Intelligent Technology for Truck Crane Accident Prevention

By Leonard E. Bernold,[1] Steven J. Lorenc,[2] and Erik Luces[3]

Abstract: Side- and shock-loading of cranes can cause boom and turret drive gear failures with fatal results. However, traditional overload systems do not protect against these types of critical loading conditions, and crane capacity charts only consider the normal loading case, vertical lifts. In the maintenance of bridges, crane operators in any state department of transportation are presented with situations in which they have to pull debris and entire trees that are lodged against bridges. Dragging and shock-loading are commonplace. Researchers from the Construction Automation and Robotics Laboratory at North Carolina State University have developed an innovative crane monitoring system capable of warning an operator who enters a danger zone and storing information about critical events on an electronic device. Acting like a black box on an airplane, the storage device allows this information to be downloaded by a supervisor in order to assess how a particular crew "worked" the crane. This paper presents the results of this project and discusses the basic components of the accident prevention system for cranes.

INTRODUCTION

Lifting and positioning of heavy objects is one of the basic tasks in construction. The broad array of specific needs and conditions created a wide variety of types of cranes and hoisting equipment in general. Mobile cranes, which is the category of hoisting equipment used in this study, can generally move freely around a jobsite with their own wheels or tracks and without being restricted to a predetermined travel path that requires extensive preparation. Mobile cranes are made for open spaces (Shapiro et al. 1991). They require great skill and training for proper and safe operation. Crawler, truck-mounted, all-terrain, and rough-terrain cranes fall under the category of mobile cranes. All mobile cranes are capable of traveling within a jobsite; however, wheeled mobile cranes are also able to travel on the street or highway.

Safe crane operations, in the past, depended on operator training, good maintenance, effective planning, and supervision. Safety is considered among the most critical issues involved in the success of any lift operation. However, crane accidents involving tragic deaths of innocent people and destruction of property do occur. The number of accidents has decreased only after the implementation of strict regulations by the Occupational Safety and Health Administration. Repeated boom failure accidents of truck cranes used by the Bridge Maintenance Unit from the North Carolina Department of Transportation (NC DOT) triggered the research study described in the present paper.

Throughout the summer of 1994, the Bridge Maintenance Division of NC DOT recorded four accidents involving serious damage to their fleet of 64 National Series 446A truck-mounted hydraulic cranes. The accidents involved bending of telescopic booms as well as turret drive gear failures. Just the repair of a bent boom can cost up to $16,000 in replacement parts, not including the cost of labor and overhead.

Personal interviews with crane operators provided the necessary evidence that the nature of the work in which these units are used (bridge and bulkhead maintenance) expose the cranes to frequent uncharacteristic loading conditions like dragging of waste buckets, or extrication of piles and lodged debris. The goal of the experimental research presented here was to develop and field test a control system that assists the operator in the prevention of crane accidents. One of the main contributions of this work is the successful use of the principles of pattern recognition embedded in an electronic system capable of identifying the various operating states of a crane.

An important constraint of the NC DOT Equipment Depot, which maintains/repairs the equipment, is a restriction on spending. Although the supervisors at that level felt that larger truck cranes should be bought, upper management argued that other measures, such as more training, would be sufficient. Since local highway maintenance crews have to rent the equipment from the Equipment Depot, there is no incentive not to "abuse" the equipment. In many cases more task-appropriate equipment is available but at a higher price.

BASIC HOISTING TECHNOLOGIES

Cranes and derricks are designed to lift and lower loads. Beyond this, they vary widely in configuration, capacity, mode of operation, application, and cost. The design, fabrication, and installation of such hoisting equipment is based on basic engineering principles covered in structural and mechanical design. In the case of a truck crane, the complex structure of the boom, the machinery deck, and the supporting truck frame are subject to widely varying loads. Some of the components must be designed to criteria that limit deflections and control stress levels, and to other requirements that affect the service life of the equipment (Shapiro et al. 1991). The following are the basic components: Winch, hoist drums, sheaves and blocks, and rope. The term winch refers to a combination of winding drums mounted on a frame, powered by a motor, and equipped with the necessary controls; winches are also called hoists, or hoisting engines (Shapiro et al. 1991).

Sheaves are used to change the direction of the wire rope. Assembled in multiples, they are called blocks, and they can provide any required mechanical advantage. A mechanical advantage is governed by the number of lines or ropes lifting the load. The blocks contain pulleys, or sheaves, that allow the rope to be continuous; thus, the force in all sections of the rope are considered uniform. The function of any rope is basically to transmit a tensile force from its point of origin to a point of application. To provide this service effectively, a rope must have a closely packed structural form that will remain

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compact and maintain its cross section throughout its serviceable life (Rossnagel et al. 1988).

SAFE LOADING CAPACITY

The maximum allowable load for a specific radius for a crane or derrick in a particular configuration, referred to as load rating, is a function of many variables. Besides the length of the boom and its angle, the forces exerted by wind can surpass the load value by a factor of three. Likewise, the speed of operation, the levelness or plumbness of mounting, improper revving, and other factors can create additional loading not considered in the design specifications. Consequently, load ratings are valid only within the bounds of defined conditions.

The most important factor affecting load ratings for several forms of equipment is stability against overturning; such a load is referred to as a tipping load. Load ratings are established by specifying a percentage of the tipping load. The percentage used for each type of equipment has been set based on experience. For instance, the rated load of a crane at a specified radius should not exceed the following percentages of the tipping load at a specified radius (*Rigging* 1979) (i.e., 75% for crawler mounted cranes and 85% for rubber tire mounted cranes and cranes with outriggers.)

Machine moments remain constant if a boom is not lowered, but as the radius increases, the boom moment absorbs an increasing proportion of the available moment and the tipping load decreases rapidly. As the maximum radius is approached, the rated load becomes rather small and the overturning moment can become 95% or more of the resisting moment. At such a high percentage, any small perturbation induced by wind or by any dynamic effect can create an additional load that causes overturning.

Capacity Chart

Cranes are rated according to their lifting capacity. Capacity charts show allowable loads for defined boom configurations.

Fig. 1(a) presents the capacity chart for a hydraulic telescoping boom truck–mounted crane. In the figure the different possible boom configurations that relate the crane radius and the minimum height of the boom tip to the boom lengths are shown. As indicated in the chart, a radius of 12.5 m can be reached with many different boom-length combinations, for example, with combination A, B, or C, each reaching different heights. So, for three intermediate boom extensions of 14, 18, and 22 m the boom angle would need to be set at 31°, 47°, and 55°, respectively. Fig. 1(b) presents a table with the allowable loads according to the specified boom configurations. The first column shows the load radius in meters, whereas the other columns specify the maximum allowable loads for the four boom extensions shown in Fig. 1(a) at varying boom angles that have to be used to reach the load radii listed in the first column. Because the load rating is established using the tipping load, it is expected that the acceptable capacities for all three cases is approximately equal. In fact, interpolations using the given datapoints presented in the load capacity matrix all result in 17,000 N.

The difficulties of having to depend solely on capacity charts is evident, since the calculations for each crane configuration depend on interpolations. It is apparent that the dipping load can be increased by either making the boom steeper or by shortening the length of the crane boom.

In the United States and Canada, cranes are rated under ideal operating conditions (firm support surfaces, machine leveled within 1°, load is freely suspended, experienced operator, slow operating speeds, and absence of wind.) Crane operators should account for any conditions that are other than ideal (i.e., dragging, shock-loading) and, therefore, reduce the crane ratings based on their experience. Despite the use of load-indicating devices like the load-moment indicator (LMI) in making these decisions, the Butler statistics have recorded that nearly 80% of the sample cranes equipped with LMI systems were involved in crane overturning accidents due to overload (Butler 1978).

FAILURE ANALYSIS OF NC DOT'S TRUCK-MOUNTED CRANES

Common Practice in Crane Operation

Various field trips and interviews with supervisors and crane operators provided the necessary information for modeling common rigging operations that have lead to crane damage in the past. Fig. 2 shows a disassembled telescopic boom from one of NC DOT's cranes where bending failure occurred due to overloading. Three main types of damage on the crane itself were

- Grooves on the sheave created by winching the cable while dragging a load
- Plastic deformation and failure of the boom (at the third section) due to overloading
- Breakage of gear teeth in the turret drive due to turret overloading

These three types of damage can be associated with many failure modes. The first and third are directly related to cable load vectors with significant components off the normal axis induced during dragging of loads. The second type of damage can result from overloading the boom by exceeding safe loading capacities for the different boom angles and boom extensions specified in the capacity chart. Besides the overloading case described, another cause for possible boom failures has been identified. Plastic deformation can also result from the cumulative effect of static and dynamic forces that may occur during the abrupt extrication of lodged debris, piles, tree trunks, and so forth out of the ground. After detailed observation and feedback from operators, it became apparent that many of these accidents were caused due to insufficient or inaccurate information in the moment of decision making.

When operators decide to bring the crane into one of the mentioned loading cases, they are operating in uncharted conditions. Allowable boom angles, loading capacities, or boom extensions do not consider these types of operations. Consequently, crane operators and foremen have to rely on their perception of the situation to make decisions based on their experience. The foremen, who direct the lifting operation, have limited and, many times, inaccurate methods for predicting the exact mechanical effects (e.g., stress buildup in the boom cross section) produced during loading. One of the operators interviewed mentioned that being directly linked to the machine through the hydraulic control levers allowed him to feel certain vibrations and noises produced during overloading. Nevertheless, operators felt that this type of feedback from the machine was not reliable for decision making. Many accidents prove this point.

To aid the operator and secure the crane from damages, overload-protection systems based on hydraulic pressure limits are provided as standard in many new National Series 446A units. However, these overload protection systems do not secure the crane against dragging or extrication events. In addition, operators may choose to ignore the warning signals from the protection system and operate with dangerous hydraulic pressure levels. It is necessary to acknowledge that the uncharacteristic nature of the work and the demand on getting the job done forces the operator and supervisor to push the equipment to the limit.

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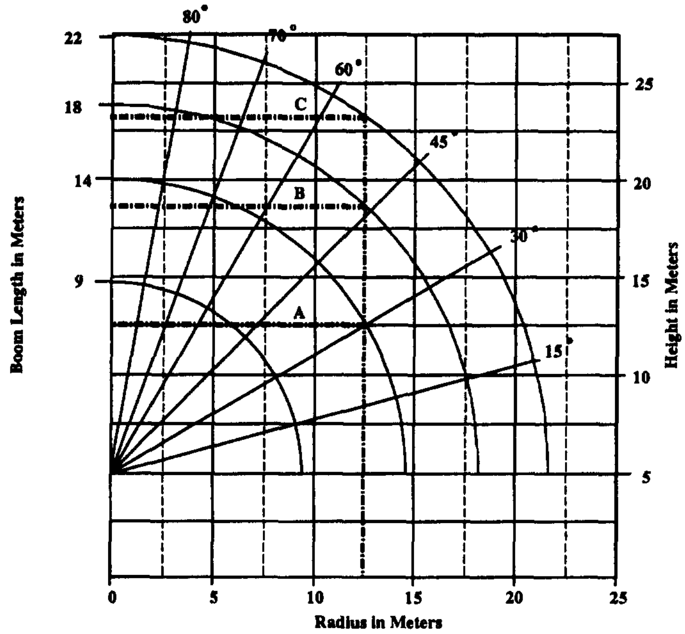

(a)

Load Radius (meters)	Loaded Boom Angle (degrees)	9 Meter Boom (newtons)	Loaded Boom Angle (degrees)	14 Meter Boom (newtons)	Loaded Boom Angle (degrees)	18 Meter Boom (newtons)	Loaded Boom Angle (degrees)	22 Meter Boom (newtons)
2	78	90,000						
3	70	70,000	78	64,000	80	49,000		
5	58	48,000	70	42,000	74	36,000	77	33,500
8	30	33,500	55	29,000	63	25,000	68	22,500
10			45	24,500	55	20,000	62	19,000
15					35	14,000	45	12,500
20							22	9,000

(b)

FIG. 1. Crane Capacity Chart with Load Ratings: (a) Possible Crane Boom Configurations; (b) Safe Load Capacities for Possible Boom Configurations

Finally, the operators introduced problems when calculating actual loads on the jobsite. Many bridge maintenance operations involve pulling of tree trunks, piles, and even water-filled vessels out of river banks. Any accurate calculation of the load on the hook is difficult in these cases. Besides this fact, the weight of most of the items used for bridge repair and maintenance is unknown, and, therefore, the operator has to estimate the load at the moment of lift. Mistakes in judging appropriately lead to overloading failures.

Definition of Critical Loading Cases

As a result of the discussed factors, three main loading cases have been identified and classified. Fig. 3 presents these cases:

- Lift case A: vertical lifting (normal mode of operation)
- Lift case B: dragging of a load (results in nonvertical cable vector)
- Lift case C: abrupt extrication (pulling of temporarily stuck objects)

Lift case A represents the intended mode of operation, namely lifting objects vertically. The stresses in the selected boom cross section for variable boom angles during vertical load lifting (lift case A) are used as a baseline for a comparative analysis of the stresses resulting from the other loading conditions.

Lift cases B and C represent situations that are not uncommon and may result in extreme stresses in the boom cross section, because they not only produce cumulative static forces but dynamic forces as well. Also, it is felt that the three main

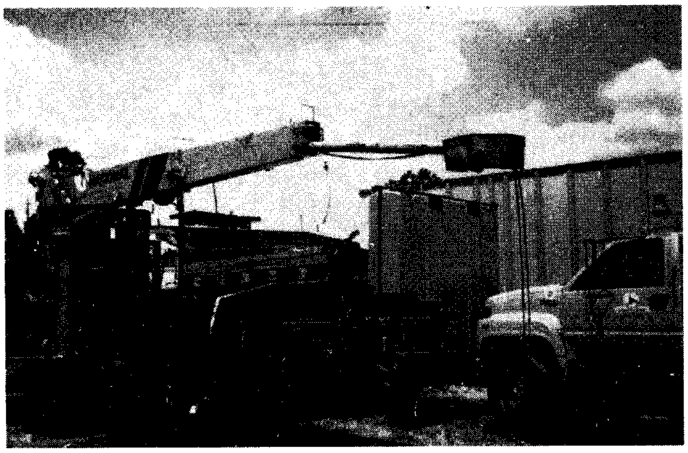

FIG. 2. Disassembled Telescopic Boom after Case of Overloading

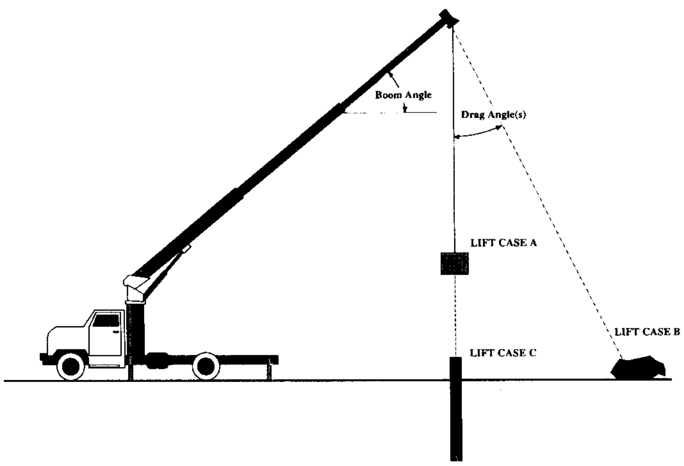

FIG. 3. Schematic Overview of Three Critical Loading Cases

types of damage to the boom and turret drive are related to these two loading cases, since they introduce significant additional forces, for which the crane has not been designed. A detailed stress analysis of these cases is necessary to support this qualitative assessment.

Turret drive failures require expensive repairs. While these damages are closely associated with lift case B, it is important to realize the special character of the loading situation that may lead to this type of accident.

Stress Analysis of Critical Loading Conditions of NC DOT Cranes

Based on the discussions with the NC DOT engineers and crane operators, past failures of crane booms have mostly occurred at the third segment. Failures do not necessarily mean breakage but also include plastic deformation that prevents the telescoping elements from retracting. Given this premise, the investigation focused on analyzing the cross section located at the base of the third segment. This boom segment has the smallest cross-sectional area and also the smallest moment of inertia.

Figs. 4 and 5 depict axis configurations used in the stress analysis. In Fig. 4, axis X and axis Y have been rotated in accordance to the boom angle to establish the axis X' and Y' used for the static analysis. The horizontal axis Z remains unchanged.

Fig. 5 introduces the selected points in the cross section that are used to calculate stresses for different loading conditions. In other words, the computation of stresses is limited to points B, C, and E, which represent the most crucial stress concentration points.

Traditionally, manufacturers provide charts that indicate the maximum load ratings for each crane type. However, this chart cannot be used to depict maximal loads when nonvertical load vectors become relevant (e.g., during dragging). For this reason, a detailed stress analysis was necessary. This section presents the analysis after the maximum load shown in the manufacturers capacity chart was introduced.

The allowable load capacities are being used to compute the allowable stresses in the critical cross section in the third segment of the boom as a basis for comparison with the stresses resulting from the other loading cases. The maximum load capacities are generally given for every possible boom angle and boom length as in Fig. 1, which presents the capacity chart for the studied crane 446A from National Crane Corp.

As indicated in the chart from Fig. 1, the lowest allowable loads are being listed for a boom length of 22 m (e.g., 33,500 N for 77°). Because this configuration represents the maximum extension of the total boom, the 22 m boom length was selected as the basis for the stress analysis.

As described in the previous section, the stress analysis focuses on the cross section of the third segment of the boom. The boom is submitted to loads that are defined in the capacity chart (=allowable), but using lift case B as the underlying loading situation. Fig. 6 illustrates the direction of the cable load force F and the normalized force vectors for a general lift case B. As indicated, the cable for F is vectored according to the three main axis introduced in Fig. 4. The drag angle is defined by the three angles Ax, Ay, and Az. For the purpose of this analysis, only two subclasses of possible dragging operations

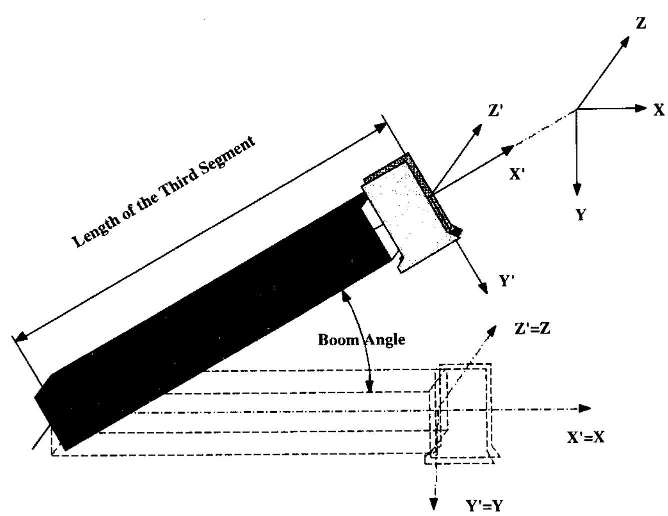

FIG. 4. Definition of Main Axes

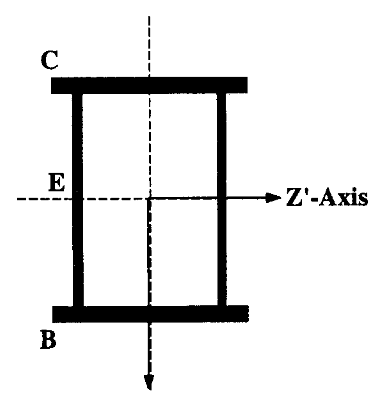

FIG. 5. Points in Critical Cross Section Used for Stress Analysis

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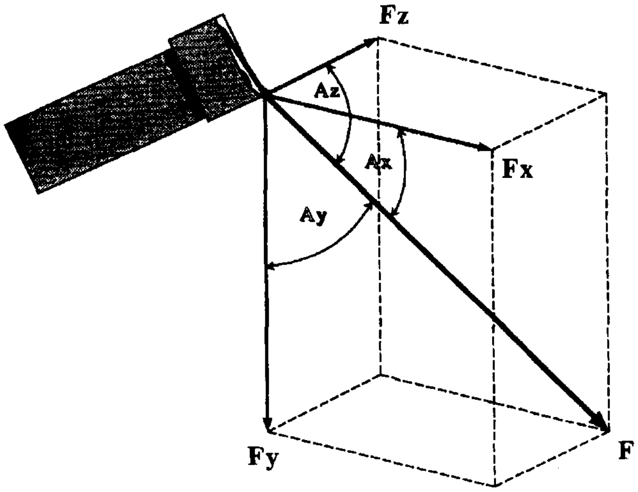

FIG. 6. Vector Model for Cable Force F

are considered, namely dragging in the *Y-Z* and *X-Y* planes (lift cases B1 and B2).

Results of Stress Computations

Maximum combined stresses (resulting from the combination of bending moments and axial and torsional loads) and maximum shear stresses produced in the third boom section for a variety of loading conditions were calculated by Luces and Bernold (1993). The following discussion is based on the detailed stress analysis data obtained in that study.

Stresses under Normal Lifting Conditions (Lift Case A)

Table 1 summarizes the calculated stresses for the allowable load capacities specified in the capacity chart (see Fig. 1). The loads and boom angles of a row represent a particular loading condition. From the table one can see that 133.7 MPa is the maximum combined stress calculated using the allowable load capacity for the different boom angles, labeled as loading conditions 1–10. The data also shows a variation between the maximum and the minimum stress of about 25%.

According to the data supplied by National Crane Corp., all boom sections are made of steel with a minimum yield strength of 413 MPa and a minimum tensile strength of 482 MPa. Thus, we can conclude that a safety factor of approximately 3 is used to prevent plastic deformation, and a safety factor of 3.60 to prevent fracture (without considering buckling.) The shear stresses in point E lie between 3.4 and 4.1 MPa.

The computed stresses in point C for each loading condition, shown in Table 1, are used as a basis for comparing stresses calculated for the different lift case B loading conditions where the directions of the force F are nonvertical.

TABLE 1. Computed Stresses for Allowable Load Ratings (Lift Case A)

Loading condition (1)	Load (kN) (2)	Boom angle (deg.) (3)	Computed stresses in MPa: Tensile *C* (4)	Computed stresses in MPa: Shear *E* (5)
1	30.0	77	99.9	3.45
2	25.1	74	104.7	3.45
3	22.7	72	106.8	3.45
4	20.2	69	111.6	3.45
5	18.9	67	114.4	3.45
6	15.1	60	119.9	4.13
7	12.9	53	124.7	4.13
8	11.0	45	127.5	4.13
9	9.6	32	133.7	4.13
10	7.6	15	123.3	4.13

Stresses during Dragging of Loads (Lift Case B)

As seen in Figs. 7 and 8, this mode of operation has been further divided into cases B1 and B2. Case B1 represents the loads that are dragged from locations that lie perpendicular to either side of the boom. Case B2, on the other hand, represents loads that are dragged from locations directly in front of the boom.

For the study of the stresses caused by lift case B1 loading conditions, the angle Ay is varied between 0° and 90° in increments of 10°. Force angle Ax, however, is kept constant at 90° (1.57 rad). Also included in the calculations of the stresses is the eccentricity D caused by the design of the boom head that prohibits the cable from slipping off the sheave.

Fig. 9 shows two main loading conditions, 1 and 9, for the two lift cases B1 and B2. To thoroughly understand the information provided by the stress curves, it is helpful to review the approach used to calculate the combined stress values. The combined stress in point C of the cross section (see Fig. 5) is set equal to the sum of the stresses produced due to (1) axial forces; (2) moment about the *Z*-axis; (3) moments about the *Y*-axis; and (4) torsion. Here, the moments clearly contribute the greatest portion of the combined stress. In other words,

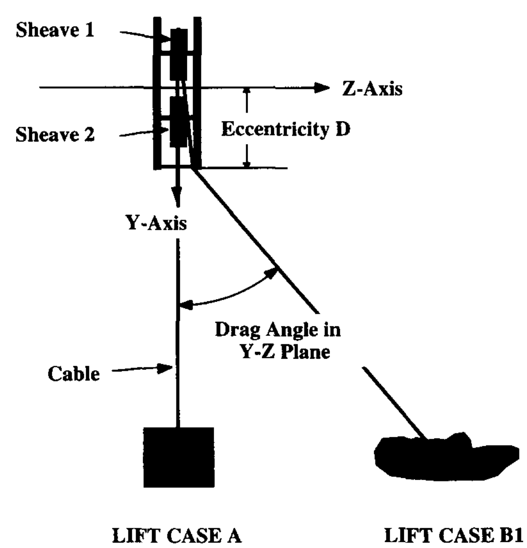

FIG. 7. Lift Case B1 with Drag Angle Ay Varying in *Y-Z* Plane

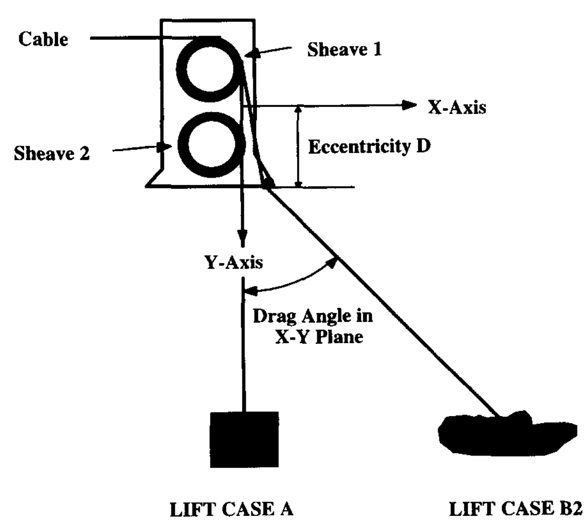

FIG. 8. Lift Case B2 with Drag Angle Ay Varying in *X-Y* Plane

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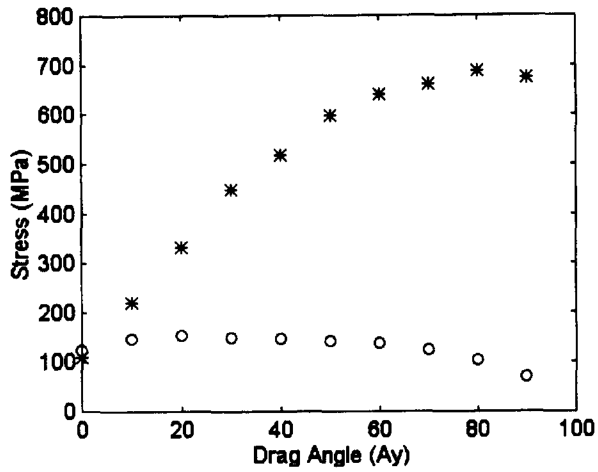

FIG. 9. Stresses for Variable Drag Angles and Loading Conditions 1 or Lift Case B1 and 9 for Lift Case B2

normal stresses resulting from axial loads are almost negligible.

The vector components of the assumed load applied to the cross section vary according to the drag angle, which consequently affects the moments produced about the axes. In addition, the different moments of inertia in the axes play a key role, considering that moment of inertia about the *Z*-axis is two times that about the *Y*-axis. It goes without saying that the different moment of inertia impacts the stresses.

Lift case B1 is the most affected by the increase in drag angle. For 30 kN and a 77° boom angle, the stress curve reaches the overall maximum of 697 MPa with a drag angle of 80°. Such a drag angle is most unlikely to occur. When considering 40° as a more probable extreme case, the maximum combined stress is 520 MPa, which again exceeds both yield and tensile limits for the steel. It can be seen from the curves that, after reaching the maximum, stresses begin to drop. This effect occurs as the drag angle increases causing the moment about the *Z*-axis to drop at a much higher rate than the moment about the *Y*-axis. Furthermore, the action of these moments on the cross section is affected by the moments of inertia, which in sum causes the combined stress to drop.

In lift case B2, the maximum combined total stress is 473 MPa for an 80° drag angle when the assumed load is 30 kN and boom angle is 77°. For a 40° drag angle, the combined stress, for the same loading condition, is 373 MPa, which is still very close to the yield limit. Should any small increase in the drag angle occur at this point, the 414 MPa yield limit will be exceeded.

It is also noticeable that for every loading condition the maximum combined stress in the cross section is reached when the drag angle is equal to the boom angle. In this case, the force applied is perpendicular to the boom, thus producing the maximum moment. Beyond this point, the component of the force producing the moment about the *Z*-axis decreases, and, consequently, so does the combined stress value.

Dragging loads may also have a serious effect on the turret drive, since this part of the crane system is designed to resist only the forces produced by the increase in acceleration of the free load during the rotation of the crane. By engaging the turret drive, the stress buildup in the teeth of the gears may exceed allowable limits, causing serious damages. In this case, it is important to consider the boom angle as the most critical factor affecting the turret drive. With lower boom angles, the horizontal component of the boom length increases, thus increasing the torque applied to the turret drive.

It is also important to notice the dynamics involved when adding the rotational motion factor to the dragging case, which may result in an instantaneous stress increase much greater than those obtained in Fig. 9.

Stresses during Extrication (Lift Case C)

This type of operation involves a great deal of predominant dynamic factors. The principal dynamic factor to be considered is the acceleration of the mass of the object to be extricated (piles, tree trunks). Changes in acceleration of the object being pulled out of the ground will ''rocket'' the force applied to the cable, submitting the whole system to very high stress levels in that moment. This will cause the boom, which is initially deflected by the load, to cyclically deform until the system regains static equilibrium. The kinetic energy of the system will result in an oscillatory action until it is dampened out, or, if too high, result in breaking of the boom or some of its supports.

STATE-BASED REAL-TIME CRANE MONITORING SYSTEM

A state-based system is defined as a system of independent states with transitions between those states. Information from sensors triggers the transition from one state to the other as the system moves through its phases. Each state specifies which variable is to be controlled.

Overall Structure

The system is configured into four major components: (1) sensors; (2) interface hardware; (3) data acquisition and monitoring software; and (4) crane operator and controls.

The sensors (p0, p2, 1c, . . .) used for monitoring the operational states of the crane during the operation are shown in Fig. 10. For the field test, an inclinometer was mounted to monitor the levelness of the crane during the operation.

Three areas of interface hardware are presented: (1) sensors-computer; (2) human-computer; and (3) computer-machine. In the first case, the data collected from the sensors during the operation is processed by the computer using pattern recognition algorithms for the detection of operational state changes. The human-computer interface uses several communication channels: screen outputs, sound signals, and printouts of electronic logs. Regarding the computer-machine interface, the automatic shutdown of hydraulic valves during dangerous situations has not been implemented in the first prototype. Fig. 10 shows the monitoring system based on the ''human-in-the-loop'' control approach.

The data acquisition and monitoring software is a code written in QuickBasic 4.5 that was developed for collecting and analyzing data from the various sensors mounted on the crane. This software contains three major elements: (1) program initialization and menus; (2) data acquisition and conversions; and (3) state recognition algorithms. The data acquisition and conversion functions are responsible for reading sensory data from the different channels of the DAS 16G1 A/D converter board.

As for the crane operator and controls, the on-line assist approach keeps the human operator in the control loop to directly benefit from his expertise in crane operations. Once the monitoring system has informed the operator of the hazardous loading conditions through audio and visual means, a correct action based on the best criteria can be executed. In addition, the written log can have a positive psychological effect on the operator, since it may relieve him or her from following inappropriate requests from the crews to perform tasks in abnormal conditions (i.e., dragging the waste bucket with the winch.)

As the operator makes the final decision, the corrective ac-

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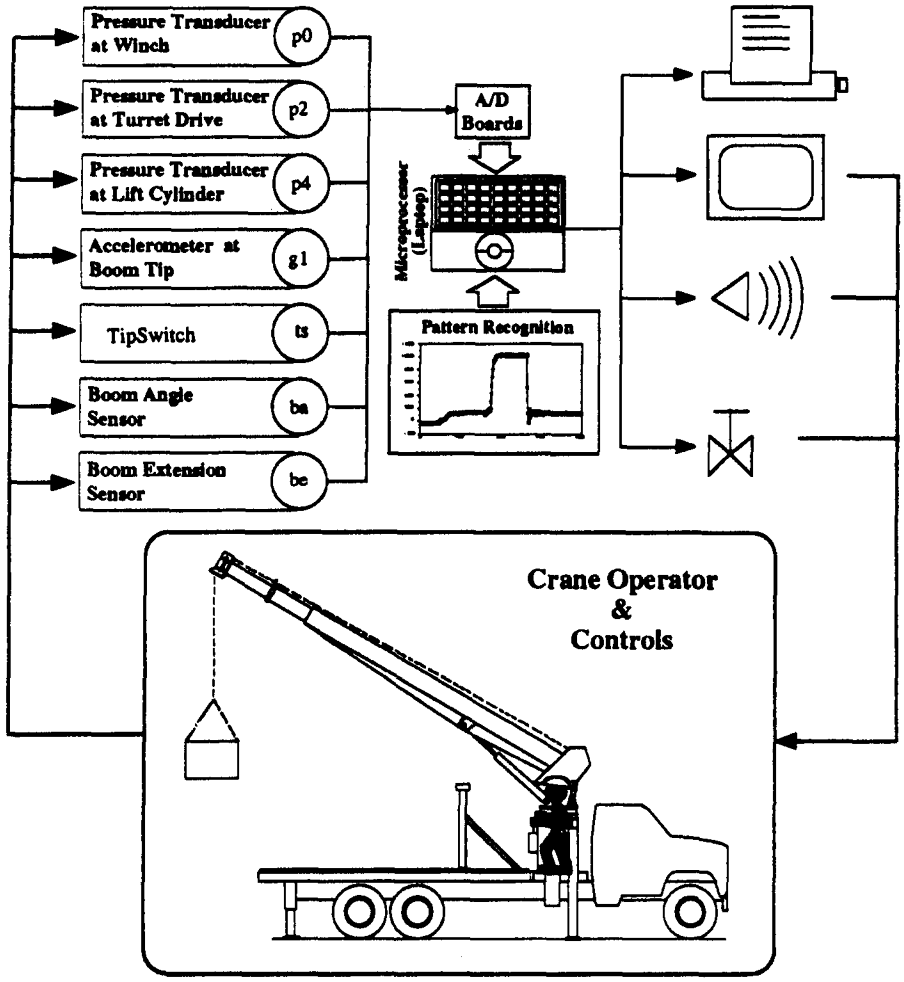

FIG. 10. "Human-in-the-Loop" Control Architecture

tion can be executed by operating the control levers or switches. As an example, a typical decision to prevent boom overloading is to reduce the load radius in order to increase the rating. To execute this decision, the operator pushes the boom-up control lever, and, consequently, the load-moment decreases as the load starts moving toward the crane.

Monitoring of Operational Stages

Specific indicators are being used to recognize the four operational stages. They are organized in a sequence that follows the common procedures of craning operations. The sequence of the four stages is (1) set-up; (2) boom position; (3) lift operation, and (4) end operation. Each of the stages is characterized by specific requirements that need to be fulfilled in order to bring the crane into the next stage. The control code has been organized in modules following this same sequence.

Crane Setup Stage

The crane setup stage comprises the monitoring of the levelness of the crane. The corresponding module is coded to display the data collected from the Sheavitz dual-axis clinometer and check for a levelness range of $\pm 1°$ off the horizontal plane. Whenever this threshold is exceeded, the code executes commands to sound a siren and to display a warning message. The level of the crane is shown in both graphical and numerical formats. In addition to the levelness, the boom angle is also monitored to detect the transition from the crane setup stage to the boom positioning stage.

In the case of unlevelness, the screen message for the operator would read "crane is unleveled." This message would be accompanied by the siren mentioned earlier. After the crane is leveled, the siren would go off and the operator would proceed to manipulate the boom by lifting it off the parking stand where it rests. Lifting the boom to an angle of 3.5° or more is enough for it to become free from its parking position. Once the boom is lifted beyond this angle, the system assumes that the operator is ready to position the boom on top of the load.

Boom-Positioning Stage

Monitoring of both boom angle and boom extension provides the operator with the necessary feedback to reach the desired boom configuration safely. By having a direct means of knowing boom configuration values, the operator can work with more confidence within the operating range defined by the load ratings of the crane. In addition, the load value on the hook is measured in order to detect the transition to the next stage. In fact, once the boom is properly positioned and the cable safely hooked, the first significant increase in cable load indicates the starting of the lift operation stage.

Lift Operation Stage

A variety of operational states within this stage are possible. During this stage a series of sensors are used to detect operational conditions, which reach from normal operation to dragging and extrication.

Similar to the previous stage, lift conditions like load, boom angle, and boom extension are continuously displayed on the computer screen. These same values are constantly monitored to detect the next and final stage.

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Termination Stage

The end of the operation is determined when the load, boom angle, and boom extension meet the logical values correspondent to a parked boom. These values comprise a load equal or close to zero, a boom angle less than 3.5°, and a boom extension of 5.8 m, which corresponds to a fully retracted telescope. Once the combination of all three values meet the established parameters, the control program displays an acknowledgment message on the screen (i.e., "Lift operation has terminated—good job") and instructs the shutdown of the system.

Monitoring Hierarchy of Lift Operation

Recognition of the operational states during this stage is based on an established sensor-monitoring hierarchy. Fig. 11 depicts the many possible operational states that can be encountered during the lift operation.

The sensors in the highest level of the monitoring hierarchy correspond to the TipSwitch and the pressure transducer mounted on the lift cylinder. These sensors measure the inclination of the cable, in the case of the TipSwitch, and the hydraulic pressure variations in the lift cylinder.

Whenever either one of the sensors exceeds the threshold limits, the control system determines the following new states, which can be vertical cable or quick release of load.

Nonvertical Cable State

Once the nonvertical cable state has been encountered, the next step is to establish if the loaded cable is nonvertical by measuring the variation of the pressure at the lift cylinder. This fact may define the loading condition as critical or noncritical.

The detection of a nonvertical cable and an unloaded boom most commonly represents a rigging phase in which the crew is manipulating the hook while preparing the load. Nevertheless, the detection of a nonvertical loaded cable is representative of a load-dragging condition, which presents a hazard for the crane. Also, in addition to measuring the load on the cable, the TipSwitch is still monitored for the case of the cable inclination being corrected. In this case, regardless of the load on the hook, the system assumes that the operation is back to normal.

Dragging State (Lift Case B)

The first commands executed by the computer program are (1) print warning message on the computer screen; (2) APPEND the new state, time, and date to the electronic data logger file; and (3) sound the siren alarm.

The dragging of loads can occur in many different operational modes. Most commonly, dragging is executed with the winch (dragging with winch state). In a second common case, the load is dragged by rotating the boom to the left or right using the turret drive. This case is indicated by the two states "turret dragging left" and "turret dragging right."

In a worst-case scenario, the object being dragged can shock-load the boom by getting stuck. Such an incident occurs if the operator does not interrupt the dragging operation. The corresponding state is called extrication during dragging.

A further level of information about the dragging with winch state can be attained by determining the direction of a

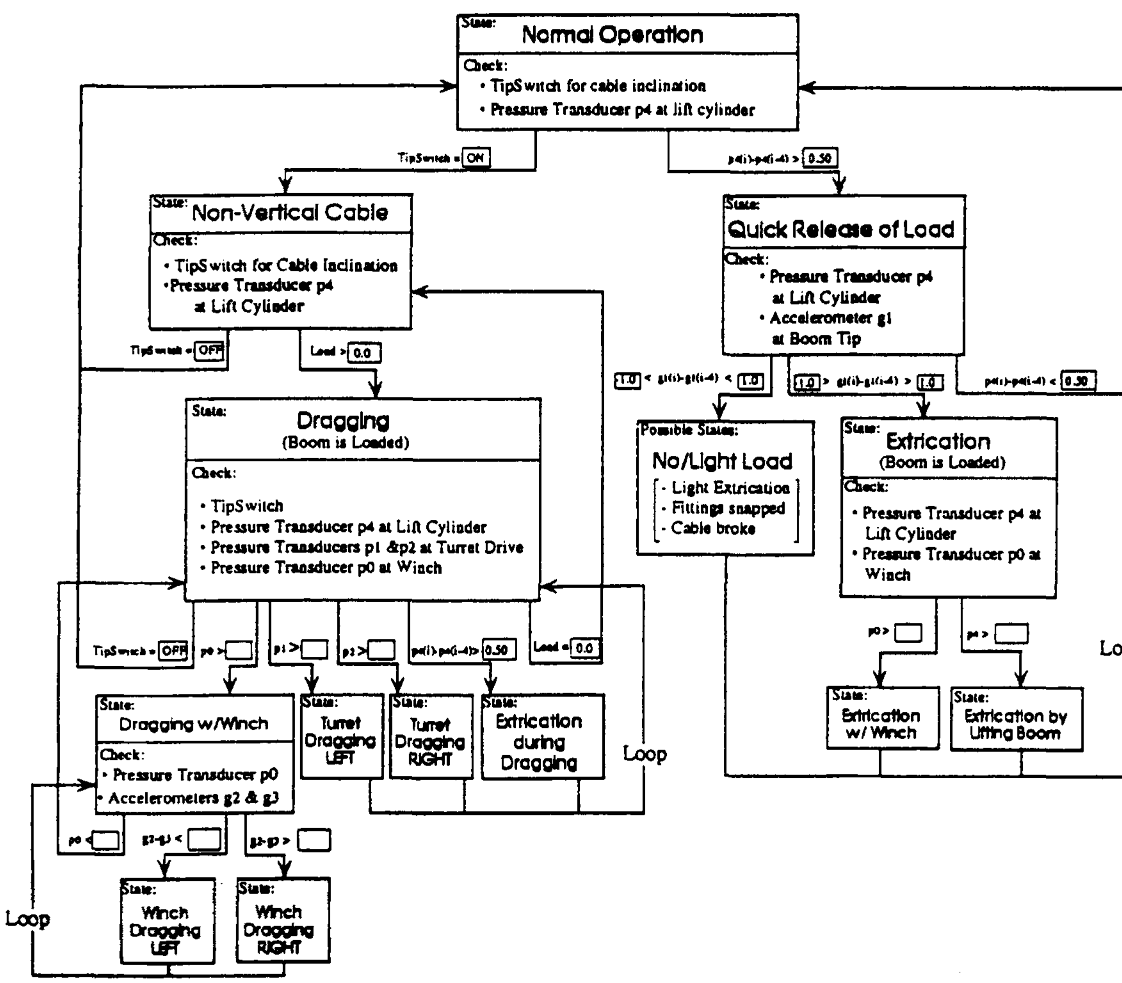

FIG. 11. Sensor-Based State Monitoring Hierarchy

possible torsional deflection in the boom. This could be accomplished by calculating the difference between the orientation axis of the accelerometer g2 mounted at the boom base and the accelerometer g3 positioned at the boom tip. These states are called winch dragging left and winch dragging right.

Quick Release of Load State (Lift Case C)

The second branch of the hierarchy connected to the root state of normal operation is triggered when the difference between four readings from the pressure transducer at the lift cylinder exceeds a minimum of 0.5 mV. As soon as this condition is detected, the quick release of load state is triggered. Because of the rapid development of this event, the system considers this state as a flag to analyze the last four readings of the accelerometer g1 at the boom tip.

Based on the outcome of the analysis, the system either loops back to the normal operation state, enters the extrication state, or enters the no light load state. While the latter state is considered nonhazardous, the extrication state represents one of the critical loading conditions that the system is designed to detect.

Extrication State (Lift Case C)

The algorithm that detects extrication is immediately followed by three commands: (1) print warning message on the screen; (2) append present state, time, and date to the electronic data logger file; and (3) sound siren alarm.

Field Test

As an example, a real lift operation (see Fig. 12) that took place in Selma, N.C., on Jan. 3, 1995, was recorded. The operation, under the supervision of Jimmy Marler of the bridge maintenance department at Selma, involved the replacement of treated lumber seals to be fitted under a rural bridge. The seals weighed in excess of 363 kg (800 lb), and had to be fitted under the bridge by dragging them into position.

A written log of crane conditions during the lift operation was retrieved from the files automatically created by the computer. Every time the monitoring system detects a change in the operational state of the crane, the control routines identify and append the new states into an ASCII file named after the date on which the event took place. As noticed from the electronic log, the monitoring system was able to detect in real time the critical loading case of load dragging. In addition, recognition of all other operational states was recorded starting from the crane setup stage until the termination state.

The operator's comments on the system's performance were positive, since it provided valuable information for decision making during the lift. As an example, knowing the amount of load on the hood motivated the operator to read the load rating chart, and consequently, increased the level of accuracy and effectiveness in his decisions when choosing maximum boom angle and boom extension. He also felt that the electronic log of the operation was a valuable backup document, since he knew not to heed to improper requests from the crew (e.g., dragging of the waste bucket).

Once the job was finished, the supervisor retrieved and reviewed the electronic log. In agreement with the operator, the supervisor also considered the electronic log a valuable document for keeping track of crane operations, and, furthermore, an essential record for retrospective analysis in the case of accident. However, he requested specific information on lifted loads and boom configuration to be appended in the log.

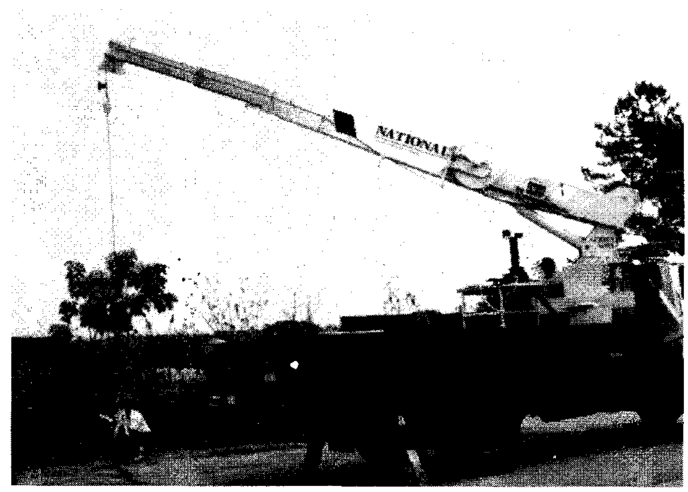

FIG. 12. Field Testing of Crane

CONCLUSIONS

Since they cause boom and turret drive gear failures, crane manufacturers and American Society of Mechanical Engineers standards warn against side and shock-loading of crane booms. Several crane accidents at NC DOT, however, have demonstrated that these accidents are not uncommon and result in costly repairs. The main objective of the presented research project was to develop and test an intelligent monitoring system that can be used to retrofit existing crane hardware. It was shown how a set of sensors and special devices were built and electronically integrated using an analog/digital converter and a laptop computer. A detailed analysis of the site operation led to a control software program that was tailored for craning operations commonly performed by crews working for NC DOT's road maintenance department. Experimental work with a fully operational crane provided the necessary data to build a feature-based prototype system that was eventually tested by operators in the field. It was found that the exposure of operators to the prototype system gave an opportunity to consider their valuable input for building the monitoring software, and ended up in requests for added capabilities to the system.

In summary, the project allowed the research team to explore the potentials of retrofitting "old" machinery with the purpose to turn them into "smart" and self-monitoring systems. The success of the prototype led NC DOT to request a first "smart" crane capable of assisting the crane operator to stay within safe loading conditions. In addition, the monitoring system is relatively inexpensive. The cost of the sensors used in this prototype cost under $3,000. With the addition of an embedded system, the cost of a fully operational system is estimated at under $30,000. At this cost, by preventing simply one accident, the unit will more than pay for itself.

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