

ENHANCING EXISTING CRANES BY A SEMI-AUTOMATIC NAVIGATION SYSTEM

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ABSTRACT

Following previous feasibility studies on the subject, this paper presents the actual conversion of an existing full-scale 5-ton payload crane into a semi-automatic "Handling Robot". Although performed in a laboratory setting, this crane - by its size, degrees of freedom, and mode of operation - resembles typical construction cranes, mainly tower cranes, and they can be enhanced in the same manner, similar components being used. The system allows operation of the crane in either a manual or a semi-automatic mode, and it can be taught to memorize up to 50 different benchmarks, i.e. particular points at the construction site, as well as safe routes among them. The major components of the system include: a programmable controller, three speed regulators, three encoders, several limit switches, a wireless remote control set, and a user-friendly M.M.I. (Man-Machine-Interface). Most of the components can be installed externally in the vicinity of the crane's joints and inside the cabin, with minimal intervention in the original wiring. Following the physical retrofitting of the crane, a series of tests examined performance, accuracy, repeatability, and safety aspects. They demonstrated a 15%-50% shortening of typical work cycles, high accuracy and repeatability, and a generally safer operation due to pre-tested paths and smoother movements with less sway and swing of the load.

1. INTRODUCTION

Cranes are not merely the largest, the most visible, and the most symbolizing equipment of construction sites but also, at various stages of the project, a real "bottleneck" that slows the pace of the construction process. Although the crane can be found standing idle in many instances, yet - once it is involved in a particular task - it becomes an indispensable link of the activity chain, forcing at least two crews (at the loading and unloading zones) to wait for the service. As analyzed in previous publications (Rosenfeld and Berkovitz, 1989,1990; Rosenfeld and Chazon, 1992) it is feasible to automate (or, rather, semi-automate) crane navigation in order to achieve higher productivity, better economy, and safer operation. Only a few other publications have dealt, during the last decade, with related aspects of construction cranes operation, e.g. Joley (1986), Varely (1987), Elsila et al. (1988) and Armstrong et al. (1993). This paper focuses on the technical aspects of the conversion of existing cranes into semi-automatic large manipulators. By mainly external devices, mounted on the crane, it becomes capable of learning, memorizing and autonomously navigating to preprogrammed targets or through pretaught paths.

The following sections describe various facets of crane automation: First, the necessary components and their technical characteristics are reviewed, along with some selection criteria. These are followed by installation and integration of the new components with the existing crane. Next, the Man-Machine-Interface (MMI) is presented with the different modes of operation it provides. Finally, the highlights of a set of controlled tests are reported followed by conclusions and recommendations.

2. MANUAL VERSUS AUTOMATIC OPERATION

The three major degrees of freedom of common tower cranes are presented in Fig. 1. In some cases, the crane is mounted on tracks which provide a fourth degree of freedom, while in other cases the tower itself is "telescopic" and/or the "jib" can be raised to a diagonal position. Since these additional degrees of freedom are not used routinely during normal operation but rather are fixed in a certain position for long periods (days or weeks), they are not included in the automatic mode of operation, although their position must be "known" to the automatic system.

2.1. Manual operation

In most configurations, each major joint has its own separate electric motor, controlled by the crane operator by either "joysticks" or "push buttons". A typical half-cycle of hauling in regular, manual operation is performed by the operator, approximately, according to the following stages:

1. He first assesses the location of the target with respect to the present location of the hook.
2. He, intuitively and only roughly, plans a free and safe path for taking the hook from the present location to the vicinity of the target.
3. He operates the joysticks and/or the buttons so as to follow his preplanned path.
4. During the "long-distance" navigation he inserts, as necessary, certain changes or corrections to the path as originally planned.
5. Upon arrival in the vicinity of the target, he goes through a fairly long trial-and-error process of fine maneuvering, relying mainly on hand signals from, and/or radio communication with the people at the theater of operation.

2.2. Automatic operation

The initial benefit of crane automation is the shortening of this process by two means:

- a. *For long-distance navigation*, the crane need be "taught" (only once) a safe and efficient route between any two points, and later "play back" this route whenever necessary, much faster than by repeated manual navigation.
- b. *In fine maneuvering* there are two possibilities: If the loading or the unloading points are fixed, they can be pretaught, and the fine-maneuvering time can be saved. If the loading or unloading points remain, not at exactly the same point, but in the same vicinity, then instead of interpreting and indirectly using the signals or the instructions of the people at the scene, the operator may allow their foremen to perform the fine maneuvering themselves, with the aid of a simple remote controller and with all necessary safety precautions being applied.

According to previous studies (Rosenfeld and Berkovitz, 1989,1990), these two improvements can save more than a quarter of the cycle time in typical construction activities.

2.3. An example of automatic navigation

An illustrative example may involve the casting of a concrete slab on a typical floor, say the 11th, of a high-rise building. The concrete is supplied by truck-mixers that can be directed to *exactly* the same discharge position (they also have adjustable chutes for fine positioning). The crane would usually use a bucket of 0.5-1.0 m

(approx. 1.5-3 tons when filled with concrete), being thus required to perform several hundreds of almost identical cycles from the discharge position of the trucks to the 11th floor, and vice-versa. With the proposed system installed on the crane, the operator would have to "teach" his crane *only once*:

1. To navigate safely the long-distance from the truck discharge position to the top of the building;
2. To wait for manual intervention in fine maneuvering and casting;
3. Upon emptying of the bucket, to withdraw gently upward;
4. To follow the pretaught long-distance navigation back to the truck; and,
5. To "land" the empty bucket softly and precisely on the ground beside the truck.

The operator should be able to send the crane through these pretaught partial paths by simple push-button instructions while keeping full control and responsibility in his hands, with the option of manual intervention at will.

The entire task, which involves several hundreds of similar cycles for each floor, would be done much faster, safer, and more efficiently. Furthermore, as described so far, the operator must intervene in each cycle upon arrival of the bucket in the vicinity of the casting area and rely on indirect feedback in the form of instructions or signals from the casting crew foreman. However, with additional enhancement and safety precaution, and with the proposed computer-controlled automatic system in place, the operator may delegate some limited operational capability to the foreman, and let him perform directly this little portion of fine maneuvering with the aid of a simple remote controller. Such a remote controller can be integrated into his "walkie-talkie" two-way radio communication device, to become effective only if, and only while, the crane operator authorizes him explicitly by pushing simultaneously a special "Enable Foreman" button on his dashboard.

There are multiple additional improvements that can be incorporated in conjunction with computer-controlled cranes, but they are beyond the scope of this paper. General information on advanced sensors for automation and robotics can be found, for example, in Kak and Albus (1985) and Pugh (1986).

3. MAJOR COMPONENTS OF CRANE AUTOMATION

In order to achieve the previously described features, the crane should be furnished with the following seven types of "hi-tech" devices:

1. A Central Processing Unit (CPU) with adequate memory and computational capacity.
2. A Controller with multiple input/output connections, to govern the motion of the joints and handle feedback signals.
3. A Man-Machine-Interface (MMI) with a small keypad and several lines of alphanumeric display.
4. Encoders or pulse generators - to be mounted on each joint of the crane and monitor their movements.
5. Sensors, limit switches, and other devices for either frequent calibration of the encoders or for safety purposes.
6. A wireless remote control system with several "smart walkie-talkie" devices, to be distributed among key foremen on the site.
7. Speed regulators attached to the motors of each joint, to ensure "smooth" acceleration and deceleration of the hook, thus minimizing the swing and sway of the load.

Fig. 2 presents a schematic block-diagram of these components. Most of the components do not require interference with the crane wiring. The installation can be auxiliary, so that the already existing manual operation would not be hampered. If for any reason (e.g. if a temporary operator is untrained in automatic operation) it is preferable to work manually, then one single main selector can be switched from "Automatic" to "Manual", and the common manual operation is immediately resumed. This is an important feature that can greatly ease, psychologically, the acceptance of any innovation. The "safety-net" of the old and familiar operation is always there in case the sophisticated automatic system fails or the operator is unwilling or unable to use it.

4. FLOW OF INFORMATION THROUGHOUT THE SYSTEM

The human interface with the system is the MMI. An experienced crane operator needs merely a few hours of training in order to start working with the automatic option. The emphasis in training should be on safety aspects and efficient strategies rather than on the basic operation. The MMI is as simple to operate as the ATM (Automatic Teller Machine) used daily by millions of ordinary people - whoever holds a credit or other bank card - with no training at all. Just like an ATM, the crane's MMI consists of a small display "screen" and a keypad with ten digits plus a dozen or so function keys. Space limitation in this paper does not allow to demonstrate here a full cycle step-by-step. Nonetheless, the principle is that various points within the crane's work-envelope are stored in the machine's memory by actually taking the hook to the desired point and assigning a code number to it. Each such point is memorized by the positions of the crane's joints, as defined by the encoders attached to them. If, for example, the operator wants to send the hook to point 17, he presses the following keys: "Go-to", "1", "7", "Enter". The computer immediately retrieves from the memory the "target position" of each joint in order to bring the hook to point 17. It also "reads" the present position of each joint from the proper "current position" registers, which are updated in real-time with every movement of the crane. Quick comparisons of these pairs of data ("target position" minus "current position") result in several simultaneous instructions to the controller to operate each motor in the proper direction and speed, in order to close the "gap" between the target and the current positions of each joint. At this instance, the speed regulators also come into action, imposing a gradual (rather than a "jumpy") increase of speed from zero to the selected maximum velocity (provided that the distance is large enough to develop full speed). Meanwhile, the encoders attached to the joints are continuously generating electric pulses, and sending them to the controller (this is the feedback loop), where they are converted immediately into digitized information, reflecting the "current position" of each joint as it changes. The CPU "reads" the information at very short intervals (up to 100 milliseconds), and "decides" when to start decelerating each motor according to the preselected regime of its speed regulator. As a result, the hook approaches the target in a smooth trajectory, and performs a precise and soft landing. In fact, the software is more sophisticated than this simplified explanation: An additional feature, for example, is the definition of several "through points" along the path in order to secure a safe route of the hook, which must pass in their vicinity (with generous tolerances) but without performing a full "landing procedure". Another enhancement includes various external devices for safety and calibration purposes. These may interrupt the normal feedback loop and override its instructions, without losing any information. A third important feature is an automatic correction procedure of "overshootings", which brings the hook back to the target with the preset precision. These and other details will be elaborated on in a forthcoming paper.

5. TESTING OF THE INSTALLED SYSTEM

As mentioned earlier, this entire system was assembled "in-house" from commercially available components. It was mounted on an existing, 15-year-old, 5-ton payload overhead crane, presented in Fig. 3. It has been serving a large testing hall for structural building components at the Israeli National Building Research Institute, located within the Technion campus. In most of its features, this crane resembles typical construction cranes, yet its convenient indoor location, and the fact that it was not very busy, allowed thorough experimentation with various alternatives of components and modes of installation, as well as the systematic testing of their performance. The latter was done in two major categories - space performance and time performance - summarized in Table 1. The tests have so far been performed in two rounds. Lessons from the first round were implemented towards the second. The results, shown in Table 1, are from the second round, which can still be improved (if desired) by hardware and/or software improvements.

5.1. Space performance

The tests in this category included the following:

Accuracy, which checks the absolute accuracy of arriving, from any arbitrary point within the crane's work envelope, at a prerecorded point, marked very precisely when recorded ("Go-to"). The accuracy was checked separately for each joint, and with different loads within the crane's capacity, in order to discover any slippage or systematic error in it.

Repeatability, which indicates the consistency of the system in running back and forth between two points, each joint separately. Repeatability is measured by the scatter of the results in multiple cycles, irrespective of their absolute location. It should be measured under similar conditions and with the same load.

Path navigation checks the extent to which the hook indeed follows the pretaught (safe) path. It discovers whether (additional) "through-points" are necessary to secure a collision-free journey. These tests resulted in some generalized lessons with regard to important heuristic rules for the insertion of critical through-points for avoiding obstacles.

The first two tests were performed with the aid of a heavy, compact load of an accurately dimensioned steel block, presented in Fig. 4. The third test, as well as the next two time-performance tests, were carried out with the aid of a large steel frame, presented in Fig. 5.

5.2. Time performance

With respect to the obtainable time savings, two types of tests were carried out:

Long-distance Navigation from the loading zone to the unloading zone, and vice-versa, without high precision. The durations of manual navigation by a skilled operator through predefined "safe corridors" of a number of paths quite typical of construction sites, were compared with the time required for automatic navigation through the same paths by the same operator. Multiple measurements began only after several "learning cycles" in both options.

Fine-maneuvering around the target with the steel frame of Fig. 5 had been measured in multiple repeated cycles. In one option, resembling the conventional mode

of operation, the operator could not rely on his own vision, due to the distance and/or obstructions; thus he was forced to rely on radio communication and hand signals from the theater of operation. In the second option, the "foreman" on the scene was given a (restricted) remote control device, and performed the fine maneuvering himself.

Table 1 concisely presents the results of all these five tests:

Table 1: Concise results of performance tests

Test Category	Specific test	Concise results
Space Performance	Accuracy	± 2 to 10 cm, depending on the specific joint
	Repeatability	Within 1 to 4 cm, depending on the specific joint
	Path Navigation	Critical "through points" must be pre-inserted or inserted during a special "slow motion" test cycle
Time Performance	Long-distance	Time savings between 15% and 40%, depending on the complexity of the path
	Fine maneuvering	Savings of up to 60%, depending on the accuracy required

CONCLUSION

The prototype discussed herein proved, without a doubt, the feasibility of automating existing cranes. The marrying of fairly delicate high-tech components with the rough and cumbersome parts of construction cranes, turned out to be a successful integration. It not only improves the crane's efficiency, but also softens its motions, reduces its structural and mechanical wear, reduces the swing and sway of bulky loads and improves its overall safety.

The performance tests resulted in better-than-necessary accuracy and repeatability, and quite an accurate path navigation (provided that a few critical "through-points" are pre-inserted in the "teach" phase).

Time savings in long-distance navigation varied between 15% and 40% - increasing with the complexity of the route; while time savings in fine-maneuvering were even higher - up to 60% - increasing with the required degree of accuracy. The overall savings in typical cycle-times varied between 15% and 50%.

A few faults of this experimental prototype need further attention towards field implementation. The major recommendations are:

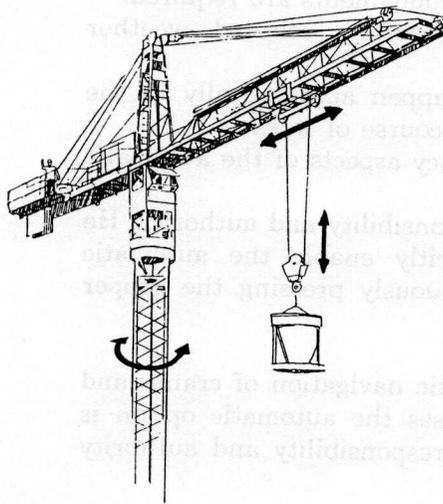


Fig. 1: Joints configuration of a common tower crane

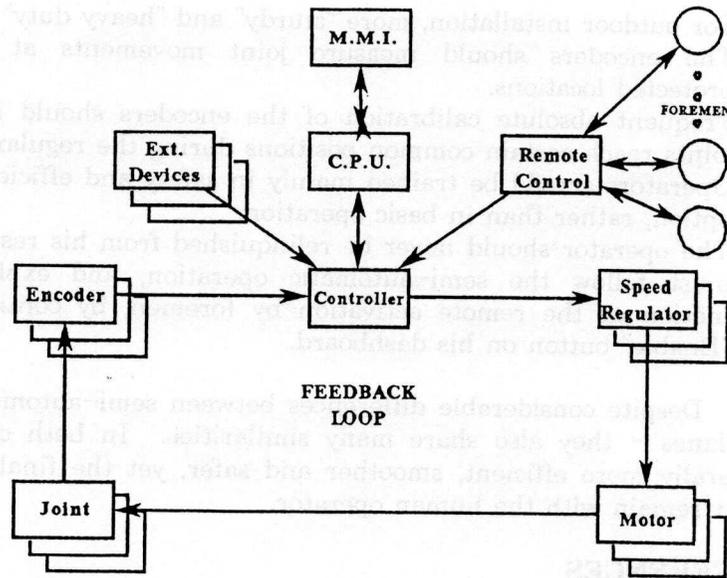


Fig. 2: Major components of crane automation.

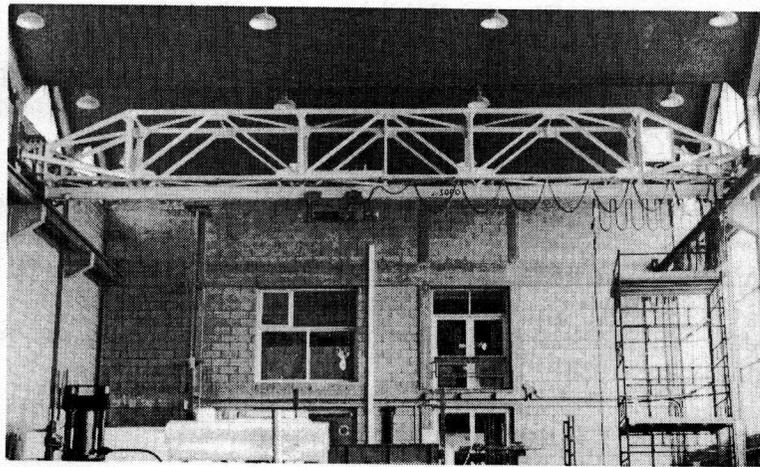


Fig. 3: Overall view of the prototype crane



Fig. 4: Accuracy and repeatability tests

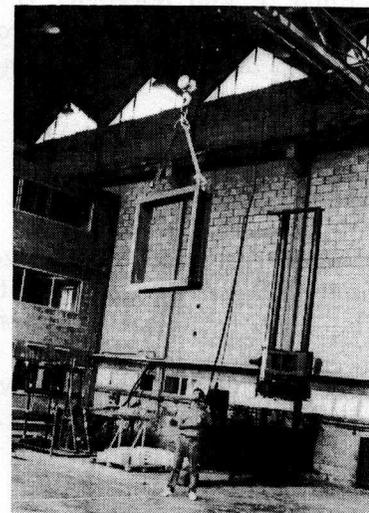


Fig. 5: Path-navigation and time performance tests

1. For outdoor installation, more "sturdy" and "heavy duty" components are required.
2. The encoders should measure joint movements at carefully selected weather protected locations.
3. Frequent absolute calibration of the encoders should happen automatically as the joints reach certain common positions during the regular course of work.
4. Operators should be trained mainly in safety and efficiency aspects of the automatic option, rather than in basic operation.
5. The operator should never be relinquished from his responsibility and authority. He must follow the semi-automatic operation, and explicitly enable the automatic motion or the remote activation by foremen, by continuously pressing the proper "Enable" button on his dashboard.

Despite considerable differences between semi-automatic navigation of cranes and airplanes - they also share many similarities. In both cases the automatic option is generally more efficient, smoother and safer, yet the final responsibility and authority must remain with the human operator.

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