Vision System for Tower Cranes

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Abstract: Operators of tower cranes enjoy a bird's eye view of the site, which undeniably contributes to work safety and efficiency. Yet their work often involves blind lifts, as well as other viewing difficulties, that impede full utilization of the potential inherent in the operator's location atop the crane. This paper reports on a tower-crane-mounted live video system that offers a solution for such difficulties, and consequently, enhances safety, improves productivity, and brings about direct and indirect cost savings. The development and implementation of the vision system are described as a successful academia–industry research and development joint effort. Work studies of numerous craning cycles resulted in considerable time savings, depending on the nature of the lift, lighting conditions, and viewing obstructions. In addition, a detailed list of benefits drawn on the basis of feedback received from the field is presented. The paper is aimed, first and foremost, at project managers as well as construction equipment and safety practitioners, who daily experience those situations that have prompted the development of the system. Researchers may benefit mainly from the lessons learned with respect to the role of academia–industry cooperation in the introduction of innovative systems in construction.

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Introduction

One of the differences between tower and mobile cranes is the location of the operator cab: at ground level in mobile cranes; at the top of the crane in tower cranes. Remote controlling of tower cranes, either from ground level or any other convenient location, is possible but not common (Peurifoy et al. 2006), and is associated more with the operation of the smaller self-erecting, telescopic-mast, bottom-slewing tower cranes and rarely with that of the hammerhead or luffing-jib, top-slewing construction cranes that dominate the urban construction scene (see Fig. 1 for basic crane types and terminology).

This difference, which is not merely technical but rather part of the concept of tower cranes versus that of mobile cranes (Shapiro et al. 2000), grants the tower-crane operator the advantage of a wide field of vision and a complete view of the site, which are helpful for rigging, craning, and unloading. With clear lines of sight, productivity is improved and safety is enhanced (Peurifoy et al. 2006). But even with the operator positioned at the top of the crane, several operational difficulties associated with the operator's vision are often unavoidable.

Fig. 2 depicts five situations illustrating five different visibility limitations that are, typically, an inseparable part of tower crane operation. The most common limitation is the obstruction from the operator's view of the theater of work, i.e., the loading area, unloading area, or travel path [Fig. 2(a)]. This problem, often termed a "blind lift," exists, to some extent, on the vast majority of construction sites. Another limitation is caused by poor lighting conditions. This can be either darkness at dawn or late-hour work [Fig. 2(b)], which is only partially compensated for by artificial lighting. Moving the crane hook from broad daylight to shaded areas [e.g., elevator/stairway shaft; Fig. 2(c)] also challenges the human eye's capacity for quick adaptation to sudden changes of light intensities. Fig. 2(d) exemplifies yet another situation in which an increasingly inconvenient angle of vision is created with the increase in ratio between the lifting radius and the vertical distance to the loading/unloading area. This limitation is experienced, for example, when handling heavy, oversized elements, such as precast concrete planks that require both precise positioning of the lifting hook over their center of gravity and precise placement. The final limitation is the great, mostly vertical, distance of the loading/unloading area from the operator eyes [Fig. 2(e)]. This situation, which is always the case in high-rise construction, may also occur in lower structures, in which the crane is often assembled to its full height already at the beginning of construction, either because of site constraints or to save the costs and work interruptions of crane climbing processes during construction (Peurifoy et al. 2006).

As experienced by all those involved in construction site operation, the above-listed limitations have a major negative effect on both productivity and safety on site. Today's partial solution, as with mobile cranes, is commonly the use of signal persons. But any means that can lessen the dependence on signal persons is welcome: the cost of labor is high; the nature of tower crane service requires the simultaneous positioning of signal persons at various locations; all too often signal persons are undertrained; communication-related misunderstandings occasionally occur and language barriers exist sometimes (most notably in recent years, with the growing use of foreign workers); and responsibility for

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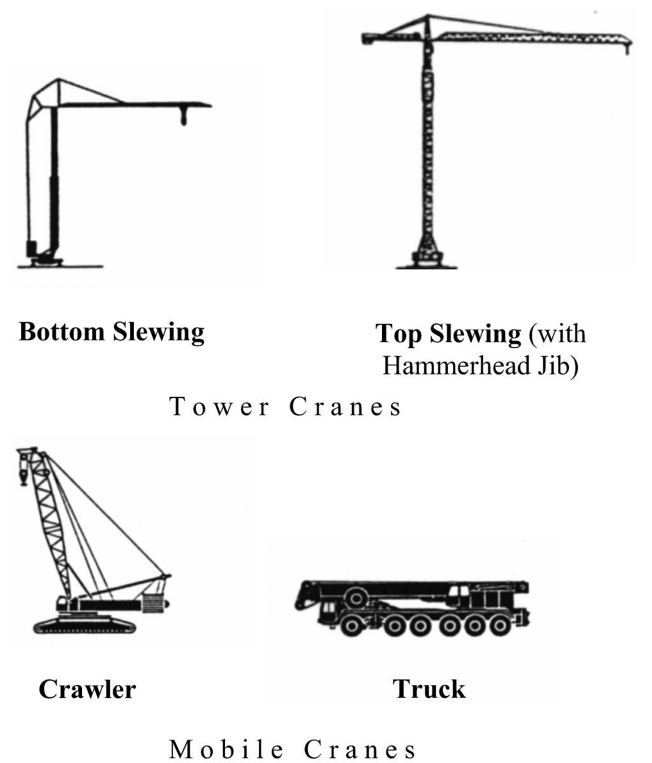

Fig. 1. Basic crane-type terminology

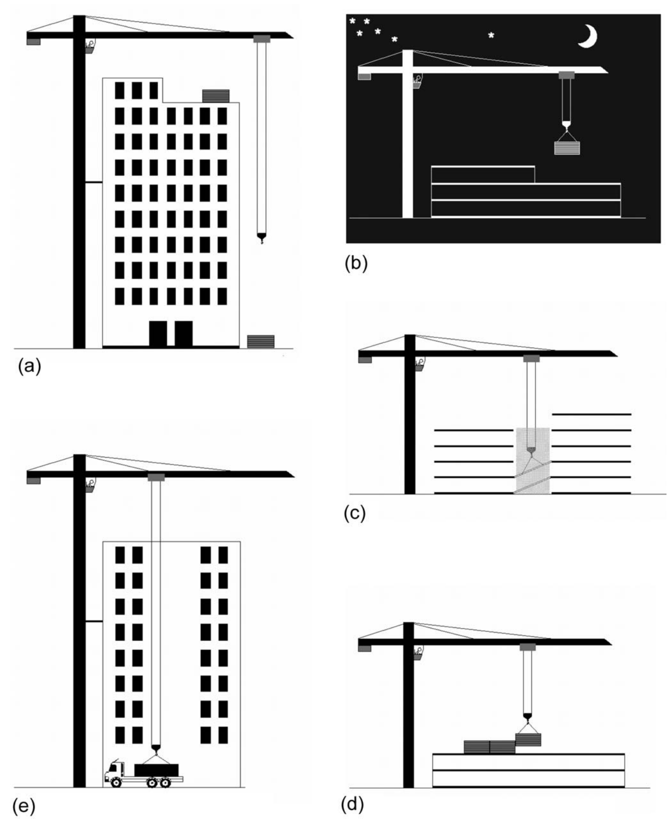

Fig. 2. Visibility of load from operating position: (a) obstructed loading/unloading area; (b) dawn/dusk hours or night work; (c) shaded loading/unloading area; (d) loading/unloading area at inconvenient angle of vision; and (e) loading/unloading area at a great distance

the lift is undesirably distributed (Häkkinen 1993; MacCollum 1993; Ross 1996; Neitzel et al. 2001; Shapira and Lyachin 2004, 2008).

This paper presents a crane-mounted camera system developed with the view of countering these limitations and their resulting negative effects, and thereby taking full advantage of the potential of the crane operator's bird's eye view and control of the site. The paper describes the development of the system as an academia–industry collaborative effort, its implementation and assimilation as an indispensable operator aid on numerous construction sites, work studies showing how it reduces crane cycle times and speeds up construction, and testimonies as to its many other benefits.

Background

The basic idea is not new. Rear-mounted cameras to aid truck drivers have been in use for many years. Everett and Slocum (1993) developed Cranium, a mobile-crane mounted camera for improving productivity and safety. Rosenfeld (1995) listed video cameras among various safety and efficiency improvement devices that can be incorporated with computer-controlled tower cranes. Video cameras mounted on two Lampson crawler cranes have reportedly been key to the success of a major, unique tandem lift in Australia (Kennedy 1996). *Cranes Today* magazine (2000) reported that close to 1,600 crawler cranes in Japan were fitted with wired close-circuit television cameras as a safety feature; Techno Fine, one of the manufacturers mentioned in that article, now offers crane camera systems in the United States (Techno Fine 2006). In Europe, Orlaco, a Dutch manufacturer of camera-monitor systems for land and sea vehicles, offers vision solutions for cranes (Orlaco 2006). Finally, in his editorial on technology progress, Vallely (2005), editor for *Cranes Today*, lists cameras fitted on top of crane booms as the first of four examples given after maintaining that "there can be no compromise on crane safety equipment."

Common to all these devices is the concept of providing the operator with a vision aid, which reduces the problem of concealed work areas, and consequently improves on-site productivity and safety. A camera is mounted onto the crane such that it constantly follows the load. The image is transmitted (mostly by cable) to a monitor located in the operator cab, and the operator can thus see work and hook-travel areas otherwise not within his or her line of sight.

The general advantages of such a system for *tower* cranes on building construction sites are obvious, while its cost is relatively low. The price of systems offered on the market is in the range of US$15,000–US$25,000, which adds, as a conservative estimate, 4% to the price of a new average-size, top-slewing tower crane. In a more developed and competitive market, camera-system prices are likely to go down and constitute an even smaller percentage of the crane's price. Systems are also offered on a lease basis of around $500 per month, a small fraction of the monthly site operation cost. However, up until the experience reported in the present paper and in spite of these advantages and low costs, such systems have not found their way to any considerable number of sites employing tower cranes. This has been conspicuous mostly in Europe, the cradle of the tower-crane culture, where a mere handful of these systems were used in the late 1990s. This, at a time during which tens of thousands of top-slewing tower cranes

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were in use throughout Europe (Shapira et al. 2007). In a scholarly review of crane safety in the construction industry published in December 2001 (Neitzel et al. 2001), crane cameras are not even mentioned among the various safety devices listed. It was not until the end of 2005 that *Cranes Today* magazine (Howes 2005) was finally able to report on a somewhat increasing interest in tower-crane-mounted cameras, although not in numbers that even compare to mobile-crane cameras of various types (including rear-view and winch-view cameras).

Given this state of affairs, the acquisition by construction companies in Israel, since 1998, of dozens of systems as reported here, and the change this has brought in work modes and crane operation on numerous construction sites, are exceptional and worth learning from: the product, its development and introduction into the market, as well as lessons learned through close field monitoring of its on-site service. Nearly 1,000 top-slewing tower cranes were used in Israel in recent years (CIS 2005), an impressive number by any standard, and certainly relative to the country's population of seven million [compared with a similar number of tower cranes in the entire United States, with its population of 300 million (Shapira et al. 2007)]. Roughly 10% of these cranes are used on high-rise construction projects, the natural (though not only) market for tower-crane cameras. Between 1999 and 2001, about half of those high-rise cranes were equipped with the vision system as described in this paper, virtually reaching the point of market saturation. This took place not only in an inherently conservative industry (Tatum 1987; Rosenfeld 1994; Dulaimi et al. 2002), but also during the peak years of a deep recession of the Israeli construction market, which unsurprisingly resulted in a reluctance on the part of construction companies to invest funds in anything that did not appear to be essential.

Development

Development of the vision system began in early 1998. Two immediate needs were determined as crucial in the development of a prototype: (1) to gain the cooperation of a major construction company and access to one of its sites, preferably a busy one, that would serve as a testing site; and (2) to conduct work studies with the hope of obtaining satisfactory results, namely shorter crane work cycles, right from the beginning.

At that time, a major project [100,000 m^2 (1,100,000 sf), nine-story shopping and entertainment complex] was under construction in Haifa, simultaneously employing six tower cranes (Fig. 3). It was built by a joint venture of two of Israel's top 10 construction companies (D&B 2005). This site met the criteria that had been set and, additionally, offered a substantial extent of overlapping work envelopes among its tower cranes, which would put the prototype system to rigorous testing.

The camera research and development (R&D) project was presented to the top management of that construction project and gained its approval and willingness to cooperate. A 54-m (177-ft) high free-standing Comedil CT 603 tower crane was designated for the job [the rightmost crane in Fig. 3(a); the leftmost crane in Fig. 3(b)]. In addition to the high crane density situation, the work area (loading, unloading, and/or travel) was hidden from the sight of this crane's operator for a considerable part of the time. The crane was continuously busy throughout the entire workday, and occasionally worked during the night as well. At the time of the prospective testing, the crane's work assignments were to include a variety of repetitive, duty-cycle lifts. All these parameters rendered this crane ideal for the testing of the camera in a real, constrained site environment. Last but not least important, was the fact that the two operators assigned to this crane were highly recommended by their employers; their cooperation would be essential for the success of the testing.

On-site testing started with the installation of the first prototype in early July 1998. Eventually, two additional prototypes, each an improved version of the former, were installed and tested over the next three months. During this period, numerous long visits were made to the site by the R&D team, usually involving a climb up to the operator cab. These visits included observations, interviews with the operators and signal persons, and a variety of technical operations to install, maintain, and run various checks on the system, performed mainly from the crane's jib and under the trolley. Crane work was not to be interrupted, a requirement that added another dimension of complexity to the entire effort.

In parallel, time studies were conducted, as described in detail later on. Initial results were encouraging, as were the conclusions derived from the various observations and interviews. Responses of the two crane operators after having used the system for just one day were rather enthusiastic. Primarily, they mentioned the help it provided under circumstances where the load was not within their sight (e.g., behind walls), in darkened areas (e.g., inside shafts), and when precise location of the hook above the center of the load was required. One operator ran his own test: without looking at the camera, he guided the hook directly above what appeared to him to be the center of the load to be lifted. He then checked the image on the camera only to find out he was about 2 m (7 ft) off center. The two operators attested both to the sense of confidence the camera instilled in them and to the higher speed at which it enabled them to operate the crane. Even when still using signal person guidance within full view of the work area, the camera enabled them to see the signals more clearly, and in fast travel it added another angle of vision to help identify objects located beneath the moving load.

Toward the completion of the development phase, all people involved—researchers, crane operators, signal persons, and site personnel—shared the conviction that the system clearly constitutes an operator aid and improves both site productivity (through shorter crane cycle times) and safety. Upon termination of the initial development at the test site (development was then to proceed to other sites with each of the first newly installed commercial systems), the crane operators would not part with the system and the monitor in the cab; they had gotten used to working with and benefiting from it. This is mentioned here because it was, in itself, an important supportive indication as to the merits of the system.

System

In its current final form, the system comprises two main modules. The *moving unit* (Fig. 4) is installed on the trolley that travels along the horizontal crane jib (in a hammerhead, top-slewing tower crane). This unit includes a high-resolution, autofocus video camera that is permanently directed downwards at the work scene, with the lifting hook constantly located at the center of the image. The video image is processed and transmitted to the crane operator cab via wireless communication.

The *stationary unit* is installed in the cab. It receives and decodes the video transmission, and displays it to the crane operator on a high-resolution color monitor. The operator can control the picture and navigate through different zoom modes as required.

The continuous video transmission is performed at a radio

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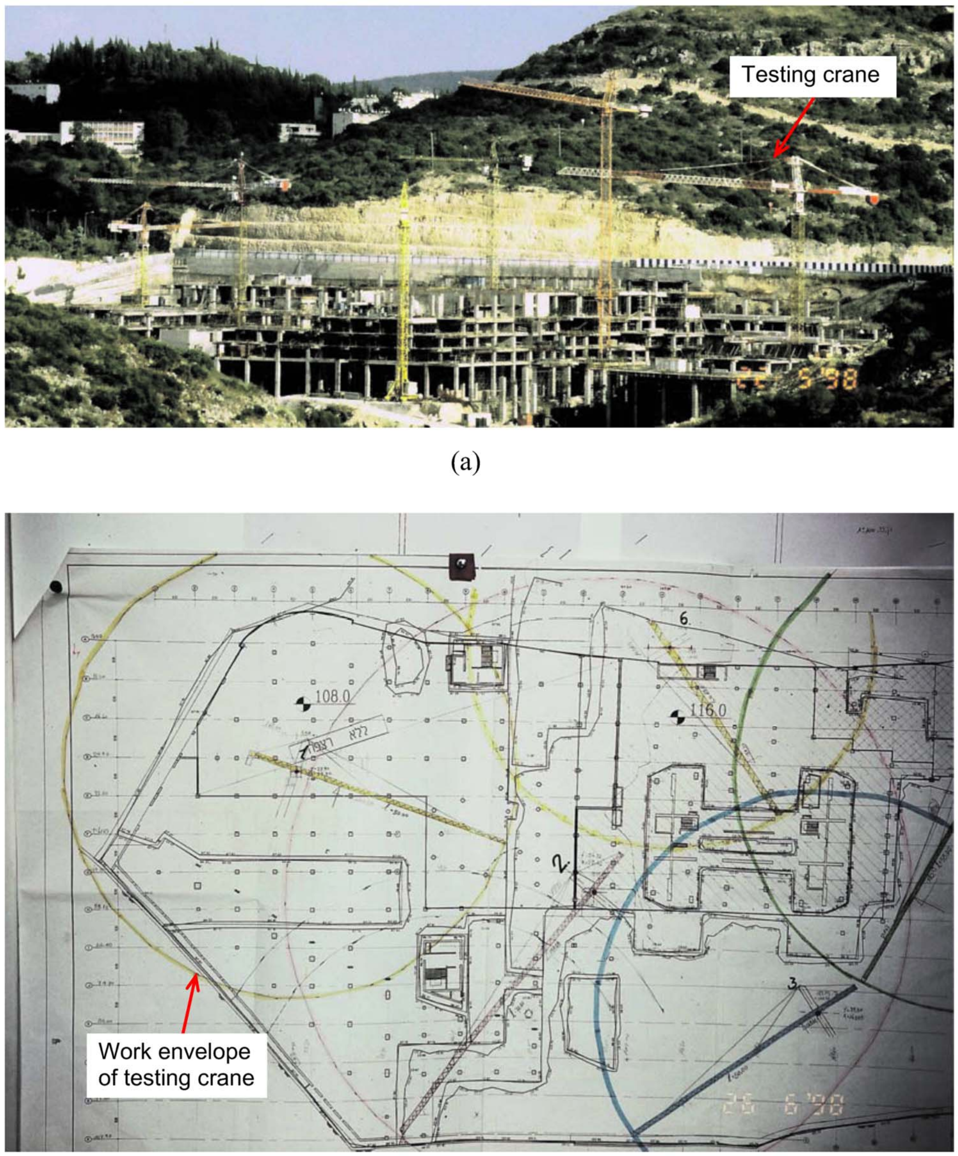

(a)

(b)

Fig. 3. Testing site of the vision system (Haifa, Israel): (a) general view of six overlapping tower cranes; (b) site layout plan showing work envelopes of five of the six cranes

frequency of 2.4 GHz, while the moving unit is remotely controlled from the cab using radio signals in the form of 433 MHz pulses. Directional antennas are used on both the transmitter and the receiver for communication (always horizontal in hammerhead tower cranes) between the cab and the moving trolley. The transmitter's antenna concentrates the radio energy in the desired direction, while the directional antenna on the receiver picks up almost no disruptions ("noises") from undesirable directions.

Rechargeable batteries (12 V), connected to solar panels that usually suffice to keep the batteries constantly charged, power the moving unit. The solar panels are mounted on the handrails of the trolley's service balcony (see Fig. 4). As a backup alternative (rarely required, and usually only during the winter), the batteries can also be charged overnight using a 12 V charger, situated in the cab, and an easy-connect cable. The primary function of this charger is to provide 12 V DC power supply to the stationary unit inside the cab, namely, the color monitor (CRT or LCD), the video decoder, and the remote control transmitter. The charger is fed directly from the cab's electric supply (100–400 V AC input), and is protected against electrical surges and spikes. The moving unit is also protected against overcharge on the one hand, and battery depletion on the other. To save energy, if unused for an extended period, usually 30 min, the entire system turns off automatically. The moving unit is housed in a sealed, weatherproof aluminum case, equipped with shock absorbers that dampen trolley vibrations.

Special attention was given to minimizing the weight of the system parts that are mounted on the trolley, such that the lifting capacity of the crane at maximum reach—commonly in the range of 1–6 ton (2,000–13,000 lb) (Peurifoy et al. 2006)—is practically unaffected. This was accomplished by using advanced, lightweight materials as well as by careful design of the mount brackets. The combined weight of the entire moving unit and power supply unit in the final system configuration is 25 kg (55 lb).

Throughout development and until the system reached its

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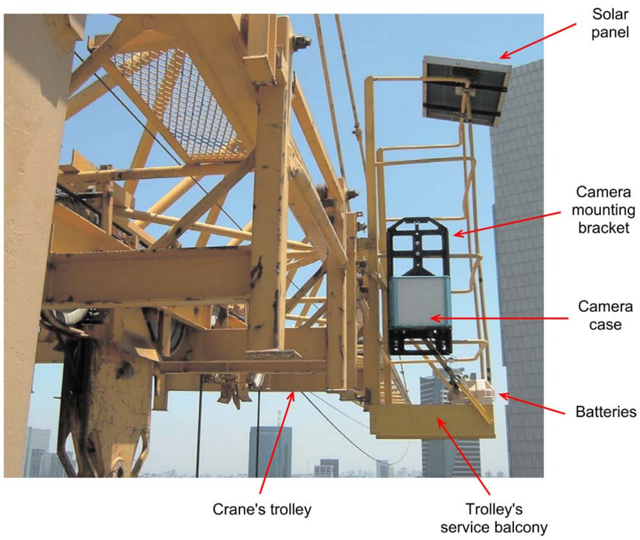

Fig. 4. Vision system: moving unit and power supply unit

present final form, emphasis was placed on providing the operator with an aiding device that caters to the unique work environment of the construction site in general and within the operator cab in particular, as well as to the operator's modus operandi. Tower cranes enjoy a lifespan of 20 years and more (Rosenfeld and Shapira 1998; Shapira and Lyachin 2004). Most vision systems would, therefore, be mounted on used, and in many cases even old, cranes. These cranes commonly have tiny cabs and space is quite limited, a factor that must be carefully considered when deciding on the size of the monitor and its location. The location of operation buttons took into account the various other tasks of the operator, who must be facilitated, not impeded by the system. Likewise, continuous zoom was ruled out in the course of development, as it was found to distract the operator's attention. Most cranes, therefore, do with two preset zoom levels, while three or more levels are recommended only for cranes over 150 m (500 ft) high. The modularity of the system and its mountability on any crane model were deemed rather important, as they mean a significant upgrade for a sizable population of cranes. To that end, various alternatives were devised and field tested with respect to the system's mounting location and brackets, until the present solution was reached. Another important consideration in that regard was the securing of unobstructed access by crane service personnel to their regular work posts. Other decisions made during development addressed options for power supply and recharging, various ergonomic aspects, and alternatives for the bidirectional radio transmissions between the trolley-mounted moving unit and the stationary unit inside the operator cab.

Work Studies

Methodology

Work studies were conducted with the objective of measuring the effect of the vision system on the speed of crane work. Cycle times were, therefore, measured for identical lifts with and without the use of the system. The data were collected using the direct time study following the recommendations of Mundel (1985), Oglesby et al. (1989), and the International Labor Organization (ILO 1992). More specifically, the methodology presented by Rosenfeld and Berkovitz (1990) for crane work studies was adopted. When designing the studies, great attention was also paid to various limitations, as pointed out by Price and Harris (1992), recognizing the inherent difficulty to generalize productivity rates in construction due mainly to the varied work environments and worker skills. Hence, an effort was made, when measuring times with and without the system, to isolate and maintain unchanged those lift parameters that render lifts identical (e.g., type of load, crane operator, lighting conditions, weather); other parameters—and mainly the geometric relations of building–crane–load—could not be maintained without change, and therefore, had to be normalized.

Fig. 5 shows the cycle-time recording sheet. Times were recorded using the continuous timing method. Each row in the table in Fig. 5 refers to one full cycle, from start of loading to end of landing (first half-cycle) and return (second half-cycle). For time recording purposes, each half-cycle is divided into four segments. The first half-cycle comprises: (1) loading (or rigging); (2) travel (from start of lifting to start of landing); (3) landing; and (4) waiting for start of unloading (or unrigging). The breakdown of the second half-cycle is identical, but in the opposite direction, i.e., unloading, travel, landing, and waiting for reloading. This is unlike the common breakdown to two segments only, loading and travel (and then unloading and back-travel) (e.g., Elsilä et al. 1988; Price and Harris 1992; Leung and Tam 1999). The term "landing" used here refers to the "fine maneuvering" done at a speed that is slower than the "long distance" travel speed (Rosenfeld 1995), as the load approaches its unloading site and until it comes to a complete stop. Given the nature of crane work and following the findings of Rosenfeld and Shapira (1998), it was expected that the vision system would be particularly effective in shortening cycle times during this segment of the cycle.

A total of more than 1,400 cycles were measured over numerous days (and some nights), both during the system development phase (one site) and during the first implementation phase (six more sites). Of these (aiming at various other analyses as well), 519 cycles were recorded for repetitive, duty-cycle operations (predominantly concrete placing), and hence, were useful for the current analysis. These were not simulative time studies carried out in a controllable, laboratory environment staged for testing; rather, all recordings were done on real, working sites, under normal, rugged construction site conditions. It should be noted that cycle time recordings without the use of the system could be conducted only on sites designated to start using the system, yet before it was installed. Once the system was installed on the crane, the operators (as well as site management) would not consider working without it. Since most projects ordering the system opted for the shortest order-to-installation time possible, the choice of projects for these work studies was practically limited. Leveling of the learning curve, however, did not play a limiting role, as it practically did not exist; operators testified and were also observed to have started getting used to working with the camera and gaining benefits from the images on the monitor instantly.

Transformation Model

A transformation model to normalize the geometric relations of building–crane–load travel path had to be developed and applied, for measurements with and without the vision system. On real work sites, it is impossible to repeat measurements of a series of the very same lifts, since work progresses and moves on to different locations/floors. Therefore, the application of such a geo-

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Time Recording Sheet for Project………………………………
Date…………… Recorded by………………… Sheet No…… Weather………………… Crane Operator……..……… ☐ **With** ☐ **Without** Camera

Load	From (pick point)	To (drop point)	Travel			Record time at:								Cycle time (min-s)
			Horizontal (trolley, m)	Vertical (hoist, m)	Slewing (jib, °)	Start loading	Start lifting	Start landing	Finish landing	Start unloading	Start lifting	Start landing	Finish landing	

Mark on plan: ☐ Pick location ☐ Drop location ☐ Travel path
Obstructions on travel path (including overlap crane): ……………………………………………………………………………………………..…
Field of vision (at pick/drop location): ………………………………………Number of workers: at pick location……….. at drop location………..
Signalperson (Yes/No, additional duties, level of involvement): …………………………………………………………………………………..…
Details of load: ……...…
Work started on site at…………… Work ended on site at……….. Crane started working at……...…… Crane finished working at……………
Stoppage of crane work (Yes/No, causes, comments): ……………………………………………………………………………………………..…
Bottle neck in crane work (Yes/No, causes, comments): ……………………………………………………………………………………..……
Additional comments: ………...
………
………

Fig. 5. Vision system work studies: cycle-time recording sheet

metric transformation model during analysis of the results obtained was a prerequisite for conducting comparisons of cycle durations with and without the system.

Shriki (2003), who investigated tower-crane cycle times, formulated such a model with respect to two work modes of crane operators: consecutive and simultaneous. Static-base (as distinguished from rail-mounted traveling) tower cranes feature three hook motions: vertical (hoisting), radial (trolleying), and circular (slewing). Ideally, these three motions would be carried out simultaneously throughout the crane's work. This, however, almost never happens in reality, as hook movement must be carried out consecutively to some extent, depending on various factors. These two work modes and the factors affecting them have been addressed by studies of hook travel times and crane location (Leung and Tam 1999, Leung et al. 2001; Zhang et al. 1999; Tam et al. 2001). Shriki's work (Shriki 2003) focused on the correlation between the extent of simultaneous movement and the operator's line of sight. Drawing from Shriki's findings and based on those previous studies, it was concluded that under identical conditions (e.g., lifting task, crane operator, lighting, hook view), and for sufficiently long cycle times as experienced in high-rise construction, cycle times were, in good approximation, linearly proportional to travel distances, as long as distances and times were addressed separately for simultaneous and consecutive movements. These observations confirmed that skilled crane operators engage in simultaneous operation as long as they can see the hook. But when sight is compromised and control is transferred to the signal person, operation, typically, changes into a consecutive (and slower) mode. Note that in this regard, no difference was found between complete obstruction of the hook [Fig. 2(a)] and low sight quality [Fig. 2(b–e)]; both have an equal effect on the mode of operation. The extent of simultaneous operation is obviously affected also by the ability to move the hook in a straight line between loading and unloading points, as determined by the mutual spatial locations of these points as well as obstructions along the path.

To validate the model, results of recorded and computed cycle times were compared for three series of concrete placement in slabs, S-1 (series contains 26 cycles), S-2 (20 cycles), and S-3 (19 cycles), as shown schematically in Fig. 6. Concrete buckets, loaded at ground level, were first lifted to floor level (S-1: Floor 18; S-2 and S-3: Floor 22) in a hoisting-only movement (consecutive) and then moved, along the shortest path (i.e., simultaneous movement), to discharge locations. All pairs of series were compared: S-1 and S-3 represent different heights yet the same planar location, S-2 and S-3 represent the same height but different planar locations, and S-1 and S-2 represent different heights and different planar locations. Table 1 presents results of the comparisons. Differences between recorded times and times computed by the model were found to be around 5%, and thus the model was deemed to be satisfactorily accurate.

Findings

Table 2 presents a summary of typical time saving findings. The mean time saving for total travel time was 14–29%; the mean saving time for total cycle time (i.e., including loading and unloading) was 11–26%. Much higher percentages were observed, as expected, for landing. The findings demonstrate the potential of the vision system in saving time (and costs, as a result thereof) throughout the use of the crane, whether in full view or for blind lifts. The following example illustrates this potential: one of the observed sites was a cluster of 11-story high, concrete-frame residential buildings. The repetitive floors were formed and poured in a production-line-like routine; workdays ended, five days a week, with concrete placement. The location of the truckmixer discharge point and part of the travel path of the craned concrete bucket were outside the operator's line of sight. As reported by the project manager, once the vision system had been installed, crane work was speeded up so that each day the work ended 1 h earlier than before, and 10 workers left for home 1 h earlier on each such day. Thus, during 11 such weeks (the time it took to

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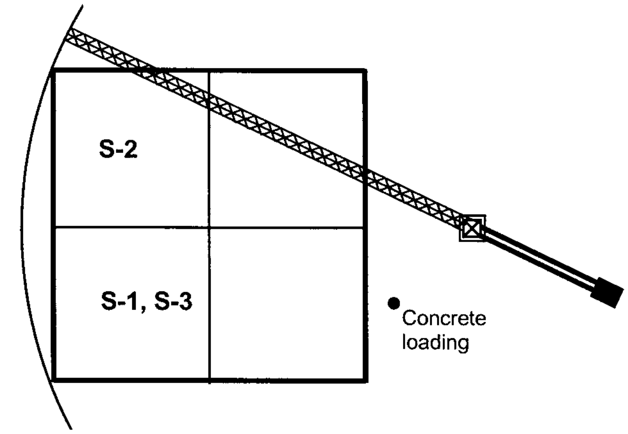

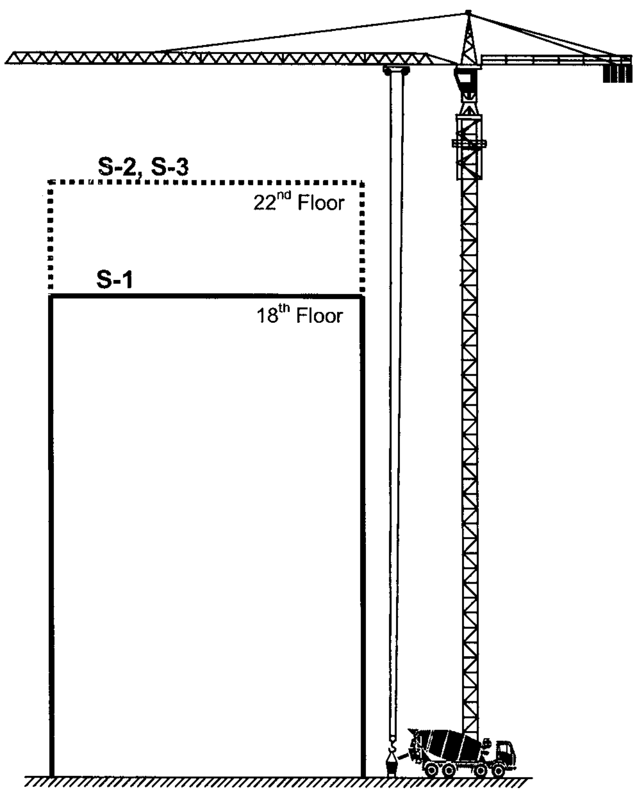

Fig. 6. Validation of model: (a) plan; (b) elevation

complete casting the frame of one building), 550 labor hours were saved. At a rate of $30 (U.S. dollars) per labor hour (McGraw-Hill 2006), this means a direct saving of US$16,500, which is within the above-mentioned range of market prices of camera-system units.

Shortening of individual cycles ultimately adds up to a shorter working time of the crane and shorter delays caused by denial of crane service to noncritical activities. Eventually this results in a shorter total engagement time of the crane on site, and can even shorten project duration, although not to the same extent as the shortening of individual cycles (Rosenfeld and Shapira 1998).

Implementation

The first commercial system was installed on October 1, 1998, on an internal-climbing Comedil CT 651 tower crane. This 170-m (558-ft) high crane served, along with another tower crane, in the construction of a 46-story hotel and residential complex in Tel Aviv. With the crane located inside the tower's shaft, all lifts originating or ending at ground level were blind lifts. The project was built by one of the two construction companies that had jointly built the Haifa project that had served as the testing site for the prototype system. The company's equipment manager had been impressed with the performance of the system during its earlier testing and, recognizing its potential as an operator aid for the construction of the high-rise Tel Aviv tower, authorized the acquisition of the system. The system was used continuously until completion of the project, 18 months later, when it was immediately reinstalled on another crane to continue its service on another company project.

As part of the cooperation between the construction company that built that Tel Aviv tower and the camera R&D team, equipment managers of other construction companies were welcome to visit the site and climb up the crane to see the system in operation. Before long, orders for several other systems were placed by other companies. One such order was for the 270-m (886-ft) high Potain MD 185 external tower crane that helped build a nearby 69-story office and residential tower. A custom-made system, equipped with special zoom capabilities given the height of the crane, was installed in March 1999 and served uninterruptedly on this project for almost three years.

By late 2001, about 40 systems had been purchased and were employed by the leading construction companies in Israel, and several others were procured on a monthly rental basis [the 10 largest construction companies in Israel use their own fleets of cranes, accounting for 30% of the country's 1,000 tower cranes (Shapira and Lyachin 2004)]. To date (mid-2007), nearly 300 projects have been built with the aid of the vision system, including practically all the high-rise buildings constructed in the country during those years. On some of these projects, several systems were in use at the same time. Several companies acquired multiple systems, up to 14, a fact that further attests to the benefits perceived to be gained by the use of the system.

This success must be attributed mainly to the advantages offered by the system. Marketing was virtually nonexistent (information about the system spread among construction circles mostly by word of mouth), and hence it cannot be considered a success factor.

Academia–industry cooperation must have played a major role during implementation, as it did during development and testing. Each unit installed was closely monitored by the R&D team. Regular visits were conducted to the sites. Scheduled meetings and interviews with site personnel covered not only the performance of the system but also a broad spectrum of productivity and safety-related issues. This monitoring activity was used to systematically gather testimonies and quotes (see Table 3), and a library of cases, problems, and camera-based solutions was established. Typical cases from various sites were also shared with all companies using the system.

In parallel to the close contacts with construction companies, the Chief Inspectorate of Israel's Ministry of Labor was also informed of this development from the beginning, and then kept posted. With the Inspectorate expressing encouragement, it was expected that when grading safety preparedness of construction sites, labor safety inspectors would award extra points to sites that

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Table 1. Model Validation: Comparison of Recorded and Computed Cycle Times

Part of cycle	Operation mode	Prediction of Y on the basis of X ($X \rightarrow Y$)	Travel distance of X (m)	Travel distance of Y (m)	$\alpha = \frac{\text{Distance } Y}{\text{Distance } X}$	Recorded mean cycle time for X, t_x (min:s)	Recorded mean cycle time for Y, t_y (min:s)	Computed mean cycle time for Y, αt_x (min:s)	Mean difference between recorded and computed cycle times (%)
Lifting from concrete loading point to floor level									
	Consecutive	S-1 → S-2	56	67	1.20	1:35	1:53	1:54	3.3
	Consecutive	S-1 → S-3	56	67	1.20	1:35	2:01	1:54	
Movement to pour location (full bucket)									
	Simultaneous	S-1 → S-2	18	26	1.44	0:26	0:35	0:37	
	Simultaneous	S-1 → S-3	18	24	1.33	0:26	0:32	0:35	5.0
	Simultaneous	S-2 → S-3	26	24	0.92	0:35	0:32	0:32	
Movement from pour location (empty bucket)									
	Simultaneous	S-1 → S-2	18	26	1.44	0:19	0:25	0:27	
	Simultaneous	S-1 → S-3	18	24	1.33	0:19	0:23	0:25	5.6
	Simultaneous	S-2 → S-3	26	24	0.92	0:25	0:23	0:23	

employ the vision system. Reportedly, this indeed has been the case, at least with respect to several sites.

Benefits and Limitations

The vision system was initially developed and implemented based on its potential to improve site productivity and safety. During implementation, however, when responses of users were systematically elicited and analyzed, it became clear that the system offers several additional benefits. For some users these other benefits were not less important than the general improvement in productivity and safety and in themselves justified the acquisition of the system.

Whether initially predicted or only later observed in the course of development and implementation, these benefits stem from each of the four basic capabilities, or combinations thereof, imparted to the operator by the system: (1) to see (as opposed to

Table 2. Time Savings with Crane-Mounted Vision System

Time measured[a]	Day/night	Sight line	Lift	Weighted mean time saving (%)	Number of cycles: With vision system	Number of cycles: Without vision system	Number of cycles: Total
Total travel time [from start lifting to finish landing (two half cycles)]							
	Day	Low proportion of blind lifts	Concrete pouring: slabs, walls, and columns	14	197	146	343
	Night	Low proportion of blind lifts	Concrete pouring: slabs, walls, and columns	18	101	75	176
Total cycle time [from start lifting to start lifting (two half cycles)]							
	Day	Low proportion of blind lifts	Concrete pouring: slabs, walls, and columns	11	197	146	343
	Night	Low proportion of blind lifts	Concrete pouring: slabs, walls, and columns	11	101	75	176
Total travel time [from start lifting to finish landing (two half cycles)]							
	Day	Full-view travel	Concrete pouring: walls	25	14	30	44
	Day	Partly blind travel (40% of time)	Concrete pouring: slabs	29	22	18	40
Landing time [from start landing to finish landing (two half cycles)]							
	Day	Full-view landing	Concrete pouring: walls	47	14	30	44
	Day	Blind landing	Concrete pouring: slabs	75	22	18	40
Total cycle time [from start lifting to start lifting (two half cycles)]							
	Day	Full view throughout	Concrete pouring: walls	15	14	30	44
	Day	Partly blind travel (40% of time), blind landing	Concrete pouring: slabs	26	22	18	40

[a]With reference to recording sheet (Fig. 5).

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Table 3. Benefits of Vision-Aid System

Benefits	Relevant situations in Fig. 2 (a)	(b)	(c)	(d)	(e)	Selected quotes[a] from the field
Safety enhancement: By allowing the crane operator to continuously view the theater of work, the system prevents accidents and enhances work safety. Countless accidents or "close calls" result from problems in remote signaling or radio communication, when the operator has no line of sight with the load and receiving crew, and thus must rely completely and exclusively on a third party for guidance.	✓	✓	✓	✓	✓	• "Having gotten used, after such a short time, to working with the camera, working without it is like driving a car blindfolded and someone else telling you what to do." (CO) • "You've taken away my eyes!" (CO, complaining about the vision system being dismounted from the crane before the end of work) • "Signalmen training is ridiculous, if you look at their enormous responsibility." (PM)
Productivity improvement: Due to the operator's uninterrupted eye contact with the load during rigging, lifting, traveling, and unrigging, craning cycle times are reduced and productivity is improved. Quite often the crane is the bottleneck of production; faster crane work (particularly duty-cycle work such as concrete placement, setting up precast elements, erection of forming panels) means higher utilization of the crane as well as of all those working around it (e.g. workers waiting for the concrete bucket at the concrete loading and placing points).	✓	✓	✓	✓	✓	• "Thanks to your system, we save, every day, at least one hour of labor in formwork for 12 workers, crane operator, and foreman." (PM) • "If you take away the camera, I'll climb down the crane. There's still so much work until completion, that without the camera I won't be able to finish everything." (CO)
Reduced wear of load cables: The vision system offers the operator a vertical vision angle not otherwise possible. This allows the operator fine maneuvering in the immediate proximity of the façade of the constructed building, yet without touching the building. A classic example is the installation of curtain walls, during which the cable often scrapes against existing slabs/beams. Not only do cables have to be replaced more frequently, with a direct cost of thousands of dollars and indirect costs of work stoppage, but more importantly, it is also a safety concern.	✓			✓		• "Your system has saved us thus far at least one replacement of expensive hoisting ropes (inc. wages and work stoppage). This by itself justifies, the way I see it, the purchase of the system, even if other benefits are ignored." (EM)
Avoiding direct cost damages: Overturning of craned pallets carrying various materials due to a rough landing or even a "soft" collision with another object, is not a rare occurrence. The cost of a lost load (e.g., high-quality exterior cladding marble boards) in one such mishap may be comparable to that of a single vision-system unit, let alone the safety hazard it poses.	✓	✓		✓		• "I couldn't see anything, and therefore the signalman gave me instructions by radio. He said, 'Move 2 m to the right.' I must have been overshooting; the pallet hit the building and broke apart." (CO)
Working in the proximity of obstructions: With a side view only, it is usually difficult to assess the distance to obstructions, such as overhead power lines located within the crane's work envelope, and to maintain adequate clearance from them; the top view offered by the system's monitor allows exactly that. This is true also with respect to the jib or cable of a second, lower overlapping crane.	✓			✓		• "With a remote side view, you don't always notice power lines against nearby buildings." (SM)
Working in shaded areas in daytime: In broad daylight, these areas (e.g., dark shafts) appear to the human eye from atop the crane as black spots. When focusing on these areas, the camera gives a brighter, almost normal daylight image. The quick automatic adaptation of the camera's lenses is also helpful when passing between bright and dark work areas.			✓			• "Up until they installed the camera on my crane, I wasn't able to work inside the stairwell; it was dark and I couldn't see a thing." (CO)
Night work: The camera lenses are much more sensitive than the human eye. The vision system can use regular surface light, which is adequate for workers but not for the remote crane operator, in order to display a bright image of the hook and its vicinity on the monitor in the cab. This is also true for dawn and dusk hours during certain times of the year, as well as for heavily overcast or rainy days.		✓				• "Even if I can see the signalman, I can hardly see his signal at night. With the camera, I can zoom in and see not only his hand, but even his fingers." (CO)

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Table 3. (*Continued.*)

Benefits	Relevant situations in Fig. 2 (a)	(b)	(c)	(d)	(e)	Selected quotes[a] from the field
Monitoring the rigging of loads: Using the vision system (particularly by zooming in), the operator can supervise the rigging of the load prior to lifting and ensure it is done properly. Crane operators reported that for the first time in their career they have on hand an instrument that allows them to refuse the execution of a lift if they are unsatisfied with the rigging. This is a crucial safety issue; incorrect rigging accounts for a considerable percentage of crane accidents (Fair 1998).	✓				✓	• "You must understand the rigging mode of each load; every load, even if apparently simple, has its own risks, and the sling man isn't always aware of this." (EM, ex-CO) • "One example of a load that is hazardous due to its rigging is a bundle of rebars lifted by the wires holding the rebars together, the way they shipped them from the factory, instead of by proper slinging." (PM) • "Due to his cumulative experience, the operator has the know-how to tell a bad rigging and the nerve to refuse to lift it." (SM)
Controlling sway and swing: Many accidents occur due to the swaying/swinging motion of the load (Beliveau et al.1997). Competent operators usually know how to minimize this problem, either a priori or after it has started. However, a downward view was found to be of great help, particularly for lifts made near the façade of the building. A typical example is the lifting of pipes, formwork joists, or other long elements that cantilever considerably from their slinging point, and which may hit the façade or any element—permanent (balconies) or temporary (work platforms)—protruding from it.	✓				✓	• "The operator blind-lifted a bundle of 4-m long timber boards. They were properly slung and all appeared to be fine at the start of lifting. Up in the air, the load started all of a sudden to swing with the wind. Through the camera the operator noticed how dangerously close the load was getting to the building, and quickly trolleyed out." (GS)
Avoiding minor damages to work: When a concrete bucket is lifted, it drips concrete throughout its traveling path. While not a major problem, this still may be a nuisance if concrete drops hit—and then quickly dry on—form panels, precast elements, and other elements located on the ground underneath, which then have to be cleaned up. With the vision system the operator can accurately follow the lift path and navigate it so as to avoid passing over susceptible staging/storage areas, or if impractical, elements can be covered for protection. The same is true in order to avoid, for example, cars parked on the street next to the site, in cases where the jib oversails the site boundaries.	✓			✓		• "[With the camera system] you saved me cleaning up the façade curtain walls." (PM) • "Even if the damage to the periphery outside the site is minor—a car was stained with concrete marks—the resonance is high, particularly in urban surroundings." (PM) • "Before using the camera, the paint container would spray all over pedestrians, as the trolley was moved out too far, instead of stopping by the workers on the scaffold." (GS)
Unloading large-size loads from trucks: These can be tricky lifts. The operator attempts to direct the hook toward the center of the longitudinal dimension of the load (e.g. hollow-core precast slab units). To avoid rapid, uncontrollable motion of the load toward the "horse" once the cables have been stretched out and the load lifted, the hook is usually directed such that the opposite motion occurs. This way or another, this constitutes a safety concern. With its downward view, the camera system allows accurate and time-saving positioning of the hook at the center of the load. A similar case is the lifting of an oversized element from within a crowded storage area.	✓			✓		• "The crane is 50 m high, but is located deep inside the excavation, such that the precast truck outside the site, located on the road above, is almost at eye level [with the cab], and I can't aim accurately." (CO)
Precise lifts: Renovation works and expansion of existing buildings are typical cases that require precise lifts. An example is the precise lowering and insertion of a concrete bucket through a tight opening in a grid of existing metal girders, where concrete is placed for new floors in an old building.	✓			✓		• "I couldn't believe my eyes: the bucket was lowered precisely in between the metal girders, and there was no signalman around." (RA)

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Table 3. (*Continued.*)

Benefits	Relevant situations in Fig. 2 (a)	(b)	(c)	(d)	(e)	Selected quotes[a] from the field
Precise placement: There are many cases in which precise placement is required, most commonly that of precast elements and large form panels. When slab units have to be placed next to each other, a camera-assisted top view allows the operator to fine maneuver more rapidly than when directed solely by a signal person. This has also been validated by Everett and Slocum (1993).	✓			✓		• "The most 'professional' lift assignment of a crane operator: setting up precast elements." (EM)
Wear and tear of transmissions: Hoisting and trolleying are two motions that, similar to a car, involve various gears and speeds: fast movement is produced at a high gear, while for slower travel the operator shifts down into a lower gear. During blind lifts, operators tend to use low gears and slow motions to a much greater extent. Thus, work is not only slowed down, but also an additional burden is exerted on the transmissions. Reverting to normal speeds and gears, as made possible by using the vision system, helps reduce the mechanical wear and tear of the transmissions and generally extends the crane's useful life.	✓					• "The money I saved on wear and tear of the crane in a single project has already paid off the investment made in buying the system." (EM)
Ergonomics: Operators frequently find themselves leaning out of the cab's window, often for prolonged periods of time, to get a better view of the load, particularly at a vertical angle. With the ability to watch the image on the monitor, work convenience is improved, as are work efficiency and safety. The operator is spared the physical effort and fatigue of getting up and bending, all the while keeping hands on the wheels and operating the crane; the operator eyes are similarly subjected to less strain.					✓	• "Operator cab—lifetime imprisonment in a solitary confinement cell." (SM) • "Finally, after having operated cranes for more than 30 years, my back will stop hurting." (CO) • "With the monitor installed in his cab, the operator feels he's been paid attention to; a content operator will work more safely and more efficiently." (SM)

Note: ✓=relevant situation; CO=crane operator; EM=equipment manager; GS=general superintendent; PM=project manager; RA=research assistant; SM=safety manager.

[a]Translated from Hebrew.

blind lifts); (2) to see clearly (as under good—as opposed to bad—light conditions); (3) to see from above (a top view as opposed to a side view); and (4) to zoom in (as opposed to a remote view).

Overall, the benefits offered by the system, with relation to common situations on construction sites (see Fig. 2), are summarized in Table 3. Table 3 also offers a sample of selected quotes from the multitude of responses that were systematically gathered from veteran practitioners, as explained earlier. A later study of the factors that affect safety on construction sites with tower cranes provided further support to some of the benefits (Shapira and Lyachin 2008). Nineteen experts—safety managers and equipment managers of the top 10 construction companies in Israel—were requested to evaluate the influence of, among other factors, operator aids (such as camera systems) on reducing site safety risks. Sixteen of the experts were intimately familiar with the vision system, which has been used on their companies' sites. On a 1 to 5 scale (very weak to very strong influence), six experts evaluated the influence of such aids as very strong, seven experts as strong, five as moderate, and one as weak.

Note that anecdotal evidence (i.e., quotations in Table 3) is used here due mainly to the inherent difficulty in measuring and quantifying safety, which is an abstract term (Hammer 1989; Shapiro et al. 2000). Comparing accident rates (including near misses) with and without the use of the vision system, another conceivable method of validating the system's contribution to enhancing safety, was excluded due mainly to the short time from system order to installation, which did not leave time for preinstallation observations and incident recording. Note also that observations appear to be the only way to record near-miss incidents, since these are hardly ever reported, even within the construction company. Overall, accidents are subject to gross underreporting (Butler 1978; McDonald and Hrymak 2002). Even if accident records were available, their usefulness in comparing safety levels, with and without the vision-aid system, would be questionable at best. Laitinen et al. (1999) maintain that "the use of accidents as a safety indicator of a single building construction site is in most cases impossible…many sites have no accidents and it is not possible to say whether they are safer than other sites with four or five accidents." McDonald and Hrymak (2002) conclude an extensive literature survey on this subject by stating: "It can be said that accident frequency cannot be considered to be a robust measure for research purposes."

Two limitations were observed in the course of implementation and discussions with prospective users. The first of these had to do with a philosophy toward the issue of responsibility during blind lifts that was adopted by a mere few, and which stood in complete contrast to the general notion of all others. Those few maintained that, while the crane operator was the one generally in charge of lifting, the responsibility during blind lifts shifts entirely to the signal person. In line with this approach, any device that aids the operator in turning a blind lift into a nonblind one, such as the vision system, is problematic, since it partially restores responsibility to the operator.

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The other limitation observed was the two-dimensional nature of the image displayed on the monitor; this image lacks the visual depth perception rendered by human eyes. Factually correct, this limitation has virtually no meaning when the operator and the work arena are distanced (when human sight anyhow lacks depth), let alone in blind lifts, when there is no alternative to the two-dimensional image. In fact, crane operators reported how the system helped them assess the load's vertical distance from the ground: when zooming in while approaching the ground, they were able to follow on the monitor how the load and its shadow gradually converge until finally merging upon contact of the load with the ground.

It should be made clear that the vision system was by no means devised as a substitute for the operator's eyes but rather to provide an additional visual dimension, whenever needed. Indeed, "devices used in place of competence and good judgment on the part of the crane operator contribute to accidents" (Alterman 1998). Incompetent operators do, however, pose a great problem, both in terms of safety and productivity, even before the issue of any device is debated, while competent operators know better than to rely on a false sense of confidence that may be instilled through the use of safety devices.

Conclusion

The vision system described in this paper has the capacity to change the mode of operating tower cranes in general, and on high-rise construction projects experiencing a great deal of blind lifts in particular. The operator has an additional vision dimension that enables an *uninterrupted* view of otherwise obstructed work areas and travel paths, a *close* view of otherwise distant areas and blurred objects, a *top* view of otherwise potentially misleading side/angled-view areas/objects, and a *bright* view of otherwise dark areas and shadowed objects. It fortifies the operator's sense of confidence, reduces the risk to all lift personnel and workers in the vicinity of the crane work, and contributes to the safety of the entire construction site. Apart from being a safety enhancement device, the system brings about better utilization of scarce crane time through shorter cycle times, and subsequently cost savings. These and other benefits were observed on the numerous sites that have used the system, both in routine work and in individual difficult situations.

The vision system was not born as a by-product of other product lines. It was devised and designed to respond to the specific needs of construction site crane work. It was developed with reference to the crane operator, the crane as a machine, the process (i.e., the nature of work), the prevailing environment on site, and the regulations.

For the R&D team, the ultimate test of this endeavor was its acceptance and adoption by construction companies. The innate reluctance of the conservative construction industry to adopt changes, compounded by prolonged years of deep economic recession in the potential markets, created a great challenge. This challenge was overcome mainly by a great deal of academia–industry cooperation.

This system and the effort that yielded it were not an isolated, one-time endeavor. They should be seen as one of many cooperative projects aiding site work and the construction industry in general on the part of academia, marrying the advantages offered by both for the benefit of a synergic outcome. Further development of safety enhancement devices is called for. As has been the experience in the current case, these devices are also likely to contribute to work efficiency and to bring about cost savings. In parallel to cooperating with construction industries, regulation authorities should be approached on the issue of possibly mandating the use of a vision system on certain projects. A proposition has to be made that includes quantitative measures to objectively evaluate dynamic conditions such as the height of the crane and the proportion of blind lifts on prospective sites.

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