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PHOTO-NET II: a computer-based monitoring system applied to project management

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Abstract

This paper describes the development and implementation of an automated real-time monitoring system for construction projects programmed in a Delphi environment. The system links time-lapse digital movies of construction activities, critical path method (CPM) and progress control techniques. It accepts digital images taken from multiple cameras, stores them in chronological order and links them to a database that contains schedule information. The digital pictures taken from up to four cameras are placed on a website from where a remote computer(s) can capture and store the pictures in the database. The system enables management staff at the contractor's and owner representatives' headquarters to follow developments at the construction site in real time. Additionally, time-lapse films of activities at the construction site taken by multiple cameras can be played back in synchrony with dynamic graphs showing planned versus actual schedules. PHOTO-NET II introduces a new concept in time-lapse photography that allows the user to manipulate the frame rate, enabling a reasonable playback time as well as the implementation of the technology for long-term construction projects using standard PCs.

Keywords: Time-lapse; Camera; Computer-based monitoring system

1. Introduction

The complexity of managing construction projects has been described by Abeid [1] and Abeid and Arditi [2,3]. The utilization of automated real-time monitoring systems and the so-called web-based systems are rapidly growing areas with multiple potential applications that range from the detection of delays at early stages of a project through collection of productivity data and support of claims to accident investigations.

As claims and disputes increase, the construction industry struggles to find ways to equitably and economically resolve them. Although some in the construction industry prefer litigation, this preference is purchased at great cost. A study indicated that fees paid to lawyers and experts in litigation had increased 425% between 1979 and 1990 while settlement and

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verdicts had increased only 309% [14]. It costs more to get less in litigation than ever before [6].

The construction project must be designed in such a way that thousands of separate pieces can be fabricated, installed, and connected to create a complete functioning structure. Thus, it is not surprising that the construction industry has gained a reputation for being contentious and prone to litigation. In order to function professionally in today's construction project, one must be able to recognize and diagnose problems as they evolve and apply the appropriate principles in order to avoid or resolve these problems [11,16].

In construction disputes, disagreements are affected by a large number of complex and interrelated factors, many of which are schedule-related. Because these disagreements are difficult to document, the use of archived digital movies of the construction activity along with synchronized work schedules is proposed in order to minimize, if not eliminate, construction disputes.

The objective of the study reported in this paper was to minimize the occurrence of construction disputes by using a software package called PHOTO-NET II that connects archived film clips to schedule and progress information. After a description of the PHOTO-NET II system and a discussion of the challenges encountered in developing the system, the results observed in a case study are reported in this paper.

2. PHOTO-NET II system overview

PHOTO-NET II is a software package developed in a Delphi environment [7] that links images taken from construction sites and standard scheduling tools such as a critical path method (CPM) engine. Delphi is a Windows programming environment that provides users with the ability to create self-contained Windows applications. Delphi can be viewed as an object-oriented Pascal-based visual programming language. The Visual Programming features of Delphi provide strong links to the Visual Components Library classes of the Windows System.

PHOTO-NET II accepts and stores digital images that when displayed in sequence creates a film of the construction activities. The software, which runs on a remote computer, accepts digital images from up to four cameras by collecting those images from a website generated by a video server located at the construction site. The imagery serves as one part of the database, while the other part is composed of the planned and as-built scheduling data input by the user during the project's pre-construction and construction stages.

PHOTO-NET II requires the use of several hardware components including a microcomputer, a set of analog video cameras, a video server, two broadband Internet connections, power and coaxial cables and fittings (see Fig. 1).

The microcomputer required to run the system is a standard unit with an Ethernet card and a hard disk of at least 20-Gb capacity. The computer can be placed anywhere an Internet broadband connection is available.

Analog video cameras are installed in appropriate positions in the construction site in order to capture key activities. The cameras are connected through coaxial cables to a video server, which is a device capable of receiving analog pictures at a rate of up to 30 fps (NTSC standard), digitizing them, and posting them on a website. The video server can be installed at any location where it can be connected to a broadband Internet connection.

PHOTO-NET II makes use of the most recent technological developments in the areas of surveillance cameras and time-lapse photography. These features include the ability to receive, manipulate and display images from multiple cameras simultaneously; the ability to use the Internet as a communication medium between the cameras and the remote computer(s); and, the ability to control the playback frame rate when playing back the time-lapse movies.

The engine that plays back the imagery data also displays two dynamic diagrams: (1) the planned versus actual schedules in a bar chart format; and, (2) the planned versus actual percentage of completion in a histogram format. The engine also shows time-lapse films of the activities at the construction site taken from up to two different cameras (Fig. 2). Alternatively, the imagery data can be shown alone on a different screen where up to four movies taken from different cameras can be displayed simultaneously and in the same chronological order. The

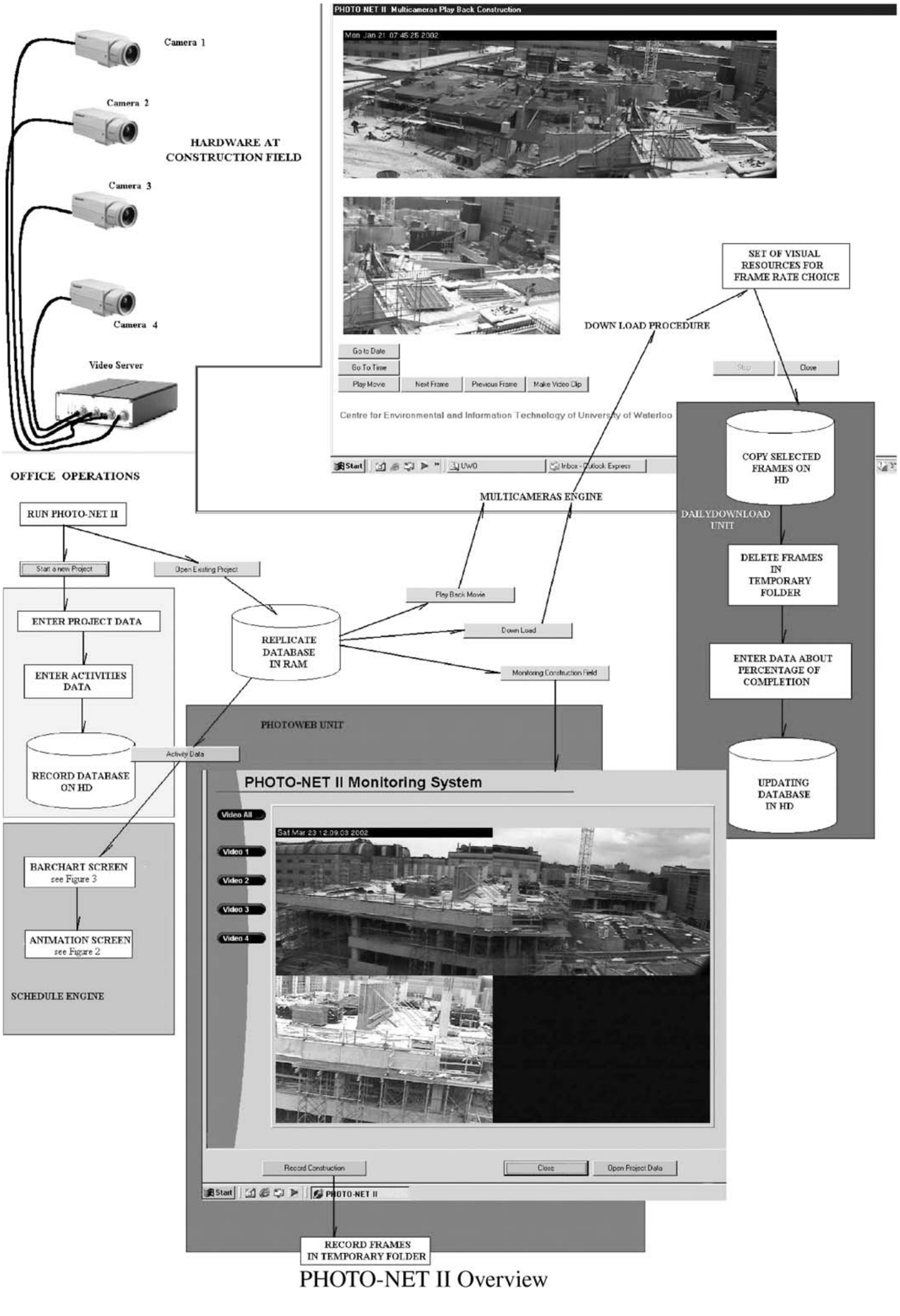
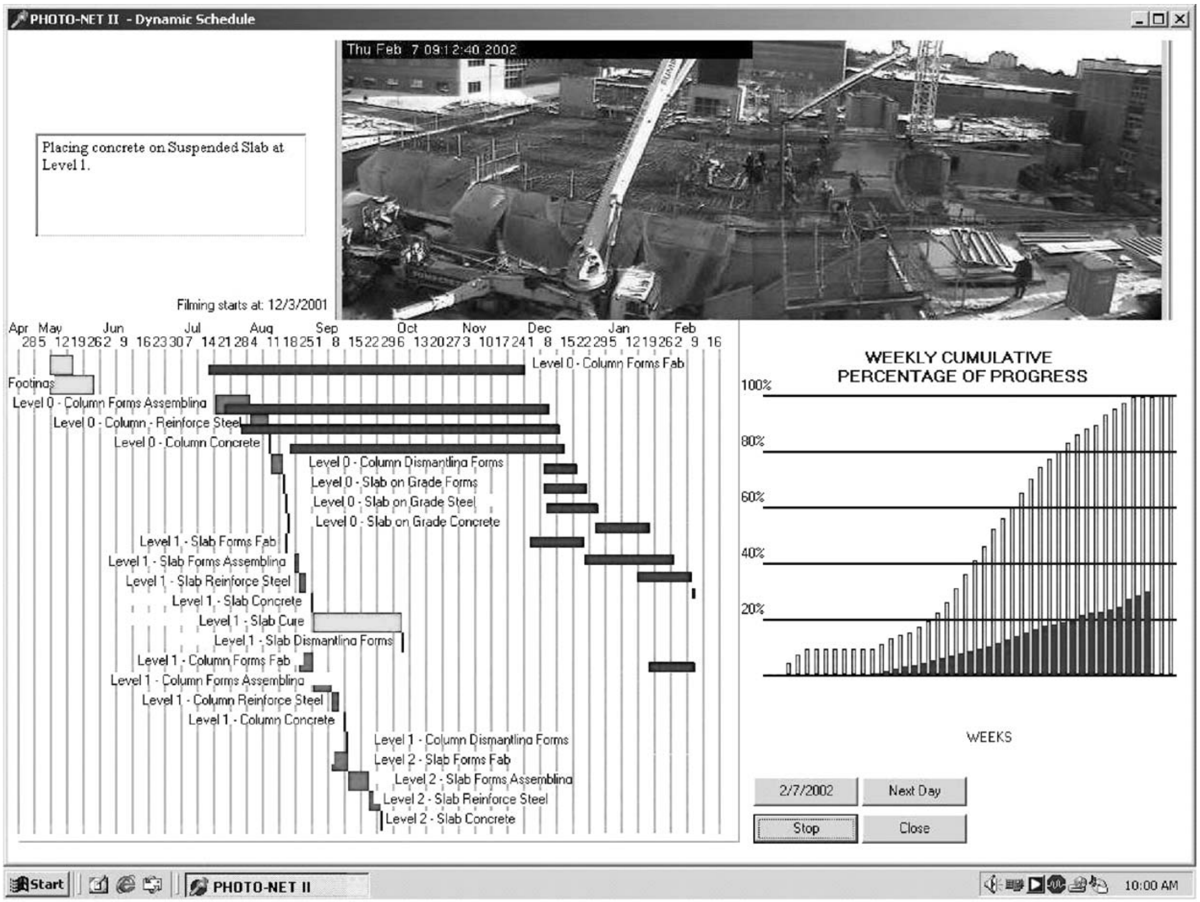


Fig. 1. System layout and hardware components.



Dynamic Schedule Screen

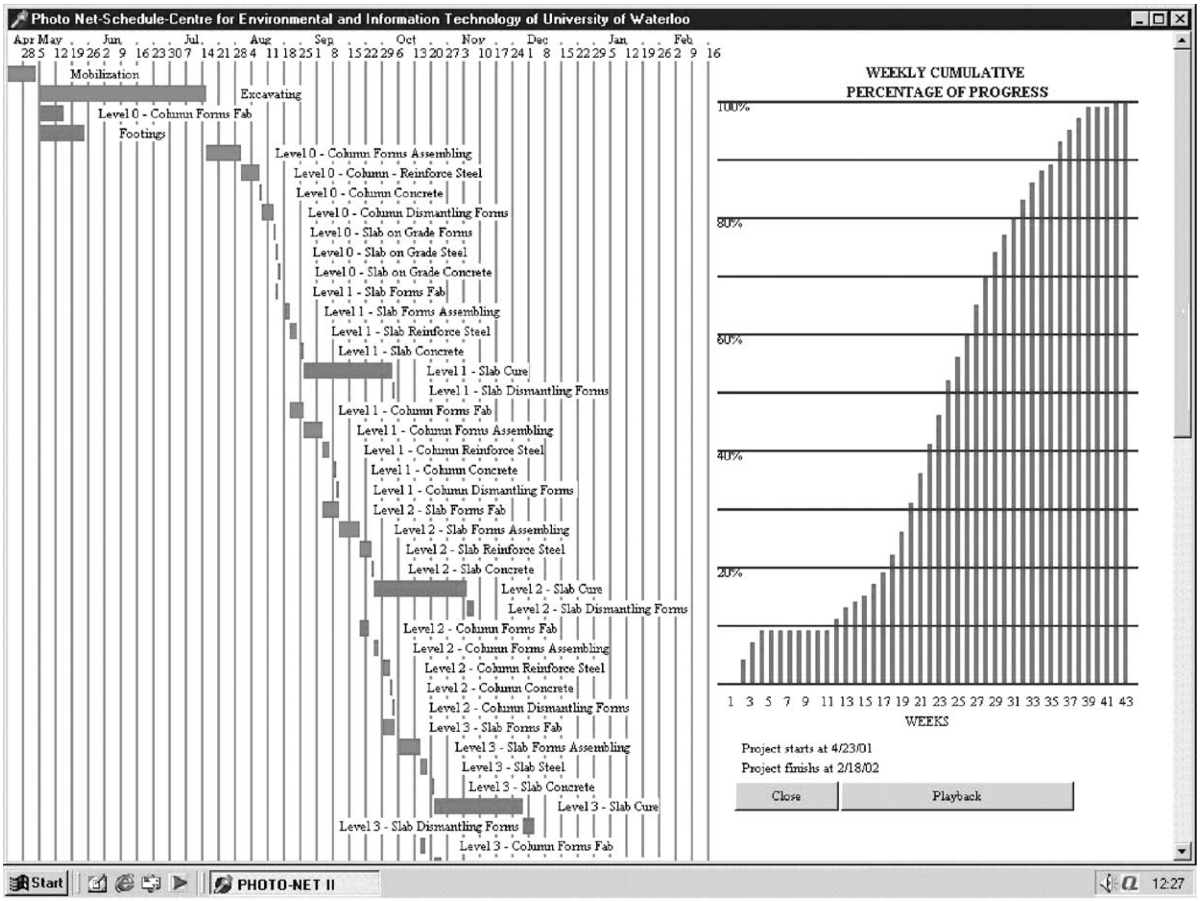
Fig. 2. Typical playback display: two fixed cameras provide a wide-angle view of site; dynamic diagram reflect imagery data.

program allows the user to change the frame rates in order to view the movies at a preferred speed, to view the occurrences in a particular day, or at a specific time. Thus, a frame-by-frame analysis of a short time interval can be conducted and stored for a significant event such as an accident, material delivery or a particularly adverse weather event. The requirements for adapting time-lapse photography to civil construction environments were investigated in depth by Abeid and Arditi [2].

This paper describes the extensive improvements and modifications that resulted from the need to overcome the difficulties that arose during the implementation of the first version of PHOTO-NET in a real-world environment [3]. The new features in PHOTO-NET II include the ability to receive, manipulate and display images from multiple cameras simultaneously; the use of the Internet as a communication medium between the cameras and the remote computer(s); and, the control of the playback frame rate when playing back the time lapse movies. PHOTO-NET II has eight main functions, namely:

- Inputting data: the user initiates a new project in the remote computer using the Input Data engine. The Input Data engine generates a screen where pop up menus are used to prompt the user to enter the data needed to initiate a new project and construct its related database. In addition to the standard information required by other scheduling engines such as name of the project, nonworking days, starting date, activity precedence and duration information, etc., the system also asks the user for input related to image management, including date at which filming should start, start and finish times of a regular working day, space in Gb reserved for the project on hard disk, and the IP number assigned to the Video Server.

- Generating a bar chart and a cumulative progress histogram: the core of the "Bar-Chart and Histogram Builder" consists of a CPM engine that generates the early and late start and finish times and floats of the activities. Based on the results of the CPM analysis two diagrams are generated and presented, namely a bar chart of the project and a histogram of the expected cumulative percentage complete (see Fig. 3).
- Calculating the maximum frame rate: following the CPM analysis, the program calculates the maximum frame rate that the space allocated for the project on the hard disk can handle based on the project's anticipated duration. The system stores frames of 360×240 pixels compressed in JPEG format to a size that ranges between 10 and 18 Kb.
- Monitoring and recording the construction activities: the construction monitoring and recording module acts as the interface between the system and the construction operations. It generates a screen on the remote computer (Fig. 4) that links with the website of the video server and presents the images captured by the hardware at a construction site in real time. This engine also allows the user to initiate a recording operation that will



Diagrams Screen

Fig. 3. Bar chart and cumulative progress histogram.

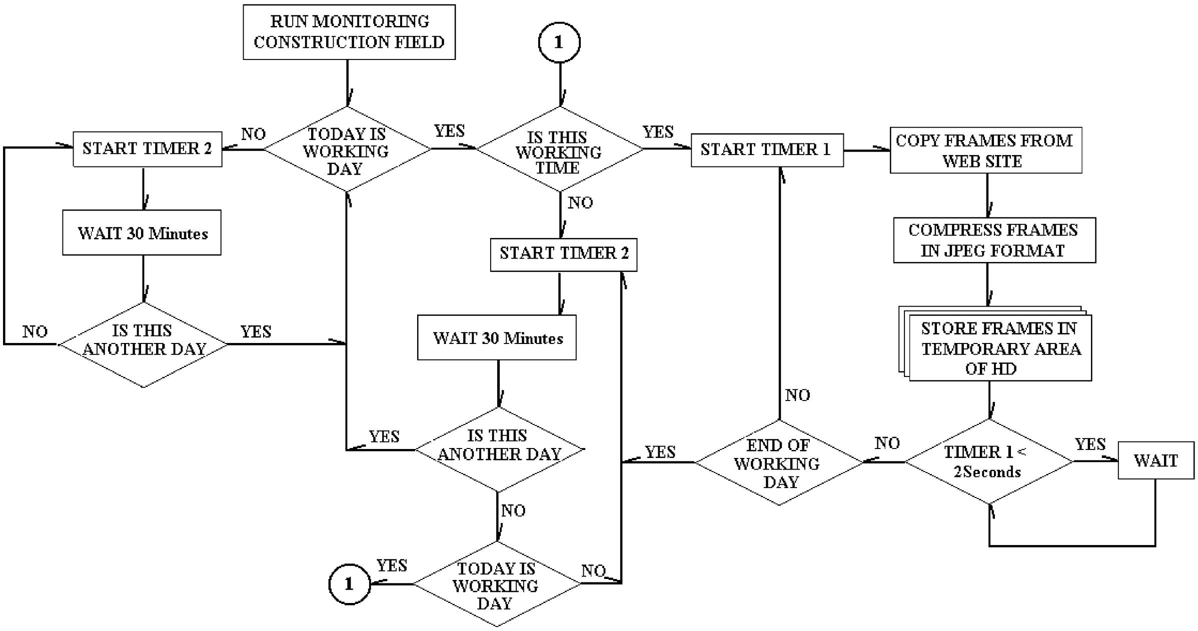
Web Interface

Fig. 4. Construction viewed in real-time from within Photo-Net II.

work continuously throughout the life of the project. If the system has a camera that can be commanded remotely, the website also allows the user to pan, tilt and zoom the camera in order to record a particular operation being performed in the field. By default the system records the entire set of images, but it allows the user to select which cameras he/she wants to record.

This routine also enables the launching of an automatic recording procedure, starting a loop with a built-in clock that allows the software to function without user interference for the duration of the project. A flow chart of the automatic recording procedure is presented in Fig. 5. Once the automatic recording procedure orders it, the program collects images from the website at a rate of 30 fpm for the duration of the working day. The images captured are stored in the temporary area of the remote computer's database.

- Downloading imagery: at the end of each workday, or after a couple of working days, the user can launch the downloading operation. The downloading engine allows the user to determine the desired rate at which the pictures are to be stored in the permanent area of the database. The user can watch the daily time-lapse photography movie (Fig. 6) by (1) playing back the frames starting at the beginning of the first workday in the temporary directory, (2) repeating the playback if necessary; and (3) going to a specific time and playing back a period of time frame by frame. The user then chooses the desired recording frame rate for a



Automated Recording Procedure

Fig. 5. Automatic recording procedure routine flowchart.

particular event or the entire workday. This way, a permanent record in the project database is created. The data in the temporary area are erased following the re-recording operation, and the system is ready to accommodate the next recording period.

- Creating link between imagery and schedule: the link between the digital images and the project scheduling data is accomplished via the user's input regarding the percent completion achieved for the activities undertaken during the same period. Percent completion provides the system not only with the amount of progress that a certain activity has achieved to date, but also implies that the activity was undertaken during that period, thus creating a link between the set of frames (movie) and the schedule of the project. In other words, time is the key attribute linking the two sets of data, namely the imagery and the progress reported for the various construction activities.
- Creating the animation: it is possible at any time to see scheduling information by playing back the movies obtained from two of the four available cameras. As can be seen in Fig. 2, the screen is divided into four windows. The top two windows are reserved for playing back the movies taken by the selected cameras. The lower left window displays the project's bar chart while the lower right window presents the 'percentage of completion' histogram. The animation engine of PHOTO-NET II displays the bar chart of only those activities scheduled to take place in a period starting 30 days before the time selected by the user and covering 15 weeks. The animation engine runs the two movies while simultaneously updating both graphs by building new bars that depict the progress corresponding to the frames displayed on the screen. Thus, the user can follow the performance of the activities shown in the movie by comparing progress with the planned bars shown in the diagrams.
- Playing back the construction movie: the playback movie module allows the user to run the entire set of movies captured by up to four cameras. The playback engine provides the user with the resources to view the construction operation on a given date and/or time. The viewing rate can be adjusted by the user. The movie can be viewed frame by frame or at an accelerated speed. This

Fig. 6. Preview of time-lapse movie prior to creation of permanent record.

facility enables the user to view any segment of the construction within a reasonable playback time.

3. Time-lapse photography

In its most traditional sense, time-lapse photography is defined by Webster's New Dictionary [17] as "a motion picture made so that when projected, a slow action appears to be speeded up". Time-lapse photography was used for many years in the fields of astronomy, biology and botanic studies to study various phenomena. In recent years, the concept of time-lapse photography was "rediscovered" in the fields of engineering and medical imaging. However, the concept was expanded to include a wide range of data types such as seismic measurements from oil fields, electrical tomography measurements of ground water, radar images from low flying satellites, and nuclear magnetic resonance imaging (MRI) of the human brain [10,13]. The objective of these studies can be defined as the creation of records with respect to time of a dynamic system placed at a particular, unchanging, physical location. The data are used to determine the changes in the system over time, and based on the knowledge gained to develop a more in-depth understanding of the system and/or to optimize its performance.

In civil engineering, applications of digital imaging technologies are becoming popular in many disciplines such as geotechnical engineering and transportation [4,5]. Potential applications of time-lapse photography in construction are many, including close-range remote sensing technology to survey topography on construction sites [12], the development of a camera-space manipulation system to assist in the control of robots in remote and/or challenging construction sites [9] and educational purposes [15]. Time-lapse photography applications in construction management and project control were examined by Everett et al. [8], Abeid [1] and Abeid and Arditi [2]. These researchers pointed out that there is no optimum frame rate for filming a construction project. A frame every couple of minutes can be enough on a rainy day when little is happening at the construction site. On the other hand, an accident investigation will require the highest frame rate possible [2,3]. McCabe and Tang [15] reported that frame capture rate, image resolution and the duration of recordings are the key parameters that affect the size of the digital file, and subsequently the consumption of computer resources and likelihood of system failure.

A special VCR called TLVCR has been used in the past to record time-lapse pictures of a construction site. This device allows the user to select the frame rate desired from a set of pre-determined rates. When working with digital pictures however the frame rate is not bound by predetermined settings and can be defined freely. The frame rate in digital operations can also be changed to a slower frame rate after recording has taken place by erasing intermediate pictures in a sequence to define a new lapse. This flexibility allowed the application of a new concept in time-lapse photography to be introduced to PHOTO-NET II. This new concept involves recording the digital images of the construction site at the highest frame rate possible in a temporary directory. This frame rate is dictated by the real speed with which the frames are sent by the video server over the Internet. In this context, a frame rate of 30 fpm was found to be reliable. Based on a preliminary review, a permanent record is generated by the user at a desired frame rate, potentially lower than the original recording rate.

PHOTO-NET II captures a picture from the website every 2 s (i.e., 30 fpm) and stores them in a temporary folder. Each picture has a unique name consisting of a set of digits formed by the date and time (day, hour, minute, second) at which the picture was taken. For example, if the desired frame rate to be recorded is 3 fpm on a particular day, the system would record the picture named as ddhhmmss, bypass the next nine frames and record the 10th one, in order to save one frame every 20 s (i.e., 3 fpm).

4. Challenges in programming PHOTO-NET II

This section describes the innovative features of PHOTO-NET II. The difficulties encountered when streamlining data generated by multiple sources along a single route (the Internet) at a fluctuating communication rate, and the solutions developed to overcome these difficulties are also discussed. Other challenges faced in the development of PHOTO-NET II include meeting different data requirements of potential users (i.e., contractor, owner, consultant), limiting the effort associated with the manipulation of relatively large computer files using standard PCs, and overriding requirement of data integrity and system robustness as it envisioned that the construction site been monitored will be located hundreds if not thousands of kilometers from the user(s). An overall flow diagram of PHOTO-NET II is provided in Fig. 7.

4.1. Developing a web-based system

One of the system's most attractive features is its ability to interact with the web. The global reach of the web, the ever increasing speed and capacity of communication networks and the availability and low cost of internet connections in most North American cities make the web an efficient and cost effective mean for transferring project imagery data between construction sites and headquarters of construction companies, owners and consultants. A web-based system also allow users at remote locations to log on for a pick or regular data downloading. Each remote station can capture data at the rates it deemed suitable for its specific needs resulting in a significant savings in computer resources. The user can see the website of the video server from inside the software and view activities at the construction site in real time. The system has been built in such a way that when the user needs to monitor the activities on the construction field, it browses the project's database searching for the IP number of the video server as an input parameter for the TWebBrowser class provided by Delphi, which is the core of Windows Internet Ex-

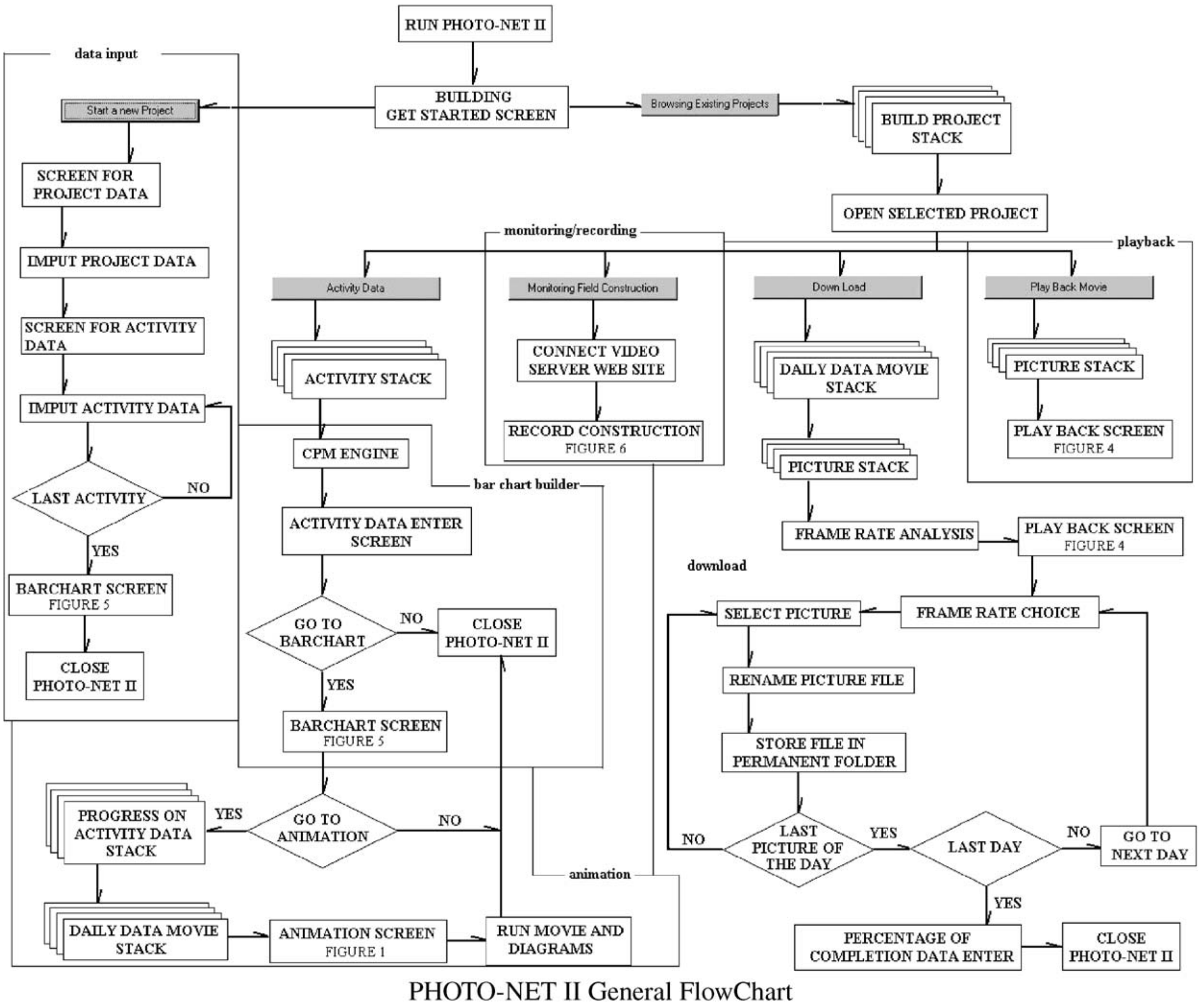


Fig. 7. Photo-Net II flowchart.

plorer. A link is then established showing the website of the video server.

4.2. Using multiple cameras

A significant feature of PHOTO-NET II is the use of multiple cameras on the construction site. Multiple cameras allow better coverage of the activities on the construction site, particularly if the construction is large and complex. A combination of fixed and zoom/tilt cameras can be used to maximize the area and/or activities covered during the course of the project while minimizing the investment in monitoring equipment. The use of multiple cameras affects not only the quantity of the imaging recorded in the temporary area of the database but also the duration of the downloading operation.

The images are obtained by copying the area of the canvas of the website reserved for displaying the images sent by each of the cameras, compressing them into JPEG format, giving a name to each file using the time at which the pictures are captured from the website, and storing the files in the temporary directory of the remote computer. Because images are captured in sequence, a lag time exists between images from the different cameras. Also, occasionally, a period of time can be missed due to failure of the Windows operating system or the video server, or delays caused by slow communication over the net. While not frequent, such occurrences must be accounted for. Thus, the system was given the capability to recognize and manage gaps during the daily recording period.

4.3. Refining the downloading operation

The first operation performed by the system during the downloading procedure is to browse the entire set of frames searching for such gaps and to calculate the expected frame rate. A procedure named Frame Rate Analysis was coded in order to calculate the lapse between frames and to classify this lapse as a gap or an acceptable lapse.

In previous research, it was determined that 10 s is an acceptable frame rate for productivity analysis [2] and so 10 s was defined as the limit for an acceptable lapse, designating longer lapses as gaps. The Frame Rate Analysis engine browses the entire set of frames determining the existence of gaps and presenting a report at the beginning of the downloading operation showing the starting time and duration of each of the gaps found.

4.4. Playing back a time-lapse digital movie

In the first version of PHOTO-NET, the pictures were recorded on a computer located in the construction site [3]. So the frame rate of the recording was severely limited by the size of the computer's hard disk and had to be constant through the entire operation. PHOTO-NET II however allows recording at different frame rates but building this facility into the system required considerable work.

In PHOTO-NET II, the recording happens remotely on a computer placed in the office of the Project Manager. The recording engine is built using multiprocessing technology that allows the user to run other tasks simultaneously. The drawback of this technology is that when the user runs other programs, the recording frame rate varies; the 2 s of lapse sometimes becomes three or even four. Playing back a set of frames at such unpredictable rates was a major challenge in an engine that links the movie to other data at run time and that uses "time" as the link.

In order to display the sequence of pictures to create the film of the construction activities, the program has to have the means to find out the file name of each picture stored in the database. One of the solutions would be to store all the file names in the database, but the amount of pictures (more than a million in the Waterloo project described in Section 5), would generate a large file, would be difficult to replicate on RAM, and would require a large number of readings from the hard disk at run time slowing the entire process.

The solution was to compress that large file into a smaller one in the same way that a JPEG engine compresses a picture, and make the software extract the name of every picture by handling the data stored in that file. To this end, a file called DailyFrame was declared to store these records. Every record in DailyFrame reserves a field for the first picture and another for the last picture of a sequence during a period that a particular frame rate has been kept. During the download operation the system checks the lapse between pictures and instantiates a new DailyFrame every time the lapse between frames differs from the previous one. This way the movie is completely mapped in a file that can reach only a couple of Mb, which can be replicated easily on RAM along with the entire database of the project when the program is started.

4.5. Synchronizing the playback operation

Synchronizing the movies obtained from the multiple cameras was another major challenge. The system is expected to play back in the same chronological order several movies that originated from different cameras. A two-dimensional array named FrameName was declared to store the imagery data using the following format:

FrameName $[C, T]$

where: C = camera's number (1 to 4), T = one of the three sets of two digits representing hour (hh), minute (mm) and second (ss).

During the frame rate analysis, the system records the earlier picture captured by each camera filling the fields of FrameName with the corresponding data. When working with multiple cameras, a time gap develops between the instances at which images are captured from the various cameras. For the case of three cameras, the time gap was found to be approximately 1 s. To compensate for this gap the following procedure was developed and implemented. The playback operation begins by browsing the camera's corresponding directory for the earliest picture taken that particular day. It is accomplished by initializing the FrameName array with the starting time of a regular working day in every camera. A loop is then started by assigning the new time as being equal to the previous time record for the first camera plus 1 s. The directory of the first camera is browsed to see if there is a file named after that time. The above described operation is then repeated for the next camera until all cameras have been checked. The loop is repeated until FrameName has stored the first set of frames for the day.

The playback engine then begins by showing the images that FrameName has stored. It then starts the above described loop again by adding 1 s to the file name until a new set of pictures has been stored in FrameName. The engine verifies that the variance between the earlier and later frames does not exceed 1 s. Frames that do not meet the 1-s variance are deleted from FrameName.

5. Case study

PHOTO-NET II was tested and debugged while being used to monitor the construction of the Centre for Environmental and Information Technology, a six-storey educational building located on the campus of the University of Waterloo, Waterloo, Ontario. Construction began in July 2001 and was scheduled to be completed by December of 2002. PHOTO-NET II was used to monitor the erection of the concrete structure of the building (total construction cost is estimated at approximately CND$34,000,000). The system was used with three surveillance cameras. Two of the cameras were in a fixed position such that their images could be merged in order to create a single wide-angle image of the entire construction site (Fig. 6). The third camera could be controlled remotely through the website in pan, tilt and zoom.

The set of cameras was mounted in a wooden frame and placed on the roof of a neighboring building, approximately 20 m from the edge of the construction site. The cameras were connected to a video server installed in a sheltered location nearby. The video server was tethered to a 10 Mbs Internet connection.

PHOTO-NET II was installed on computers located at the headquarters of the construction company responsible for erecting the concrete structure as well as at the University of Western Ontario, both sites located 130 km away from the construction site. Monitoring of construction began in early December 2001 and continued until the end of the summer of 2002.

PHOTO-NET II assisted in optimizing the operations of the concrete structure contractor during the course of the project. The following results were obtained:

- The number of trips of the senior management to the construction site was reduced as progress could be viewed on the remote computers and details could be discussed over the phone. The pan, tilt and zoom capabilities of the third camera played a major role in the progress evaluations.
- The staff of the construction company were able to compare their productivity indexes with the real productivity observed by playing back the recorded operations.
- The performance of equipment was easily observed.
- The timeliness of material deliveries to the construction site were closely monitored.
- The staff at the headquarters were able to observe the serviceability of the layout of such facilities in the construction field as the position of the delivery area, stock areas and workshops.
- It was possible to easily estimate the percentage of completion of various construction activities for progress billing purposes.
- The effects of inclement weather were clearly observed.

The trial implementation demonstrated that the system could serve as a deterrent against disputes between owners and contractors, potentially reducing the number of disputes that end up in arbitration chambers or courtrooms. The construction project encountered difficulties due to unmapped buried utilities that were found during excavation in the early stages of the project. These difficulties resulted in significant construction delays. The information provided by PHOTO-NET II could have been used to recreate the project in support of the claim put forward by the construction company for additional compensation due to the significant delay, had the system been in place at the time of the delay. It is believed that the detailed information provided by PHOTO-NET II could have promoted a rapid resolution to this claim, and a reduced possibility of litigation.

The successful implementation of the system at the Waterloo site prompted the construction company to use the system on a regular basis. A second set of cameras was installed in a second construction site. The set of cameras used in the Waterloo project is monitoring a third construction site since April 2003. A third set of cameras is scheduled to monitor a fourth site starting mid-May 2003. In addition to real-time project control, the company is considering the utilization of the data generated by PHOTO-NET II to assist in their estimating activities in similar new projects.

6. Conclusion

The combination of time-lapse photography, project control techniques and Internet technology provide a powerful tool to a project manager, enabling the remote diagnosis of construction problems in real time, enhancing communication between the site superintendent and the office staff, and providing another source of information to the parties involved in the contractual agreement regarding on-site activities. The prototype software described in this paper is capable of communicating over the Internet with surveillance cameras located at a remote site, making the proposed system suitable for remote or off-shore projects, where frequent site visits by management are impractical.

The ability to accept and process imagery data from multiple cameras allows practical implementations such as (1) producing a high resolution wide-angle view covering the entire construction site created by merging images obtained from two or more cameras, (2) providing views of the construction site from several angles simultaneously, and (3) offering maximum versatility by using a combination of fixed and tilt and pan cameras.

A time-lapse film of a construction project is a unique historical document. Thus, it is envisioned that one of the most important contributions of integrating time-lapse photography, scheduling software and project control tools is promoting a contractual environment where schedule-related claims are discussed and resolved more easily based on factual and objective information available to all parties associated with the construction process. PHOTO-NET II was successfully tested in a real-world environment and received a favorable response from the parties involved (e.g., less frequent site visits, better understanding of the project's progress, etc.). The potential benefits associated with the implementation of PHOTO-NET II can be further enhanced by adding automated image processing capabilities to augment the benefit derived from the digital data and its amalgamation with other project control related information.

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