashed red. (Digital movie courtesy of K. Mosalam, UC Berkeley).

(a)



(b)

Figure 6. Chemicals observed by an optical sensor during a shake table experiment: (a) original images and (b) images with only edges identified. The tracked object is circled. Both, single shots of the video stream and detected edges are shown in subsequent order.

SEISMIC RISK ASSESSMENT

In the context of seismic risk assessment, risk is often thought of as the identification of the risk of damage incurred during a particular earthquake event. An alternative measure may be the number of people injured or fatalities caused by the specific event. To assess this type of risk, the likelihood of occurrence and the hazard severity level must be determined in the same fashion as conventional risk assessments. In the context of earthquake hazards, not only consideration of direct impacts is required (such as damage to primary structures), but post-earthquake hazards (such as chemical spills or broken pipes) must be considered in the risk assessment as well. These hazards may often result in substantial damage to the construction, which may be avoided using the appropriate assessment tools.

POTENTIAL FOR OPTICAL SENSORS TO REDUCE RISK OF EARTHQUAKE RELATED HAZARDS

The purpose of this paper is to identify specific issues and areas where cameras and camera-based technologies and associated image processing algorithms can assist in assessing the risk due to either natural or man-made disasters. The focus of this paper is on earthquake hazards, specifically secondary (post-earthquake) hazards created within the interior of building structures. In this case, one can differentiate between damage that is associated with elements directly attached to the structure (such as connected piping networks or attached equipment) and elements not attached to the structure (such as building contents or unattached equipment). The following discussion provides specific examples from past earthquakes with reference to both attached and unattached elements.

After analyzing the damages resulting from the 1971 San Fernando earthquake, California enacted the California Hospital Act. The objective of this act was to provide an enhanced level of design and construction to improve the resistance of hospitals in California. The 1994 Northridge earthquake illustrated that structural systems used for the construction of hospitals built after 1971, considering the new California Hospital Act, performed very well. However, the piping and air handling systems in many hospitals suffered fractures along individual pipes or at joints, resulting in the temporarily closure of many hospital buildings [20]. Figure 7(a) and 7(b) show examples of sprinkler pipe leakages. In Figure 7(a), a sprinkler inside the Olive View hospital at the ceiling level is shown, while Figure 7(b) shows leakage on the outside of a building near Olive View Hospital resulting from a sprinkler system damaged during an aftershock. To ensure that the fire prevention system of a building is still functional after an earthquake, guidelines provided by the Federal Emergency Management Agency [17] points to improved standards and the need for flexibly mounted piping. However, older structures may not conform to current understanding of earthquake demands resulting in failure of sprinkler systems. Newer structures being built according to modern design standards, such as the Uniform Building Code [21] or International Building Code [22], meet these requirements.

During the 1994 Northridge earthquake, 2500 water heaters were damaged and subsequently introduced wide spread natural gas leaks. By optically monitoring and correlating measured movements to tolerable limits, the potential for post-earthquake fires in this situation would be greatly reduced.

The 2001 Nisqually earthquake also resulted in widespread nonstructural damage. In one example, a water pipe ruptured in the mechanical room on the roof of a hotel causing 3000 liters of water in a storage tank to flood several floors [23]. Figure 8 shows the ruptured pipe and the storage tank. The proposed system of optical sensors would have been able to detect the spilling water and shut down the piping system to prevent further damage to the building.

Optical sensors may also reveal the occupancy in public areas and subsequently aid in determining if large equipment has toppled or slid and buried occupants. This would be particularly helpful in guiding earthquake reconnaissance teams to areas of distress while removing the need to survey unoccupied areas. Figure 9 shows an example of a failed ceiling element that may have buried several occupants. This photograph was taken at the

(a) (b)

Figure 7. (a) Broken sprinkler in Olive View hospital after Northridge earthquake in 1994 (Courtesy National Information Service for Earthquake Engineering (NISEE), University of California, Berkeley). (b) Sprinkler pipe leakage after an aftershock of the 1994 Northridge earthquake near Olive View Hospital (Courtesy NISEE, University of California, Berkeley).

Instituto Politecnico National in Mexico City after the Mexico earthquake in 1957. An optical sensor may be able to tell if there were people in the area now covered by the ceiling element.

Additionally, using optical sensors, a blocked escape route can at least be recognized and occupants can be advised to use another escape route. Although the Federal Emergency Management Agency [17], for instance, recommends that certain materials such as hollow clay or unreinforced masonry should not be used around stairs, elevators, and corridors to keep escape routes clear, it is well known that these materials are used in such areas nonetheless.

Telecommunication is another important area where optical sensors may assist in evaluating and minimizing seismic risk, particularly due to the strong linkage with today's economy. A loss of communication services can be extremely costly on both a

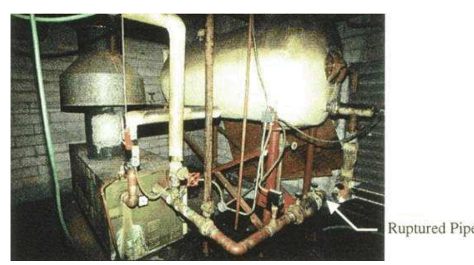


Figure 8. Ruptured pipe of the supply line to a 3000 liter storage tank in the roof top of mechanical room – 2001 Nisqually earthquake [23].

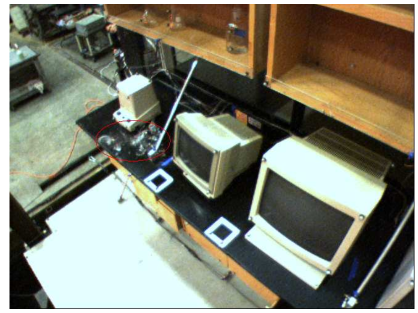
Figure 9. Ceiling of the eastern 4-story unit of the Instito Politecnico Nacional – 1957 Mexico City earthquake (Courtesy NISEE, University of California, Berkeley).

local and national scale. Consequently, backup systems are generally provided for added redundancy. Depending on the type of services provided, the backup system is either (i) activated after failure of the main system is detected or (ii) operated in parallel. Optical sensor networks can also assist in identifying failures within a telecommunication system. This information may then be provided to early warning systems to prevent the entire system from failing. For example, if one monitors a communications rack with hundreds of cables connected to it, the movement of this rack can be traced. If the movement exceeds a predetermined limit, a warning can be issued to maintenance staff and wires and cabling surveyed for potential damage.

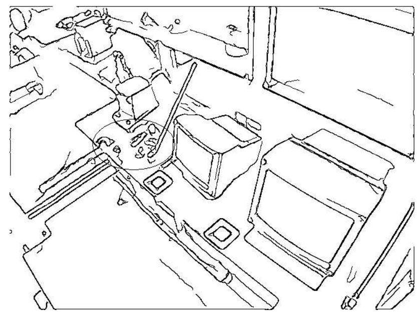
Another important example is related to potentially hazardous areas, such as biological or chemical science laboratories. These laboratories often contain hazardous chemicals unrestrained and mounted on shelves or bench tops. Spillage of these chemicals may result in subsequent hazardous areas within the structure. To further exasperate this, fire may also result where these chemicals are exposed to each other or combined with leaking gas or other fluids. Optical sensors can assist in detecting these types of situations and thus reduce hazards by turning of gas or other piping systems or warning people to prevent them from entering such hazardous areas. This facilitates a rapid method to inform the emergency personnel to be aware of such types of critical situations and be more attentive to primary hazard zones.

USING THE OPTICAL RECORD FOR RISK ANALYSIS

An example of how one may apply the optical record to risk analysis is shown in Figure 10. Part (a) of that figure shows one frame of a video stream captured during a shake table experiment which highlights a glass containers residing in the shelf falling down during shaking. Upon hitting the bench top the container breaks as can be seen in the image. Different image processing techniques may be utilized to extract further details from this image.



(a)



(b)

Figure 10. Glass container hitting the bench top during one of our shake table experiments; (a) shows the original image while (b) detects the breaking glassware using an edge detection algorithm.

By subtracting a reference image depicting the usual arrangement from the actual image it can be detected that there is a glass container missing in the upper shelf. Also, this method discovers that there is additional broken glass on the bench top. Of course, a robust thresholding is necessary to avoid false alarms.

A continuous monitoring approach using edge detection algorithms is able to reveal this situation as shown on in Figure 10(b). The path of the container can be tracked and its changing physical shape observed. In this case, even the individual parts of the broken glass container can be tracked using the video stream. Consequently, it is possible to determine that this container is broken. If it is known what kind of material was stored in this container, a hazard warning can be issued by the system automatically pinpointing that a potential risk exists in this area.

COMPARING OPTICAL TECHNIQUES WITH OTHER MODELS

Techniques available for monitoring the interior of building structures during earthquake motions and thus providing data for risk analysis include primarily analog sensors (wired or more recently wireless, force, displacement, acceleration, etc.). It may be difficult with such sensors (primarily due to the mass of the sensor itself) to mount and detect the damage to the glassware described in the previous section. However, if such an incident results in secondary hazards (such as a fire), smoke detectors will reveal the situation. But even then, it is not possible to determine the reason for this hazard nor it is possible to estimate the risk because it is not known why the fire occurred. The continuous monitoring approach proposed in this paper can provide detailed information about what exactly caused the hazard. This allows the system attached to the sensors to provide a more detailed risk analysis in case of such an event.

IMPENDING CHALLENGES

The use of optical sensors during an earthquake is rather challenging, primarily due to the potential for shaking of the sensor itself. This requires all captured images to be aligned before making any assertions about object movement within the scene. Therefore, some type of reference point in the scene is necessary.

The use of optical sensors at high frame rates to monitor nonstructural elements or other building equipment result in a huge amount of data, even when low-resolution images are acquired. Ideally, this information should be processed in real-time. In other words, the system must be fast enough to estimate the whole scene captured by the sensor at almost the same time the images are taken. In addition, most optical sensors require robust lighting conditions. During the nighttime or when building lights are not available, acquiring images with an optical sensor may be difficult. Night vision devices may resolve this problem. Finally, architects and designers need to be convinced that such systems are useful in emergency situations and that the benefits outweigh the additional costs.

The current implementation of the system described in this paper is able to capture and analyse scenes in a mock laboratory during simulated earthquake events. Displacement of objects in the scene can be conducted directly from the video streams. In the future, this system needs to be extended in order to be more versatile in recognizing and tracking objects. In addition, the system needs to be tested in the field to proove its usability when it is exposed to a real world example.

SUMMARY

In this paper, potential areas in which optical (camera-based) technologies can assist in risk assessment were identified. Several field application examples are described, largely encompassing the areas of civil infrastructure monitoring. Since optical (camera-based) systems can be particularly powerful for monitoring both local and global movements within a scene or environment, natural hazards such as earthquakes are an important application area for these new technologies. It is observed that concepts in the methodology applied to general civil infrastructure systems are readily applied to other types of natural or man-made hazards. Two important areas where optical sensors may be useful in seismic risk assessment are (i) early warning systems and (ii) post-earthquake assessment. Specific examples include: automatically shutting certain systems down to reduce the hazard, avoiding hazardous situations altogether, or warning people or rescue personnel of such impending hazards.

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