CRANIUM: Device for Improving Crane Productivity and Safety

By John G. Everett,[1] Member, ASCE, and Alexander H. Slocum,[2] Associate Member, ASCE

Abstract: Cranes are the most important pieces of equipment on many construction sites. While technological advances have been made in crane hardware, the communication system used to coordinate the crane operator's actions with other craftsmen has not changed in decades. Crane operators frequently cannot see the loads they are moving, so they rely on hand signals relayed among craftsmen. This paper introduces the CRANIUM, a video system designed to improve productivity and safety of crane operations by improving communications. A video camera mounted on the crane boom transmits an image to a television monitor in the crane cab. The operator has a real-time picture of the loads and craftsmen which might otherwise be out of direct line of sight. A full-scale fully-operational prototype CRANIUM was designed, fabricated, and extensively tested in the field. Experimental results show that for moderate and high precision lifts, productivity can be increased 16–21%. Crane safety is also improved.

Introduction

Cranes, ranging from small cherry pickers to huge tower cranes, are among the most important pieces of equipment on many construction sites. Because construction cranes operate in constantly changing work environments, heavy reliance must be placed on the crane operator's skills (Shapiro 1988). The mechanical technology used by cranes has improved dramatically in the past several decades, but the techniques for coordinating the crane operator's actions with other craftsmen have not. Cranes "have advanced at such a tremendous pace that technology has, in many ways, outstripped the ability of people to apply these machines safely" (Dickie 1975).

Objective

The objective of this paper is to introduce the CRANIUM, a video system designed to improve communications between crane operators and other craftsmen. Reductions of delay in communication lead to productivity improvements. Reductions of errors in communication lead to safety improvements.

Current Practice

Crane operators move huge machines and loads based on the limited information they obtain from a communication system developed long ago when cranes were much smaller and less powerful. The crane operator relies on information supplied to him by other craftsmen, typically the person

[1]Asst. Prof. of Civ. and Envir. Engrg., Univ. of Michigan, 2352 G. G. Brown, Ann Arbor, MI 48109-2125.

[2]Flowers Career Development Assoc. Prof. of Mech. Engrg., Room 35-008, Massachusetts Inst. of Tech., Cambridge, MA 02139.

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who attaches the load to the crane's hook in preparation for lifting, or the person who receives and unhooks the load. The distance between the crane operator and the other craftsman, combined with the background noise of a construction site preclude verbal communication.

To facilitate communication between crane operators and other craftsmen, a set of hand signal has been adopted by the construction industry and the craftsman directing the load acts as the *signalman*. The signalman and the load are frequently located where the operator cannot see them due to obstructions in the line of sight, long distances, or insufficient lighting. In such situations, a *tagman* becomes necessary. Located at a point in direct line of sight of both the signalman and the crane operator, the tagman observes the signalman's hand signals and relays the signals to the crane operator.

An alternative method of communication involves the use of two way radios or walkie-talkies. The characteristics and problems associated with radio communication are beyond the scope of this paper.

Communication Problems

The use of a tagman creates two types of communication problems: signal delays and signal errors. A signal delay is the time interval between the time a hand signal is given by the signalman and the time the crane operator sees the signal given by the tagman. Signal delays always exist when a tagman is employed and they hinder productivity.

The second type of communication problem arises because of errors in signal transmission. The tagman may, for whatever reason, change the signalman's signal, or the tagman may fail to relay the signal entirely. Signal errors may or may not exist when a tagman is employed. Given the size and weight of construction materials, errors in signal transmission can be disastrous.

Both signal delays and signal errors can be eliminated or at least reduced by using the CRANIUM.

CRANIUM

The CRANIUM is a video system that allows the crane operator to see what is happening at the lifting point (Everett 1991). The prototype CRANIUM consisted of a high-resolution color video camera (Burle Model TC200) with a motorized lens (F1.8, 12.5- to 75-mm zoom) mounted at the tip of a crane's boom. The crane operator controlled the lens' zoom and focus from the cab. The video components used in the prototype were selected on the basis of price and availability; other comparable components could also be used.

A robust housing was designed to protect the camera and lens from the harsh environment and abuse of construction sites. The lower end of the housing contained a recessed Plexiglas window for the camera lens. Shock-absorbing mounts connected the camera to the interior of the housing. The entire unit was sealed against precipitation.

A damped gimbaled mounting system was designed to maintain the camera housing's orientation relative to vertical, independent of boom motions. The mount and camera housing are shown in Figs. 1 and 2. Two self-aligning pillow blocks (bearings) are bolted to the top of the camera housing. The pillow blocks support a steel shaft that is rigidly connected to the crane boom. As the angle of the boom changes, the camera housing "hangs" and

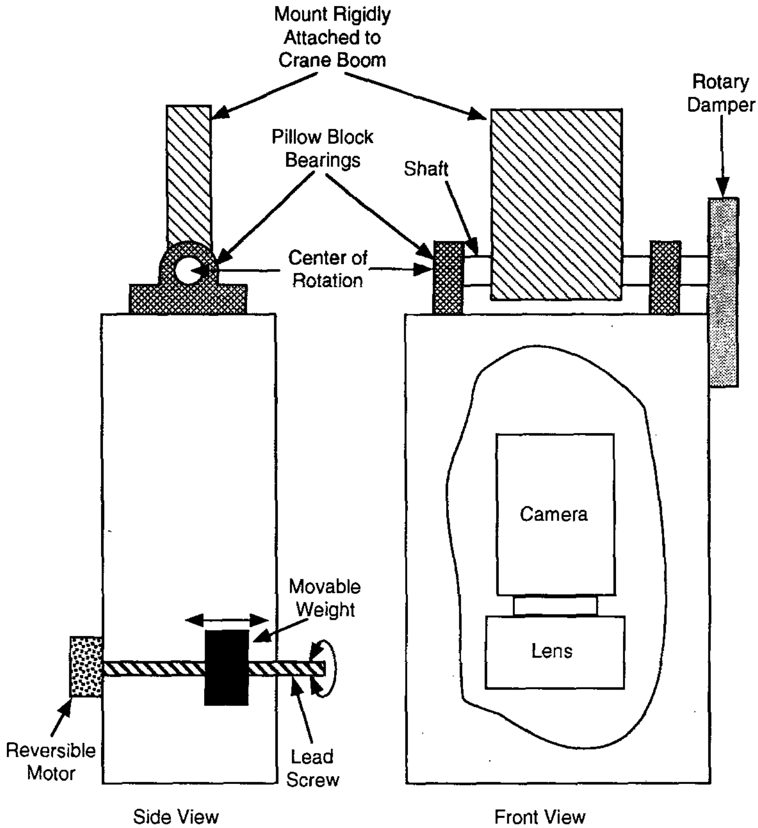

FIG. 1. CRANIUM Camera Housing with Damped Gimbaled Mount and Angle Adjustment Mechanism

maintains its vertical orientation. Rotary dampers reduce angular oscillations of the housing about the shaft due to boom movements and gusts of wind.

A 23-cm (9-in.) color television monitor (Burle Model TC210) located in the crane operator's cab allowed the operator to see a live image of the load and the craftsmen directing the load, assuming the video equipment was properly oriented relative to the crane and craftsmen. The monitor was positioned so that the operator could easily see the screen, without the monitor obstructing the operator's normal field of view.

Mounting and Pointing Camera

Based on discussions with crane operators, the camera was initially placed at the tip of the boom pointing straight down. This scheme has several advantages. The camera always points to, or "looks" at, the load. As the crane swings left and right, booms up and down, or as the load is hoisted or lowered, the camera remains directly above the load. (Actually the load hangs beneath the camera).

During preliminary field testing, prior to the experiments described next, the operator realized he did not want to look exclusively at the load in the

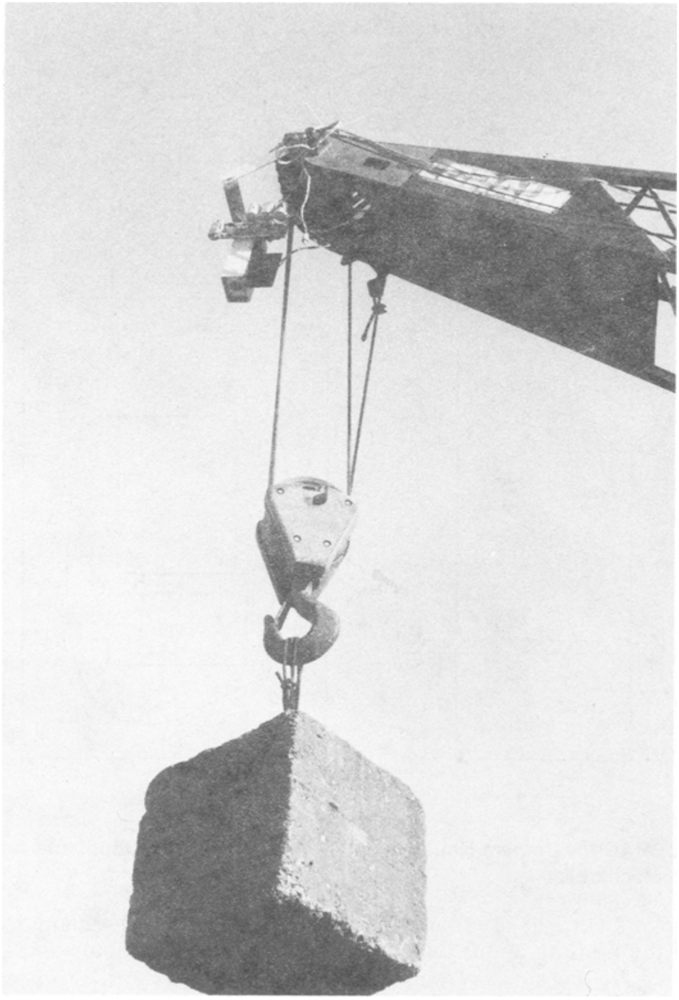

FIG. 2. CRANIUM Camera Unit Mounted on Crane Bottom

TV monitor. He also needed to see the signalman. The operator could zoom the image in and out with the motorized lens, but it was difficult to produce a satisfactory image on the monitor. If the camera zoomed in for a close-up, the load filled up the screen. If the camera zoomed out for a field of view wide enough to include the signalman, the signalman's image on the monitor was so small that it became difficult to interpret hand signals.

A satisfactory solution was to provide a mechanism to allow adjustment of the angle of the camera with respect to vertical. A motorized lead screw moves a weight that changes the center of mass of the housing-weight system as shown in Fig. 1. Gravity keeps the center of mass of the housing-weight system directly below the housing's axis of rotation. As the center of mass moves, the angle of the camera housing relative to vertical changes. An

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important feature of this design is that the adjustment of the angle of the camera is independent of the angle of the crane boom.

The crane operator controls the angle of the camera from the cab but it need not be changed very often. For repetitive lifts, the angle can be set once and ignored until job conditions change significantly. Typically, an orientation is chosen that centers the signalman's image in the TV monitor, allowing the crane operator to zoom in on the signalman for a clear image of the hand signals.

FIELD TESTS

The hypothesis to be tested during the field testing was that use of the CRANIUM video system would improve the safety and performance of cranes when compared to the conventional crane operation using a tagman. Although improvements in safety can only be qualitatively assessed here, improved performance can be measured by a reduction in the lift duration or the time required to complete one round trip lift cycle.

Experiments were conducted at the Operating Engineers' Training Center in Canton, Mass. The center has its own dedicated equipment, typical of equipment used on real construction sites, and instructors at the training center are veteran crane operators with some flexibility in their schedules to allow them to participate in experiments such as those to be described. The training center offers a laboratory setting where structured experiments with controls and many repetitions of identical crane lift cycles can be performed without the costs, schedule pressures, and liability issues associated with an active construction site. Mr. Tom DelZoppo operated a Lorain 45-tonne (50-ton) truck crane with 18 m (60 ft) of boom. Two apprentice operating engineers served as signalman and tagman.

Three field experiments, each simulating a typical crane operation, were conducted. The experiments were designed so that the crane operator could see neither the target area nor the signalman. In each experiment, a control baseline was established by repeating one lift cycle several times using current practice and a tagman. The same lift was then repeated many times using the CRANIUM instead of a tagman. This situation allowed the crane operator to see the signalman's hand signals directly by watching the television monitor. A time break of two hours between the set of control lifts and the set of CRANIUM lifts reduced the chance for learning effects to be transferred between sets of lifts.

Experiment A

This experiment simulated construction work, such as demolition or clamshell excavation, where accuracy is not critical and high-impact landings are permissible or even desirable. The lift used for experiment A required positioning an empty concrete bucket in a target area (d = 3 m) on the ground on the far side (relative to the crane operator) of a construction trailer. The return portion of the cycle required swinging the crane and bucket 90° to a target that was in view of the operator, eliminating the need for a second signalman-tagman team during the experiment. Fig. 3 shows the layout of the equipment and craftsmen.

Experiment B

Some crane operations require a compromise between speed and accuracy. Experiment B simulates a common activity such as unloading a truck

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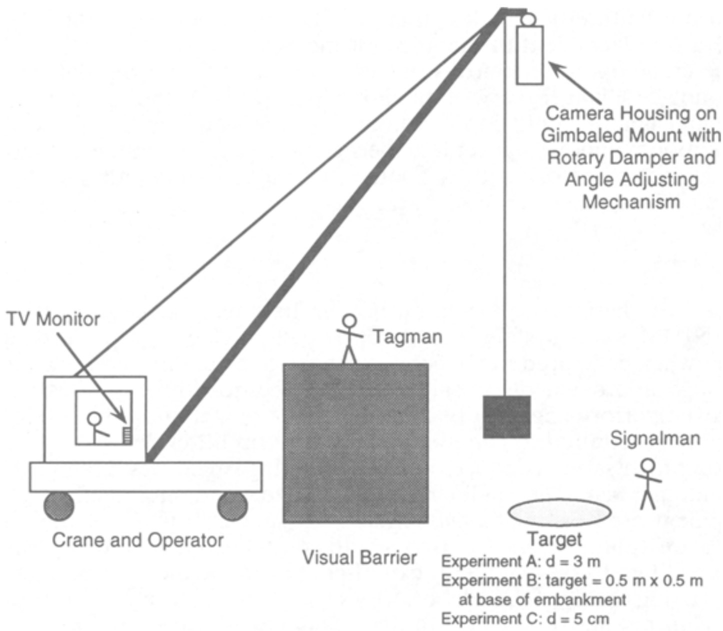

FIG. 3. CRANIUM System and Experimental Layouts

into a shake-out area. The materials must be gently unloaded in an organized fashion, but accuracy within about 0.5 m is acceptable.

The lift used for experiment B entailed lowering an empty concrete bucket over an embankment and touching down on a target block (0.5 m × 0.5 m) at the base of the embankment. The return portion of the cycle required swinging the crane and bucket 90° to a target on top of the embankment in view of the operator. In experiment B, the tagman could not anticipate hand signals from the signalman, but could only relay the hand signals after he saw them. This situation is typical of many repetitive lifts on a construction site. Everyone involved knows where the load is going, but each person in the communication chain must wait for information from someone else. Fig. 3 shows the layout of the equipment and craftsmen.

Experiment C

In many crane operations very accurate positioning is essential, regardless of the time expended. An example of this type of work is the placement of structural precast concrete elements.

The lift used for experiment C required positioning a large (1 m^3) concrete block onto the ground on the far side (relative to the crane operator) of a construction trailer. The goal was to gently position one corner of the concrete block within 5 cm of a target cone. To simulate typical crane operations, the cone was moved between lifts so the operator could not anticipate where the load was to be positioned. As in normal high accuracy crane operations, the operator had a rough idea of where the target would be, but could not anticipate the exact spot. The return portion of the cycle required swinging the concrete block 90° to a target in view of the operator. Fig. 3 shows the layout of the equipment and craftsmen.

In addition to the stringent accuracy requirements, experiment C required the operator to boom up and down to adjust for the change in radial distance between the target cone and the crane. Booming up raises the boom, moving the load up and toward the crane operator. Booming down lowers the boom, moving the load down and away from the operator. Frequently the load had to be hoisted before booming down, to prevent dragging the load on the ground. This wastes the time previously spent carefully lowering the load. The added complexity of the lifts not only increases the mean cycle duration, but leads to learning effects. After several cycles, the signalman improves his ability to correlate booming up and down with raising and lowering the load.

Results

During the field experiments, the volunteer tagmen were alert and enthusiastic. Their responses to the signalmen's signals were as quick as could be expected. Observation of less enthusiastic tagmen on real construction sites suggests that the field test results reported next may underestimate the potential time savings possible when using the CRANIUM.

Experiment A

Fig. 4 shows the results of experiment A. The unit lift durations for the control and CRANIUM lifts are plotted versus the lift repetition number. Superimposed on each data series is a curve showing its cumulative average time (CAT). The CATs smooth out scatter in the data and make trends more obvious.

There was little difference in duration between the control lifts and the CRANIUM lifts. Observations of the actual field tests suggested possible reasons for the similarity. In repetitive lifts, the operator is able to align the line (the wire rope that lifts the load) with a tree or other landmark on the horizon. Although the operator watches the tagman or signalman for directions, the operators can estimate how far to swing and he can anticipate the hand signals.

Furthermore, in experiment A the exact angle of swing was not critical. The operator had to keep an eye on the tagman for safety, but the operator could move the crane to the target quickly and nearly independently of outside information or assistance. The operator could also anticipate when to lower the bucket. The only feedback the operator required was when to stop lowering and when to start hoisting the bucket for the next cycle. Not only could the operator anticipate most of the signals from the tagman, but the tagman could anticipate signals from the signalman.

Experiment B

Fig. 5 shows a scatter plot of the control and CRANIUM unit lift durations as a function of the lift number, and curves indicating the respective CATs. The plot clearly shows a reduction in cycle duration when using the CRANIUM. Comparing the CRANIUM CAT (58 sec) to the Control CAT (69 sec) at, say, lift number 10 gives:

$$1 - \frac{58 \text{ sec}}{69 \text{ sec}} = 0.16 = 16\% \quad \text{(1)}$$

A reduction in total time for ten lifts of about 16% is achieved when using

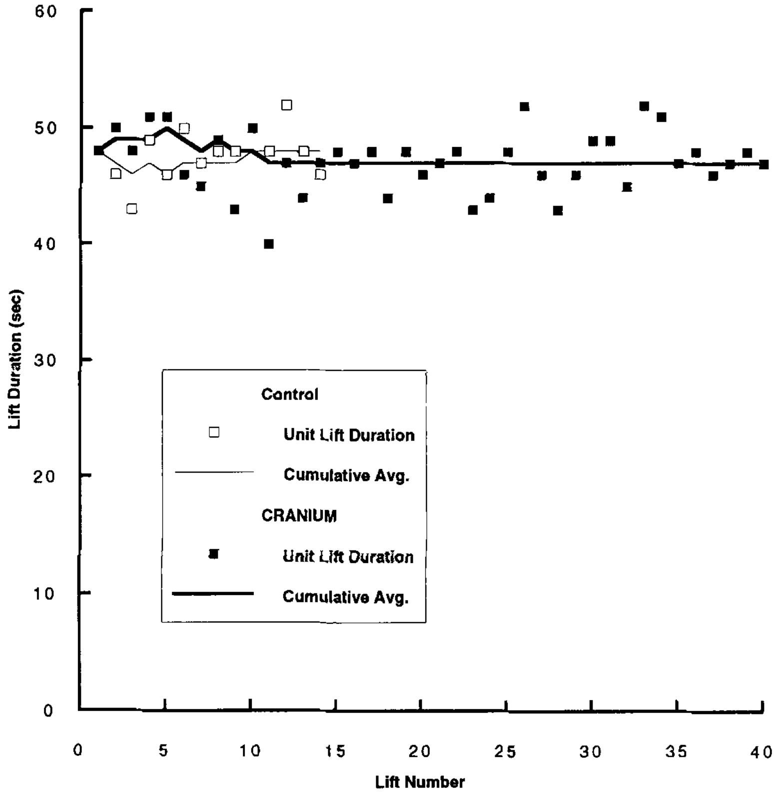

FIG. 4. Experiment A Lift Durations

the CRANIUM to help position a load with moderate positioning accuracy requirements.

Experiment C

Fig. 6 shows a scatter plot of the Control and CRANIUM unit lift durations as a function of the lift number, and curves indicating the respective CATs. Fig. 6 clearly shows shorter cycle durations for the CRANIUM series compared to the Control series. Comparing the CRANIUM CAT (94 sec) to the Control Cat (119 sec), again at lift number 10, gives:

$$1 - \frac{94 \text{ sec}}{119 \text{ sec}} = 0.21 = 21\% \quad \text{(2)}$$

When using the CRANIUM for high accuracy lifts, a reduction in cycle duration of 21% was measured. Fig. 6 also shows a decrease in cycle duration as the number of repetitions increases, for both the control and CRANIUM series. "It is widely accepted that production rates or productivity for performing repetitive construction tasks will improve with additional experience and practice" (Thomas et al. 1986). This phenomenon is known as the "learning curve" or "experience curve." The difference between the CAT curves appears to be slightly greater for the first few repetitions, and slightly

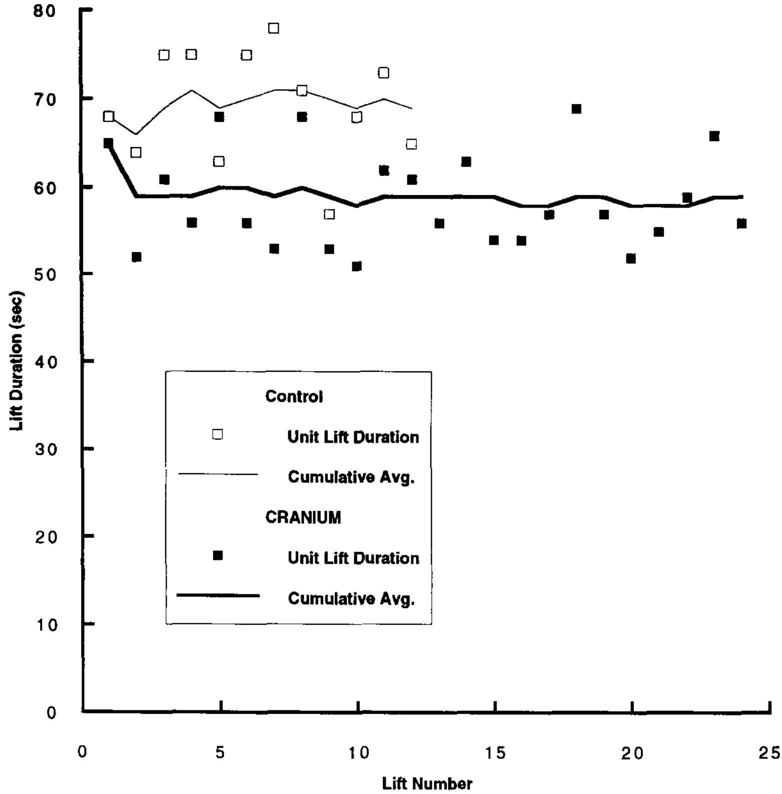

FIG. 5. Experiment B Lift Durations

less for the last few lifts in the experiment. The control lifts exhibited a 91% learning curve; the CRANIUM lifts were 92%.

Analysis

The experimental results show that the CRANIUM improves productivity. Safety improvements were not measured, but appear to be an important feature of the CRANIUM system. The following sections trace the path of signals from the signalman to the operator and offer explanations of how the CRANIUM improves both productivity and safety.

Productivity Improvements

The signalman's signal travels to the tagman's eyes at the speed of light, but slows down while being processed by the tagman's brain and hand. This situation is shown in Fig. 7. In practice, the time required for a tagman to relay a signal depends more on his alertness and motivation than physiological limits of hand-eye coordination.

Crane operators feel that the tagmen's job is the most important, and should be assigned to one of the most experienced and reliable crew members. On most jobs, however, tagman are the least experienced or least productive crew members. They spend a large portion of their work time

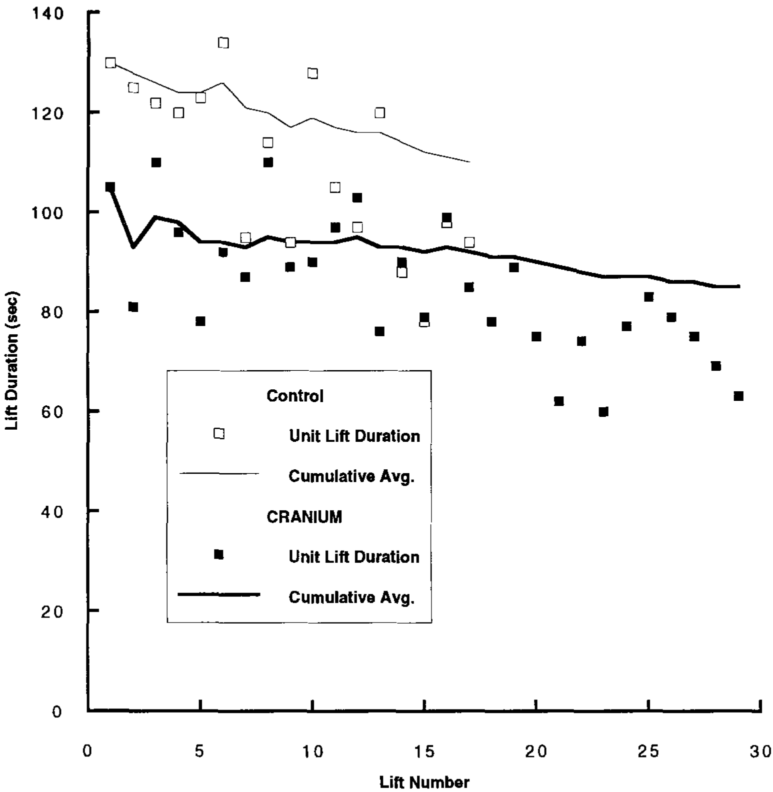

FIG. 6. Experiment C Lift Durations

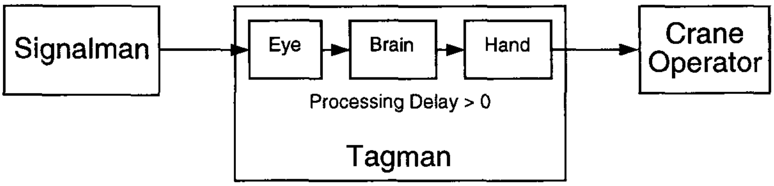

FIG. 7. Signal Delays Created by Tagman

idle, then for a brief period during each lift cycle, they perform their signal-relaying duties. As critical as the tagman's duties are, after hours, days, or months of such uninspiring work, it is not surprising that the tagman may be less than fully attentive to his task.

Only after the tagman relays the signal to the crane operator can the operator respond and move the load appropriately. Signals to move the load are delayed, but signals to stop moving are also delayed. Most operators prefer to approach the target slowly, rather than risk overshooting it and having to reverse the motions just completed.

Overshooting the target also creates safety problems. Operators quickly adapt to signal delays by adopting a "move-and-wait" strategy. "This means the operator can commit only to a small incremental movement 'open loop,' i.e., without feedback (which actually is as large a movement as is reasonable without risking collision or other error), then stopping and waiting one delay period for feedback to 'catch up,' then repeating the process in steps until the task is complete. This is unacceptably tedious except for simple tasks where long waits are acceptable" (Sheridan 1992).

In contrast, the CRANIUM system diagrammed in Fig. 8 eliminates delays in signal propagation by replacing the tagman. Now, the signalman's signal travels through the CRANIUM, where the camera and monitor process the signal at electronic speeds, to the operator. The crane operator's strategy now becomes completely different. The operator no longer has to move and wait; he can operate with real-time information.

Safety Improvements

Some crane industry practitioners feel that the potential safety benefits of the CRANIUM are so important that they would use the CRANIUM regardless of its effect on productivity. During field testing, the first writer was describing how one of the experiments should be conducted to accurately measure cycle times and productivity changes. The crane operator, said, "You keep talking about production. Forget production. This thing [the CRANIUM] is for safety."

The tagman not only creates signal delays just discussed, but introduces signal transmission errors as well. The hand signal relayed to the operator may not be the same signal the tagman received. No information system is perfect, but when tonnes of construction materials are involved, errors can be fatal. Indeed, it is "rare for a crane operator to complete a career without being involved in a fatal accident" (Kelley 1986). Safety changes are difficult to quantify, but a qualitative description of the communication system helps explain signal errors.

In the field of information theory, the uncertainty of information is denoted as H. When considering the information system between the signalman and the crane operator, there are two sources of uncertainty. The uncertainty of the stimulus or the hand signal given by the signalman is denoted $H(\text{in})$. The uncertainty of the response, or hand signal that the crane operator receives is denoted as $H(\text{out})$. The information system shown in Fig. 9 represents conventional crane operation with a tagman.

The tagman introduces three additional functions to the system. The following information is contained in Edwards (1969):

> $H_{\text{out}}(\text{in})$ is the information which is in the input but not the output, and is therefore lost. This is called equivocation. It may be regarded as the uncertainty associated with the stimulus when the response is known. $T(\text{in; out})$ is the information which is common to both input

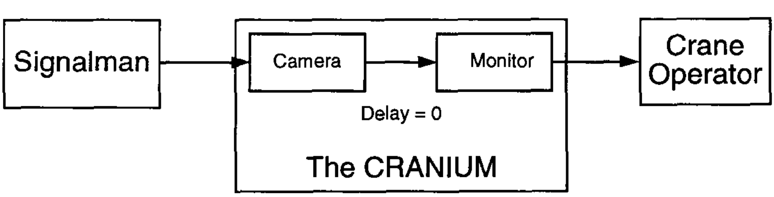

FIG. 8. No Signal Delay with CRANIUM

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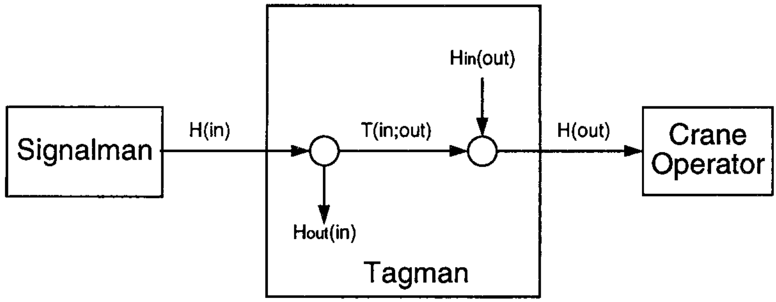

FIG. 9. Signal Transmission Errors are Possible in Conventional Crane Operations, H(out) ≠ H(in)

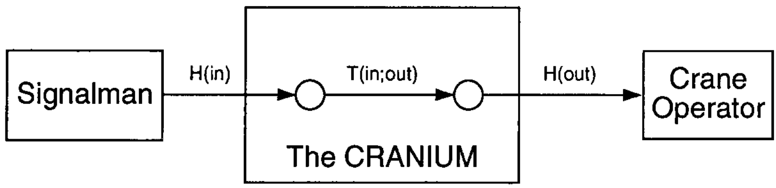

FIG. 10. CRANIUM Eliminates Signal Transmission Errors, H(out) = H(in)

and output. This is called transmission. H_{in}(out) is the information which is in the output but not in the input, and must therefore be generated in the system itself. This is called ambiguity or noise. It may be regarded as the uncertainty associated with the response when the stimulus is known.

From Fig. 9, it can be seen that

$$H(\text{in}) = H_{\text{out}}(\text{in}) + T(\text{in; out}) \quad (3)$$

and

$$H(\text{out}) = T(\text{in; out}) + H_{\text{in}}(\text{out}) \quad (4)$$

Subtracting (4) from (3) gives

$$H(\text{in}) - H(\text{out}) = H_{\text{out}}(\text{in}) - H_{\text{in}}(\text{out}) \quad (5)$$

The difference between the input and the output is a function of equivocation H_{out}(in) and the noise H_{in}(out). Ideally, the input H(in) and the output H(out) are equal, but the tagman has the opportunity to introduce both types of error into the information system. The operation has no way of knowing whether or not the signal he receives, H(out), is the same signal that was given to the tagman, H(in). The operator must trust the tagman.

Fig. 10 shows the information system when the CRANIUM is used. There is still the possibility that information will be lost (e.g., the image on the monitor is out of focus or disappears) so H_{out}(in) may still exist. In cases where the crane operator is not absolutely sure of the signal being given to him, the correct procedure is to halt all movement until the problem is resolved. This reduces H_{out}(in) to zero, but may add a time delay. There is little chance of noise in the form of a hand signal spontaneously generated by the CRANIUM, so $H_{in}(out)$ also reduces to zero.

The ideal situation is where the crane operator has a direct line of sight to the signalman. In this case neither $H_{out}(in)$ nor $H_{in}(out)$ exist. In this situation

$$H(in) = T(in; out) = H(out) \quad \text{(6)}$$

With both $H_{out}(in)$ and $H_{in}(out)$ reduced to zero, the CRANIUM information system is identical to the ideal case. Even in the ideal case, the uncertainty of information, H, is used rather than the signal or information itself. There is still the possibility that the signalman will give a wrong or unintended signal, or that the operator will misinterpret a correct signal.

Industrial Relevance

In addition to the theoretical arguments and field test measurements, a real-world example illustrates the clear difference between move-and-wait operation and operation with instantaneous feedback. A veteran crane operator with a crane rental firm in Watertown, Mass., recounted the following story.

This crane operator had been positioning construction materials to the far side of a building, relying on a tagman's hand signals. After some time, he noticed that he could see the load, the target area, and the signalman's hand signals reflected in the glass facade of a building across the street from the construction site. He started watching the reflected image of the signalman's signals rather than the tagman's signals. At the end of the shift, the craftsmen who had been working in the target area approached the operator and raved, "Wow! We've never seen anyone drop those loads in so quickly and accurately! You're the best operator we've ever worked with! How did you do it?" The operator just shrugged his shoulders and replied, "Years of experience!" He never told the crew what really happened.

This anecdote confirms what was measured in the experiments, that instantaneous visual feedback has a significant positive effect on crane performance. The befuddled crew had not been consciously timing lift cycles, but they instinctively realized that something extraordinary was happening.

Typical Applications for CRANIUM

It is difficult to select a typical lift cycle, but one can generalize by observing that some lifts, such as positioning precast concrete planks, require very gentle and accurate positioning. Once the plank is properly positioned, the crane hook may be disconnected immediately, and the crane may return to pick up another plank. In such a situation, the crane is nearly always moving, and the time savings realized by using the CRANIUM are maximized.

In other lifts such as erecting structural steel members, accurate positioning is required at both ends of the lift cycle, but the crane may be idle much of the time. Once the steel member is properly aligned, the crane must hold the member while it is bolted or welded in place. In such a situation, the absolute savings in positioning time per cycle may be realized, but the savings will be a smaller percentage because the total lift cycle is extended by the holding and waiting time.

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Example: Direct Economic Benefits

Most construction crane operations are moderate- and high-precision lifts similar to those simulated in experiments B and C. The cost-benefit calculations below assume the CRANIUM will reduce cycle durations by 10%, a conservative estimate well below the experimentally measured range of 16–21%.

A common application for large cranes is structural precast concrete erection. Table 1 shows the precast erection crew hourly and daily costs including overhead and profit. Total daily cost is about \$4,650 (Means 1991). The direct benefits of reduced crane cycle time are not limited to the crane and the operator. The productivity of six steel workers, their foreman, and one oiler is also directly related to the crane's performance. Presumably one of the steel workers would act as the tagman. This position can be eliminated, or the steel worker could be assigned to another task. Eliminating the tagman gives a daily savings of 8 hours × \$44.80/hr ≈ \$360. The daily crew cost is now approximately \$4,650 − \$360 = \$4,290.

The remaining crew with five steel workers and the CRANIUM is assumed to be 10% more productive than the old crew with six steel workers. Without the CRANIUM, a one day project would cost \$4,650. With the CRANIUM, the same project would cost \$4,290 × 90% ≈ \$3,860 for a daily savings of \$4,650 − \$3,860 ≈ \$790.

These calculations do not consider waiting time for the trucks that deliver the precast elements to the site. Normally the price of the precast members includes an hour or so of truck idle time, but that cost is ultimately borne by the general contractor and the owner. Additional waiting time may be charged to the erection contractor, and eventually to the owner. Table 2 shows the costs for a precast delivery truck and driver. The total daily cost is about \$1,030 (Means 1991). The hourly cost is \$1,030 per day ÷ 8 hr/day ≈ \$130 per hour.

TABLE 1. Precast Concrete Erection Crew Costs

Means crew C-11 (1)	Hourly (2)	Daily (3)
One structural steel foreman	\$48.40	\$387.20
Six structural steel workers	\$44.80	\$2,150.40
One equipment operator (crane)	\$36.60	\$292.80
One equipment operator (oiler)	\$30.15	\$241.20
One truck crane, 150 t	—	\$1,579.60
Daily total	—	\$4,651.20

Note: Source: *Building Construction Cost Data, 1992* (Means 1991).

TABLE 2. Truck and Driver Crew Costs

Means crew B-34K (1)	Hourly (2)	Daily (3)
One truck driver (heavy)	\$29.00	\$232.00
One truck tractor, 240 HP	—	\$499.60
One low bed trailer	—	\$296.10
Daily total	—	\$1,027.70

Note: Source: *Building Construction Cost Data, 1992* (Means 1991).

On construction projects in congested urban areas there may be no shakeout area to unload delivery trucks. In such cases, it is not uncommon to have several delivery trucks queued up, each at $130 per hour, waiting for the crane. Any reduction in delivery truck waiting time due to improved productivity of the precast erection crew adds to the value of the CRANIUM.

Cost of CRANIUM

The cost of the prototype CRANIUM, including all the components described earlier was approximately $3,200. This figure is based on retail prices for individual components, but does not account for labor to fabricate and assemble the components. Mass producing the CRANIUM would certainly lower the unit cost.

Assuming production quantities of the CRANIUM are manufactured, the purchase price of the end user would be approximately $10,000. The payback period for the CRANIUM system in the aforementioned precast concrete example would be payback period = $10,000/$790 per day ≈ 13 days. Clearly such an investment is attractive at any reasonable interest rate.

Indirect Economic Benefits: Compression of Critical Path and Improved Safety

In addition to direct labor and equipment savings, the CRANIUM may produce large indirect economic benefits. Crane operations are frequently found on the critical path of construction projects. By reducing the duration of critical path activities, the overall duration of the project is shortened. Improved safety also provides major economic, humanitarian, and social benefits to the contractor and the owner.

Future Research

Construction industry reaction to the CRANIUM has been overwhelmingly positive. Crane operators, union officials, apprentices, and crane rental company managers have expressed their interest in seeing the CRANIUM further developed and commercialized.

The prototype CRANIUM was designed to be functional yet easy to use. The crane operator has enough to do without having to worry about additional buttons and levers to control the camera. The primary consideration was to establish the technical feasibility and operational practicality of the CRANIUM. However, before the CRANIUM can be commercialized, the mounting system that connects the camera housing to the crane boom requires additional development. The prototype mount has one degree of freedom, and relies on gravity to maintain the camera's orientation. Future developments might give the operator more control of the camera's field of view. The mount could be adapted to follow for tangential motion as well as radial movement. An active feedback-control system could more accurately maintain the desired orientation despite wind gusts and boom movements.

Future generations of the CRANIUM might automatically track the signalman or a target point, and the operator would not have to worry about the camera's orientation at all. If the CRANIUM and an onboard computer knew where the load was and where it was going, the crane could be programmed to perform the lift automatically. The operator may need to intervene at the start and end of each cycle to coordinate with the craftsmen sending and receiving the load. For the remainder of the lift, the load trajectory could be optimized to minimize cycle time and avoid obstacles.

During field testing, the camera was placed at the tip of the boom to guarantee an unobstructed view of the load and its surroundings. The overhead view may not be the optimum angle for interpreting hand signals, but it is no worse than common situations in current practice where crane operators must look almost straight up to see the tagman on top of a building. Tower crane operators, located at the top of the tower, are used to looking down at the tagman or signalman. A better perspective of the signalman or target might be gained by relocating the camera off the crane. For repetitive lifts, the camera could be mounted on a tripod in a convenient location. It would also be possible to install several cameras throughout the construction site. The operator would require a means of switching among cameras, and would have to know when to do so.

Given a choice between looking at the signalman or looking at the load, operators prefer to see the signalman. It would be possible to let the operator see both, either on a split screen or on two different monitors. Two images would allow the operator to see a close up of the signalman and still maintain a wide perspective of the work site.

The one camera, one monitor system gives the operator a two-dimensional view, with no depth perception. Future generations of the CRANIUM may have stereoscopic or multiple cameras and three dimensional or holographic images, giving the operator depth perception and the option of viewing the image from different angles.

When the CRANIUM becomes a required component, crane manufacturers might build a flat screen monitor into the operator's console. The screen could be moved into a convenient position when needed, and stowed out of the way when a direct line of sight was available.

An issue sure to arise as the CRANIUM is adopted by the industry is training. The effect of training or long term experience with the CRANIUM has not been addressed. "Even the highly sophisticated safety devices installed on many cranes today require training for the experienced operator to understand and properly use" (Headley and Meadows 1988). At the risk of sounding facetious, most people are very familiar with television, and quickly adapt to watching video images.

Using video communication raises possibilities for fundamental changes in crane operations. If the crane operator receives all of his information electronically, he could be physically separated from the crane. He could sit in a warm, dry, quiet location and remotely operate (teleoperate) the crane. Many crane accidents involve electrocution of the operator when the crane touches overhead electrical lines. Other fatalities occur when cranes overturn. Removing the operator from the crane would eliminate these fatalities.

It would also be possible to eliminate the operator entirely by having the craftsmen who are sending and receiving the load operate the crane, as is done with overhead industrial cranes. This would require a means of coordinating and safely switching control of the crane from one craftsman to another.

Conclusions

This paper has described a new technology that can greatly improve crane productivity and safety. The CRANIUM has been designed, fabricated, and tested in the field. Significant improvements in crane productivity have been

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demonstrated, ranging from 16% improvement for lifts requiring 0.5-m accuracy to 21% for lifts requiring 5-cm accuracy.

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