Technical and Economic Feasibility of Automated Reinforcement Bar Fastening on Bridge Decks

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The investment of public funds for construction and rehabilitation of transportation facilities continues to grow. At the same time, productivity in such projects remains stagnant, and injury rates and compensation claims are excessively high. Construction automation presents opportunities to overcome productivity, safety, and cost problems associated with transportation projects. The feasibility of automating rebar fastening is examined. Rebar fastening could be an ideal candidate for automation. Because of related occupational hazards and the repetitive and voluminous nature of the task, automated rebar fastening could yield high benefits without significant investments in technical innovation.

Because the construction industry plays a critical role in the development, rehabilitation, and maintenance of the U.S. transportation infrastructure, advancements in the construction industry can have significant positive effects on the life-cycle development and performance of transportation systems. This paper discusses and evaluates the potential for automation of rebar fastening, which is particularly prevalent in bridge deck construction and rehabilitation.

BACKGROUND

The use of robots to perform various production tasks is increasing in manufacturing industries. The American Robot Association estimated that the number of robots used in the United States exceeded 100,000 in 1990 (1). Many industries are realizing the impact that full automation could have on their production. Currently, several industries have complete automation. Automation also has been accompanied by a considerable research and development effort. Robotics research is being conducted at a number of universities and commercial enterprises.

Construction, the largest U.S. industry, has not been a part of this automation trend. To date, there has been limited research in construction automation and relatively few practical construction robots developed. In addition to institutional barriers, other factors inherent to construction, such as a dynamic work environment, harsh climates, heavy materials and building components, impede automation. Thus construction robots require a higher level of sophistication, reliability, and durability than those used in manufacturing.

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Construction is an ideal industry for automation because construction operations are typically repetitious and physically demanding. Specifically, the special hazards associated with high elevations, toxic and combustible materials, noise, vibrations, heavy lifting, falls, and routine exposure to weather and dirt are highly undesirable. The construction industry expends significant amounts for medical expenses and compensation claims, and automating construction operations has the potential for reducing such claims.

In addition to enhancing safety and increasing productivity, automating certain construction activities could improve the quality of the finished product. Quality includes reliability, constructability, performance, minimum life-cycle costs, and customer satisfaction. In such a competitive industry (particularly on the international scale), the enhanced quality realized from automation could be substantial.

Only a few experimental robots have been developed in Japan, the United States, and Europe. Applications of construction robot prototypes include slab finishing, pavement cutting, excavation, sand blasting, and crack filling.

PROBLEM DESCRIPTION

Efforts to introduce partial automation into rebar preparation and positioning account for only about 30 percent of the rebar placement operation. Although most of the remaining time of reinforcement bar workers (rodmen) involves fastening, no documented studies on automation of this activity have been found.

Current rebar fastening methods call for tying bars with wire. This process requires that the worker perform in a near-constant stooping position, inducing prolonged pressure on the back, particularly the lower back. It has been estimated that disorders of the lower back region account for 400,000 work-related disabling injuries annually and result in approximately 19 to 25 percent of all workers' compensation claims (2,3). Tying bars with wire is highly repetitive and strenuous at sites such as bridge decks, and it often leads to musculoskeletal problems (4). Furthermore, the rebar "mat" forms an unstable walking surface that is strenuous on the feet, thus contributing to tripping and stumbling accidents.

Because rebar fastening may be characterized as repetitive, of low productivity, and hazardous, it could be an ideal candidate for automation. The technical aspects of automated rebar fastening include the robot components, their configuration, manipulator characteristics, motors employed, method

of fastening, and choice of sensors. In studying the economic feasibility of automated rebar fastening, the quantifiable benefits and costs were assessed, and a present worth analysis was conducted.

DESCRIPTION OF REBAR FASTENING

The construction activity proposed for automation is reinforcement bar fastening on decks, floors, and other horizontal surfaces. Rebar fastening is necessary to ensure that proper orientation and spacing of rebars are preserved during the pouring of concrete to avoid jeopardizing the quality of the cast slab. To gain further knowledge of the activity, three major bridge reconstruction projects were visited, and rodmen were videotaped over nearly an entire workday. As expected, the crew spent approximately 70 percent of the day tying rebar.

The videotapes show that bar tying is a simple but rugged process. The rodman has a waist belt of tools, a pair of pliers, and a loop of tying wire. In addition to a hard hat, rodmen must wear hard-sole boots and heavy gloves to minimize the piercing of the wire to the feet and hands. The worker first moves to the local area that he intends to tie, lodges his feet on the rebar mat for stability, stoops in a double-bent position, and then ties intersections within his reach (Figure 1), which takes an average of 6 sec for an experienced worker. The worker then moves on to the next intersection to be tied.

Typically, to maximize productivity from one position, the worker reaches to tie intersections beyond a comfortable reach of the initial location. This may be one of the causes of the periodic cramping in the legs and loss of balance. After tying an average of 20 intersections, the worker straightens up to look for untied intersections, providing temporary relief to the worker's back but causing worker downtime.

At one site the workers tied bars continuously for 65 min, with the periodic pauses described, then took a 20-min water break. The workers stopped for lunch at the end of 4 hr. The rodmen had to work constantly on the rebar surface. It was observed that even those workers with years of experience tended to trip on the mat. Discussions with the workers revealed other instances in which they had tripped and fallen

on mats and falls that they and other workers had taken from decks or at work sites. The videotape of the rodmen working also revealed that workers often lodged their feet in uncomfortable positions to attain stability.

Further discussions with workers revealed that they are prone to slipping on the mat during even slightly wet and icy conditions. Bridge decks are usually the hottest or coldest areas of a construction project during periods of extreme temperatures. In winter, winds are usually high and hands tend to cramp. In summer, heat reflects off the forms, adding to the heat of the rebars themselves. One worker noted during an interview, "Rebar tying is one of the most difficult and demanding tasks in construction; there is not a day that goes by without back pain, [and] it's very tough and hazardous . . . ."

TECHNICAL FEASIBILITY OF AUTOMATED REBAR FASTENING

Establishing technical feasibility of the development and implementation of automated equipment is somewhat less structured than economic feasibility because no standard measure of technical feasibility exists. Hence, the following criteria serve as the basis for technical feasibility for this discussion:

1. Does the robot development primarily consist of off-the-shelf or otherwise proven technologies?
2. Is it likely that key technical issues can be resolved within 5 years?
3. Are many of the system components adaptable to different project environments (as opposed to being site-specific configurations)?
4. Is the task somewhat standard from one project to the next?
5. Is it possible to incorporate one or more workers "into the loop," or does the task require full automation?
6. Is any part of the task at least partially mechanized or automated?

First the technical issues associated with an automated rebar fastening system based on information found in documenta-
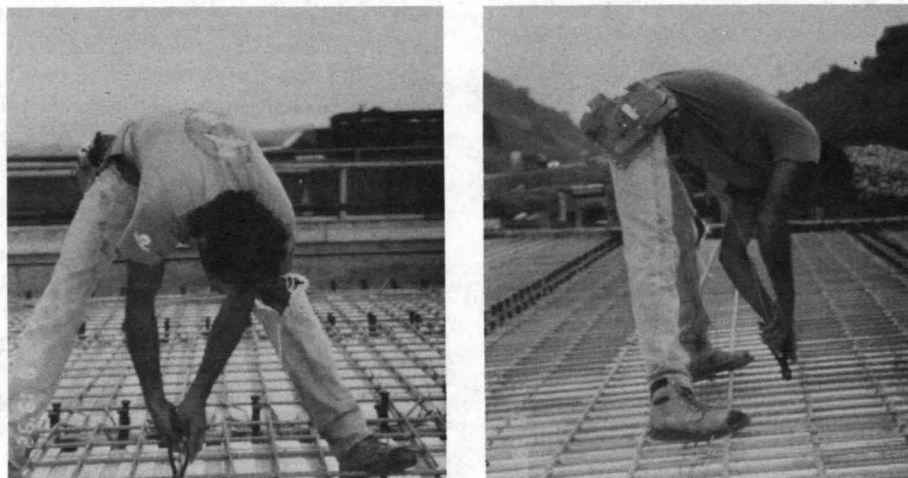

FIGURE 1   Front and side views of rebar tying.

tion of other construction or field robotic developments must be identified (5,6). Next, a concept and preliminary design of a rebar robot must be generated. This design should include the system configuration, definition of subsystems, technologies for subsystems, and a typical implementation scenario. A future study would address integration of subsystems, functional specifications, and machine drawings.

Mechanized Fastening

The method used by a robot end effector is one of the fundamental technical issues identified in the literature. Currently, rebars are fastened almost exclusively through tying intersections with wire. Developing a method for mechanized fastening poses one of the key technical issues. It is probably possible to mechanize and automate rebar fastening with wire, but it is likely that a mechanically simpler process exists.

In 1986 Rely Manufacturing of Ontario, Canada, marketed a mechanized rebar tier; however, the effort proved to be unsuccessful. Users cited low reliability and awkward maneuverability of the machine as the reasons for not adopting this product. The 70-lb machine had to be pushed by hand as its grooved wheel "rode" the rebar like rails. For this reason, other fastening concepts have been explored by equipment manufacturers attempting to mechanize the process.

Recently, Glim Manufacturing of Sweden developed a product that fastens rebar intersections by "clamping" them. The 14-lb Glim-Loc Gun (Figure 2) consists of a channelized hopper that carries the clamps that fasten the rebars and an end effector that performs the clamping. The gun is positioned vertically over the intersection to be clamped, and the worker exerts a downward force over the handles (Figure 2). This applied pressure forces the clamps out of the metal channel, automatically locking the two bars in position. The clamps are made of high-density polyethylene and offer high resistance to corrosion and extreme temperatures. They are molded

FIGURE 2   Glim Loc Gun system.

in cartridges that have several clamps. The metal hopper, which stocks cartridges, is a channelized metal container that holds the clamps and feeds them to the end effector.

The primary shortcoming of the Glim-Loc Gun is the 40 lb of vertical force that must be applied each time a rebar junction is fastened. Workers using the gun have experienced shoulder strain from applying this amount of vertical force repeatedly. However, the concept of the Glim-Loc Gun is relatively simple from an automation standpoint. Whereas the mechanical operations of tying with wire are quite intricate, only a vertical force is required to "fire" the Glim-Loc Gun. It is this concept of mechanized fastening that is adopted for the automated fastening robot.

Conceptual Design and Operation

The system components include the robot manipulator and end effector, local sensors, global sensors, controls, suspension, locomotion, power, and human interfaces. The overall system concept for a typical bridge deck application is shown in Figure 3. Suspension and locomotion are provided through a cage structure that performs similarly to an XY table and rests on the Bidwell rails that are erected before bridge decks are poured to support the paving equipment. The cage would have wheels that allow it to advance along the rails (manually or by power) as well as a clamp switch that locks the cage on the rails while the robot is in operation. The controls and the power source are housed in a box that moves over the rebar mat on all-terrain tires.

The cage supports a gantry robot that hangs from a telescopic rod. The end effector of the robot is the Glim-Loc Gun or similar system for clamping. (Figure 4 shows the manipulator and end effector in more detail.) The two-link manipulator has 5 degrees of freedom: major-z (Link 1), minor-z (Link 2), x (telescopic mount), y (rod advance), and rotation about Link 1.

A maximum of four workers are involved. Worker 1, situated "near" the current position of the robot, monitors the progress of the clamping operation. Worker 1 periodically stocks the manipulator with clamps and also has access to a kill switch to shut down the system in an emergency. Worker 2 monitors the controls, advances the controls and power supply box, and, if necessary, shuts down the system at any time. Worker 3, in front of the cage, inspects the prefastened rebars and makes any necessary adjustments in alignment and spacing. Finally, Worker 4 is an inspector or foreman who inspects postfastened rebars.

Technical Issues

The first technical issue is that of adapting the robot to bridge deck construction sites. Construction robots usually must operate in situ and therefore cannot be designed assuming a controlled environment. Instead, they must be flexible and rugged so as to function in a variety of environments with at least partial exposure to the elements, placing additional technical constraints on development. The proposed concept allows for adjustments in dimensions so as to accommodate decks of variable widths. Further, because the task does not
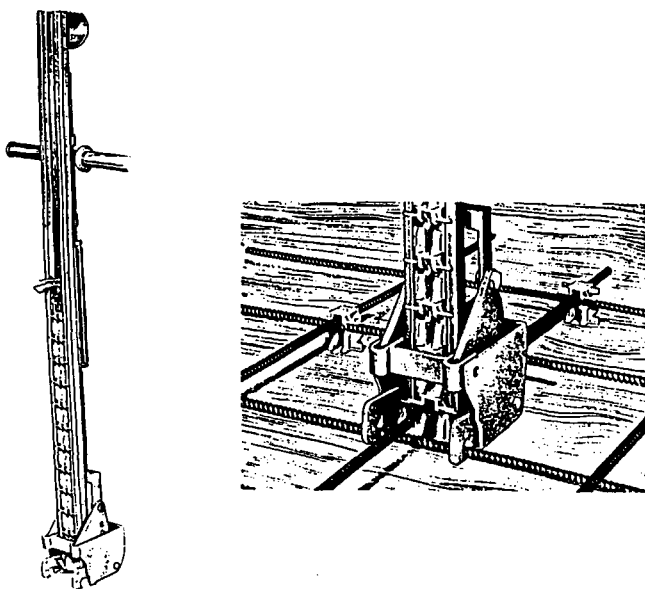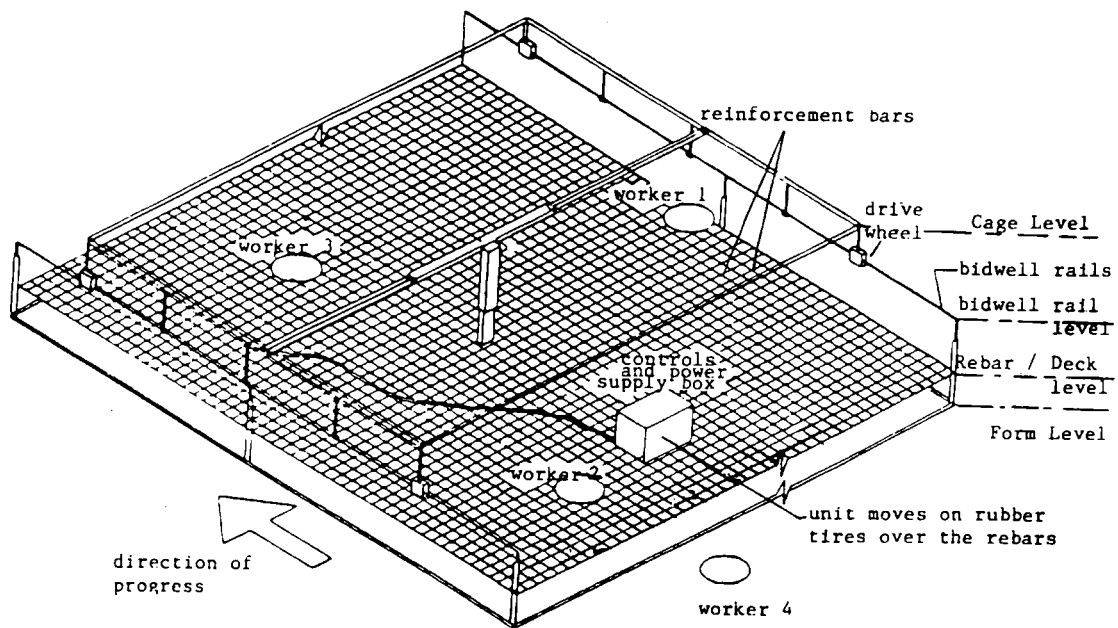
FIGURE 3   Conceptual design of rebar fastening automation system.

require using harsh materials such as solvents, concrete, sand, tars, or dust, the robot components would not be subjected to an environment as harsh as that for many other construction applications.

Construction automation must also prove safe. Although the introduction of automation eliminates many hazards, it has the potential to create new ones. For example, workers may accidentally come into contact with the robot while it is in operation. The sonar scanner on the rebar fastening robot will help to reduce occurrences of this hazard. A more detailed analysis in the laboratory or through simulation would detect other operating hazards.

Another technical issue of concern is that of mechanized fastening. While the Glim-Loc Gun or similar mechanism appears to fasten rebar effectively given an adequate vertical

force, much testing and detailed adjustments are likely to be necessary, which would probably take 6 months to 1 year. Also, it may be necessary to "pull" one rebar up against the other before fastening.

A key technical issue is sensing rebar junctions so as to align the gantry link of the robot in a vertical position directly above the junctions. Characteristics of the rebar fastening problem that affect the resolution of this technical issue include the following:

1. Typically, for reinforced concrete decks, there are two layers of rebar "mats," one about 2 in. above the form and the second (laid after the first is fastened) 4 to 6 in. above the first. This presents a complication because the sensing system must differentiate between intersections of the top and bottom mats.

2. Forms for bridge decks may be either wood or metal (stay-in-place), which have different properties with respect to certain sensors. For example, infrared sensors may successfully differentiate the heat levels between rebars and wood forms but would be less successful in differentiating between rebars and metal forms.

3. Besides vertically aligning the robot with the rebar junction, it is necessary to extend the gantry to the proper distance so that the end effector is just over the rebar intersection. The implication here is that the sensing system must also be able to measure accurately its distance above the rebars.

4. The intersection of the rebars may not necessarily be perpendicular. Thus, it may be necessary to provide an added degree of freedom in the manipulator or end effector to accommodate the realm of possible orientations of the rebar.
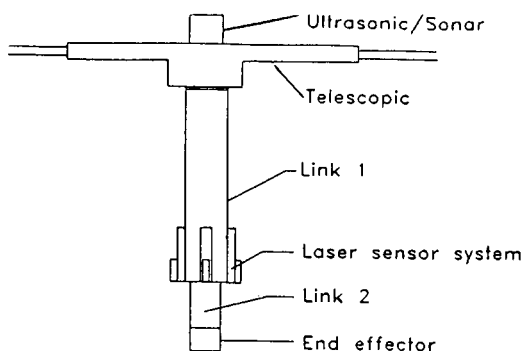

FIGURE 4   Conceptual design of robot manipulator.

A number of sensor systems may be adapted to the rebar alignment task, but some are more effective in addressing the preceding technical concerns. For example, an infrared system may produce a relatively clear image of intersecting rebar; however, it does not provide the vertical distance from the sensor to the rebar. Therefore, it is unable to differentiate between rebar junctions of the bottom and top mats. ·

A laser optical sensor system is recommended. The system would consist of four lasers with optical sensors mounted on Link 1 of the manipulator. Each laser would be able to send a laser beam downward and, using the reflected beam, measure the distance from the sensor mount to the first obstacle below.

A final technical issue is that of control software. Some development time must be spent writing and testing the software that will control the positioning and sensing of the manipulator and mobility (cage) systems. The software should allow for the exploitation of known information such as the design depth and spacing of the rebars. For example, if design specifications require a 6-in. spacing between rebars, the telescopic joint could advance the manipulator 5 in. and then employ the sensing system to determine the final local positioning for the next junction. The research and development time for coding and testing the software would most likely be 6 months to 1 year.

In light of the criteria stated for technical feasibility, it appears from the conceptual design and technical discussion that automated rebar fastening is technically feasible. The more difficult technical issues—namely, mechanized fastening and local sensing—could take advantage of technical components that are commercially available. Thus the task is primarily one of technical integration instead of technical innovation. Further, development time may be conservatively estimated at 3 to 5 years because the control software is likely to be straightforward. Automated rebar fastening requires no image processing or other complex control task requiring sophisticated algorithms.

The conceptual design of the rebar fastening robot is a unit that is assembled on site by workers according to the dimensions of the bridge deck; therefore, the concept could be adapted to a wide variety of project sites. The procedure of installation of the robot would be standard and repeated at every bridge site. Subsequent activities of the workers are also similar on all bridge decks. The system appears to be conceptually safe. Ultrasonic scanning is used to sense obstacles and a kill switch is activated automatically or manually by one of the operators whenever an obstruction is sensed.

ECONOMIC FEASIBILITY OF AUTOMATED REBAR FASTENING

For this study, economic feasibility was defined in an investment analysis framework. Within this framework the quantifiable benefits and costs of an automated rebar fastening concept were assessed and compared with the current practice. The benefits and costs were assessed for the period beginning with the present, extending through the research and development and through the expected life of the robot. The criteria for feasibility of automated equipment are typically to achieve a positive net present value or to break even on an investment in automation (7). This section identifies the probable benefits and costs of automated rebar fastening and provides insight to the types of data necessary for their assessment.

Ergonomic Evaluation of Rebar Fastening

Ergonomics is the science of designing and evaluating the workplace and work task such that the work performed is within the normal range of human physical capability, thus allowing the work to be performed safely (i.e., without injury or disease) and productively. Failure to design ergonomically can, and generally does, lead to a variety of acute and chronic injuries and illnesses, including low back pain and carpal tunnel syndrome.

Within the past 10 to 15 years, both the Occupational Safety and Health Administration (OSHA) and worker's compensation systems have recognized that this type of injury and illness is work-related, and the associated medical and legal costs have soared. (Typical compensation costs are $10,000 for a low back injury and $20,000 for a carpal tunnel syndrome case. OSHA routinely cites and fines employers with a high number of incidences of these injuries.) These costs must be considered in the economic evaluation of new approaches to fastening rebar.

A comprehensive ergonomic analysis can be used to assess the types of injuries likely to affect rodmen as well as their frequency and severity. Such an analysis is particularly useful when data revealing such information are difficult to obtain. This study, however, introduces only the concepts of ergonomic analysis as they apply to rebar tying. In the next phase of the study, field experimentation and laboratory analysis will be significantly extended, thus providing the basis for safety benefits associated with automation.

To begin assessing the ergonomics of the task, the videotapes taken at the bridge sites were studied in the laboratory. The results of this initial ergonomic study of rebar tying are briefly described, with the tasks' effects organized and discussed by body part.

The first body part of concern is the back; tying rebar involves at least two tasks that stress the back. The first is carrying and placing the rebar. Typically, the rebar is delivered to a temporary storage site at one end of the bridge. The tying personnel then carry bundles of the rebar material to the area where it will be used. From there, they set the individual pieces in place. The hazards of lifting are well known. The hazards of carrying are not thoroughly described. In this case, the workers may be carrying the rebar while walking across an uneven and unstable surface of rebar that has already been placed, thus subjecting the worker to a significantly increased chance of losing his balance. This in turn leads to an unexpected load on the body that could result in a "sudden movement injury."

Besides lifting and carrying, the actual tying task produces a prolonged static load on the lower back. All 10 persons observed tying rebar did so by bending at the waist with their legs straight. They reached down to the rebar (all the time standing on the uneven and unstable surface of the rebar they were tying) and tied. Depending on their relative leg and arm lengths, this typically required them to bend such that their

torso was below horizontal. In future work, the biomechanics of this posture will be evaluated in detail, but for this study, suffice it to say that the workers used this posture because it was the most energy-efficient, most stable, and fastest way of doing the work. In addition, the workers found that as they aged their knees would not tolerate the load associated with squatting and moving up and down. All of the workers also complained of chronic lower back discomfort.

The other body part of serious concern is the combination of hand, wrist, and arm. A number of injuries to and illnesses of these body parts that result from repetitive motion have been well documented. They include carpal tunnel syndrome, tendinitis, tenosynovitis, and ganglionic cysts. Such illnesses result from a combination of three factors: (a) relatively forceful exertions by the hand, wrist, or forearm; (b) postures that move these body parts out of the neutral position; and (c) a high rate of repetition. The initial study shows that tying rebar involves all three factors. In addition, discussions with the working personnel revealed that wrist and forearm pain, ganglionic cysts, and carpal tunnel syndrome are common complaints among people who tie rebar. A comparison of the three causative factors and the rebar tying task activities follows.

The most critical factor is posture. The wrist is in a neutral posture when the hand is a linear extension of the forearm. Tasks that cause the wrist to deviate from the neutral posture lead to injuries of the hand, wrist, and forearm. In rebar tying, the person holds pliers in one hand (which must be repeatedly closed and opened while tying) and uses the pliers to maneuver the wire around the crossed rebar. In the process, this hand makes 7 to 11 distinct movements per tie (some in flexion, some in ulnar deviation, and some in a combination of twisting one or both types of deviation). The other hand, which controls the other end of the wire, has five to eight distinct movements per tie, holds the wire in a pinch grip, and is sometimes in flexion or ulnar deviation. This combination of simultaneously twisting, squeezing, and deviating will, if done often enough, lead to a variety of injuries and illnesses to the hand, wrist, and forearm.

The second causal factor to consider is repetition or frequency. The initial observation indicated that people tie at a rate that ranges from 12 to 20 ties per minute depending on the individual, the type of tie, time of day, and the bridge location. A typical rodman's work pattern is to move to an area, place his feet as securely as possible, bend over, and then tie as many rebar junctions as he can reach from that spot, ranging from two to eight rebar junctions. The number of ties per minute multiplied by the number of hand and wrist motions per tie results in a hand/wrist movement rate of about 100 motions per minute—a very high frequency.

The last factor, force, was evaluated subjectively by observing the apparent forcefulness of the movements, having the study directors perform the task themselves, and observing muscle use on the videotape. The authors would estimate them as moderate (25 to 60 percent MVC), and we plan to quantitatively evaluate them in a follow-up study.

In summary, both the back and the hand/wrist are at significant risk of injury during rebar tying. For the hand/wrist in particular, all of the known risk factors are present and inherent to the task as it is currently done. Furthermore, persons performing rebar tying frequently complain of hand/ wrist pain. A new method of fastening rebar that removes workers from such hazards would yield significant safety benefits.

The ergonomic problems associated with rebar tying lead to a variety of musculoskeletal injuries, including lower back pain and carpal tunnel syndrome. These in turn lead to a variety of costs, including worker's compensation (medical and lost time), administrative (paper processing, injury investigations, training replacements, and supervisory time), and lost production. Worker's compensation costs vary from state to state but may be estimated on the basis of injury cost data published by state agencies and other researchers (8,9). Compensable lower back injuries average $10,000/case, and upper extremity injuries such as carpal tunnel syndrome average $15,000 to $25,000/case. The administrative and lost production costs will obviously vary considerably from company to company, but they have been studied by Heinrich (10) and others who have concluded that they average at least 100 percent to 400 percent of the direct medical and lost time costs.

As described, the nature of rebar tying is such that most of the persons who have worked for a number of years at this activity will experience upper extremity injuries and many will experience lower back pain. Nationally, the number of compensable cumulative trauma disorders increased by a factor of 10 during the 1980s. This rapid nationwide increase in the reporting of these injuries will most likely spread to the construction industry, and it is reasonable to expect that at least 5 to 10 percent of the work force will be affected annually. Assuming that about 4,000 bridges will be rehabilitated per year nationally, this equates to an annual direct worker's compensation cost of about $300,000 to $600,000 for these injuries. An additional $300,000 to $1.2 million will be incurred for indirect costs.

In addition to these costs, one must add the costs of an OSHA citation for failing to alleviate a source of lower back or repetitive motion injuries. OSHA has, under the "general duty" clause (5a1), levied substantial fines ($100,000 to $1 million) against the red meat, automobile, and other industries for these types of injuries. Companies in these industries have been fined for failing to report injuries (injured persons sought help through other sources), as well as for the injuries themselves and the failure to abate the hazard. The fines may be as high as $7,000/occurrence (i.e., each day of exposure per worker).

Estimation of Benefits

Reduction in Related Accidents

Accidents related to rebar tying include long-term back injuries; carpal tunnel syndrome; tripping; falling; piercing of the eyes, feet, and hands; and muscle cramping. By removing the worker from a stooping position to a standing position, it is expected that most of these types of injuries may be eliminated. From the ergonomic evaluation, it is found that for the approximate 4,000 bridge reconstruction projects annually, the direct costs and the indirect costs associated with injuries to rodmen due to the task of rebar fastening is $1.1 million. This study assumes that one robot could do the job

of a crew of six workers, and an average crew takes 2 weeks to complete rebar fastening tasks on these projects. A crew normally works for 8 months a year, so one crew works on 20 bridge sites in a year, therefore about 200 crews are employed in a given year.

Hence the benefits due to eliminating or reducing human involvement for one robot, or one crew, will be at least $5,500/year ($1.1 million/200). While this assessment is not extremely high, a second phase of this study would include possible injuries not yet investigated.

Increase in Rate of Fastening

Studies have shown that the productivity of a work crew for most construction tasks depreciates significantly over the course of a work shift and in periods of extreme temperatures. Automated equipment offers significant productivity advantages in that it is not likely to be significantly affected by these factors. The robot may perform the fastening task over longer work shifts and with fewer interruptions than conventional crews. Using time estimates for each of the steps of the automated fastening process and the average tying time for workers observed in the videos (Tables 1 and 2), the productivity of robot can be compared with that of current crews. The productivity of the robot has been found to be 30 percent greater than conventional crews.

Labor Cost Savings

The average rebar crew is six workers and averages about 2 weeks to complete fastening on a bridge. The crews work schedules of either 8 hr/day, 5 days a week or 10 hr/day, 4 days a week. The 10-hr-day schedule is more commonly observed. Introduction of automation will reduce the require-

ment of manual labor by at least two workers per crew. The level of automation proposed is partial where a crew of four workers are necessary for supporting the robot. Hence there is a savings of labor cost of two workers by the introduction of automation. This savings is calculated to be $103,240 annually. The computation is as follows:

A robot could work 11 months a year, considering 1 month as downtime for maintenance and repairs, and is 30 percent more efficient. Hence the robot can tie rebar for 29 bridges per year (22 × 1.3).

$$\text{Labor savings} = 2 \times 10 \times 8 \times \$22.25 \times 29$$
$$= \$103,240/\text{year}$$

where

2 = number of workers,
10 = hours per day,
8 = days per bridge,
$\$22.25$ = labor cost per hour assuming a 30 percent overhead, and
29 = number of bridges.

This quantity is significantly higher than the benefits derived from reduced injuries.

Estimation of Costs

System Components

The costs of system components depend on the specific configuration and technologies chosen in the equipment design. In general they involve an end effector, manipulator, mobility system, power supply, computing capability, and software. The total cost for the robot system was calculated to be $170,000. The breakdown of the costs follows.

Research and Development Costs

Research and development costs include the conceptual design, integration of subsystems, research into necessary upgrades in technology, software development, and testing. Estimation of these costs is based on projections of the necessary man-months of research personnel and the equipment necessary to conduct the research. For the purposes of this project, it is assumed that research is conducted at a university for 3 years and then transferred to industry for an additional 2 years of development. On the basis of cost per man-year, the costs at the university are assumed at $120,000/year, and in industry, $160,000/year.

Operating and Maintenance Costs

Operating and maintenance costs include setup, take down, transport, power, materials, technicians, and the like. Estimates of these costs have been derived from comparing them to an analogous system in use. The operating and maintenance costs for the robot were calculated to be $15,500/year, itemized in Tables 3 and 4.

TABLE 1 Productivity Estimates for Automated System

Step	Execution Time (sec)
Sensing and local orientation	2.0
Clamping and fastening	1.5
Advancing from one junction to next	1.5
Global movement	1.5
Setup and dismantling	1.0
Total (average per clamp)	7.0

TABLE 2 Productivity Estimates for Conventional Rebar Tying for a Crew of Six

Step	Execution Time (sec)
Average tying time	1.0
Straightening up and resting	3.0
Moving to reachable areas	2.0
Water, lunch breaks	4.0
Total (per tie)	10.0

TABLE 3 Capital Costs of Automated Rebar Fastening

Automated System Component	Estimated Cost ($)
Manipulator, including end effector	40,000
XY table, including telescopic rod	60,000
Power supply and components	20,000
Computing and controls	20,000
Controls interface	10,000
Sensors, laser and ultrasonic	20,000
Total	170,000

TABLE 4 Operating and Maintenance Costs of Automated Rebar Fastening

Automated System Component	Estimated Cost ($)
Power supply	3,500
Transfer and site installation	4,000
Software maintenance	500
Servicing	1,500
Clamps and end effector maintenance	5,000
Down time	1,000
Total	15,500

Nonquantifiable Benefits: Improved Quality

Automated equipment may perform certain tasks with a higher level of accuracy or consistency, which may lead to a higher quality of product. For rebar fastening, a mechanized process may be able to provide a stronger connection among the rebar. Hand-tied connections tend to loosen as workers continue to walk on the suspended rebar mat, thus possibly affecting the performance of the finished deck.

Present Worth Analysis

In assessing the economic feasibility of the robotic concept, a criterion of positive net present value (NPV) of investment is established. First, a cash flow consisting of the quantified benefits and costs over a planning horizon is formulated and discounted at various interest rates. Next, because assumptions were necessary in quantifying benefits and costs, a sensitivity analysis with respect to many variables is performed.

The cash flow consists of a research and development period, followed by a period of robot use until it has reached its design life. Robots are systematically purchased and replaced until the end of the specified planning horizon. For the sensitivity analysis, all base costs are increased by 10 and 20 percent and the base benefits are decreased by 10 and 20 percent. Base expenditures include $170,000 in capital, $15,000 for annual operating, and $520,000 for research and development; base revenues include annual benefits of $109,900 and a salvage value of $34,000. The design life of the system is assumed to be 6 years, and the research and development period 5 years. A planning horizon of 25 years and an annual inflation rate of 4 percent were used.

The NPV versus minimum attractive rate of return (MARR) of the corresponding cash flows are shown in Figure 5. The results indicate that over the range of reasonable interest rates, the robot system is an economically favorable investment. For example, at a MARR of 10 percent, the NPVs per crew replacement are $536,974, $393,379, and $249,784, for the base, 10 percent, and 20 percent cases, respectively. The favorable economic results stand for many other sensitivity tests conducted for the study but are not reported here.
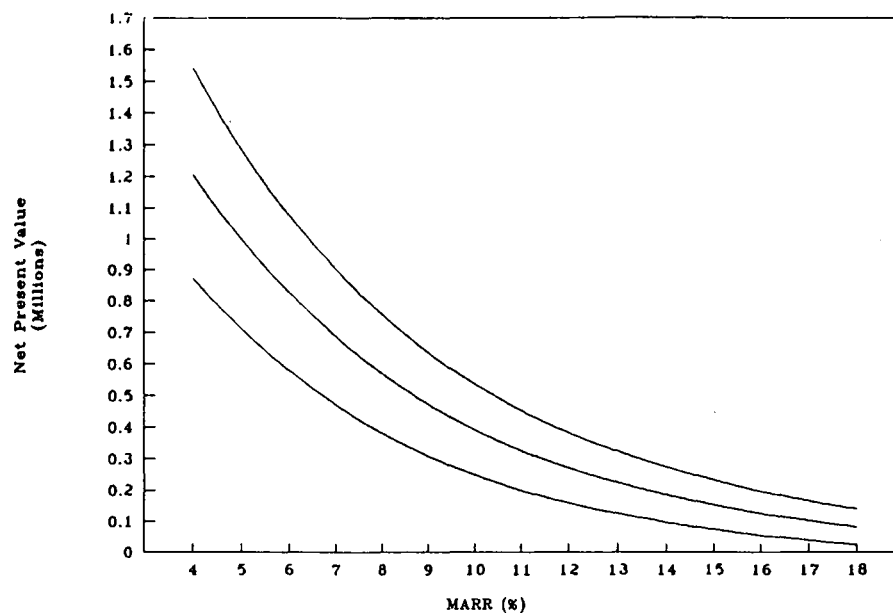
NPV of Robot Investment

FIGURE 5 NPV versus MARR of rebar fastening automation investment.

CONCLUSIONS

Videotapes of workers in the field, discussions with workers, ergonomic analysis, and injury statistics seem to indicate that productivity and safety benefits could be increased, with relatively low financial and technical investment, through automated rebar fastening. The productivity benefits significantly exceed the safety benefits of automation of this task. For this reason, additional study of the economic feasibility should focus on increasing the precision of the relative productivities of conventional crews and a proposed robotic system.

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