Sensor-Integrated Nailing for Building Construction

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Abstract: It is generally acknowledged that there is a great need to increase safety, productivity, and quality in construction. Recent developments in high-tech areas have offered the opportunity to reevaluate production methods and tools believed to be state of the art for decades. While many new construction technologies under investigation would require a revolutionary development in the industry, the potentials for evolutionary improvements of existing construction technologies are vast. This paper discusses one example of high-tech evolution in building construction that has proven to increase the productivity of nailing and promises to counter balance the loss of skilled construction workers. The present study includes both laboratory and field testing of a sensor integrated nailer in construction. The results of these tests are discussed as well as recommendations for further improvements.

Introduction

The construction industry is currently poised on the threshold of a technological opportunity reminiscent of that experienced in the late nineteenth century. At that time, new production methods, which promised great economical advantages, were developed. Scientific management techniques were created, enabling the systematic analysis of the production process.

"It will be necessary to innovate to compete in future construction markets," writes C. Tatum (1989). He adds that four major forces drive the need for innovation in construction: (1) National and international competition; (2) increase of private ownership of construction facilities; (3) complexity of tomorrow's facilities; and (4) availability of new technology (robots).

Based on this premise, researchers worldwide started to systematically analyze construction areas, disciplines, processes, and work tasks for the potential applications of automation and robotics. Frameworks for analyzing potential areas for automation have been proposed by Bernold (1986, 1987) and Kangari and Halpin (1989). However, development of many proposed robotic devices would require a total reevaluation of the appropriate construction methods in order to make the computer controlled machines cost-effective, thus requiring a revolutionary modification of traditional operations. In contrast, subtle evolutionary progress in existing technologies would not require such drastic measures in order to be profitable, and therefore would have many advantages over proposed robotic devices. This concept is based on the history of construction technology, which was generally driven by incremental improvements. One area where some interesting develop-

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Note. Discussion open until November 1, 1991. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on February 2, 1990. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 117, No. 2, June, 1991. ©ASCE, ISSN 0733-9364/91/0002-0213/$1.00 + $.15 per page. Paper No. 25853.

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ments can be observed is the improvement of power tools for construction (e.g., cordless drills). This represents a development that is geared toward increasing the productivity and quality in construction by providing better tools to the construction laborer, still the most important production resource in construction.

While the objective of better tools and equipment has generally been to increase power and speed, it must also be remembered that the skill necessary to operate these improved tools has increased, not decreased. At the same time, craftsmanship and the availability of skilled labor has diminished. This suggests that besides improving speed, power, and quality, innovation must be geared toward decreasing skill requirements.

The presented study had the objective of investigating the effect of merging a traditional construction tool with a sophisticated but simple sensor in order to increase the productivity of less-skilled workers. The nailgun, which was selected as the principal tool, was integrated with a stud sensor to form the sensor-integrated nailer. This paper will first, familiarize the reader with the basics of nailing, second, present the innovative nailer, and third, discuss the results of laboratory and field testing with the prototype tool.

Traditional and Current Uses of Power-Supported Nailing

Power-supported nailing has become extremely popular in the field of residential wood construction because as many as 50,000–100,000 nails need to be driven during the erection of a frame house. While hand nailing is still common and sometimes necessary, a variety of machines have been developed since the 1950's that have attempted to mechanize nailing.

The air-operated Powasert nailing machine, utilized by the United Shoe Machinery Corporation in 1959, was one of the first portable automatic nailing machines in service. An automatic hopper-feeding device was used to deliver nails through a plastic hose to the gun. According to Stern (1959), the length of the nail feeding hose was limited to 25 ft, which made its use in the construction industry as a portable pneumatic tool infeasible. Other machines of the 1950s and 1960s had similar nail-feeding drawbacks. The multiblow Nu-Matic nailer used gravity to bring nails to the gun's point of discharge. This system limited the machine's use to operating perpendicular to flat work areas of not more than 6 ft (2 m) by 12 ft (4 m).

The nail-feeding inefficiencies of these early machines have been solved through the introduction of machine-quality nails (i.e., few or no imperfections) that are fed through clips or coils attached directly to the nailgun. Compressed air has proven to be the most economical means of powering all but the most specialized powder-actuated nailguns, which can penetrate steel or concrete.

Nailguns are used in almost every aspect of the operation from the erection of framing systems and walls to the attachment of sheathing and trim. The critical factor in nailgun use is the location of the stud or joist. In the erection of framing systems such as stud walls, location is readily accomplished because the stud can be seen opposite the top or bottom plate. However, in the attachment of sheathing and trim the stud or joist is hidden from view. Skilled carpenters are usually able to find the studs or joists by using marks that were made on the plywood when it was tacked down (marks are made on plywood at the time of installation to insure the studs or joists are staying

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16 in. on center). However, less skilled carpenters and carpenters' helpers often cannot proficiently locate the stud or joist. As a result, the work slows down considerably while they attempt to locate the members by eye or by trial-and-error. Many times chalklines must be dropped to ensure the nails enter the stud or joist opposite the plywood. In cases such as the installation of interior base or crown molding, even the most skilled carpenters have no choice but to pull out their measuring tape and mark off the studs. The sensor-integrated nailer, described in the next section, is an attempt to solve this problem by electronically locating the stud or joist that is hidden from view.

Development of Sensor-Integrated Nailer

The design of the new nailing system was based on the following needs: (1) Nonproductive time should be reduced; (2) the accuracy of nailing (measured in the number of nails entering the stud) should be increased; and (3) nailing productivity should be improved.

It was found that the core problem in satisfying the aforementioned needs lies in allowing the laborer to find the stud behind the wall without interrupting the productive operation of nailing. One feasible solution was the integration of a stand-alone stud-sensing device with a nailgun to create a tool combination that is able to find the studs and nail at the same time. Thus, the central problem was to build an attachment that positioned the sensor at the proper location to be useful during nailing.

The prototype tool utilized the following hardware:

1. The ATRO nailgun, a coil loaded gun used for drywall attachment. The model number used was 5545002.
2. An off-the-shelf Zircon Stud Sensor, an "electronic wall stud finder" made by Zircon International, Inc., which sells for about $20.

A schematic diagram of the prototype is presented in Fig. 1. The attachment was fabricated at the University of Maryland Civil Engineering Machine Shop. Aluminum angles were used to make the connection between the nailgun and stud sensor. There were in turn bolted to the body of the

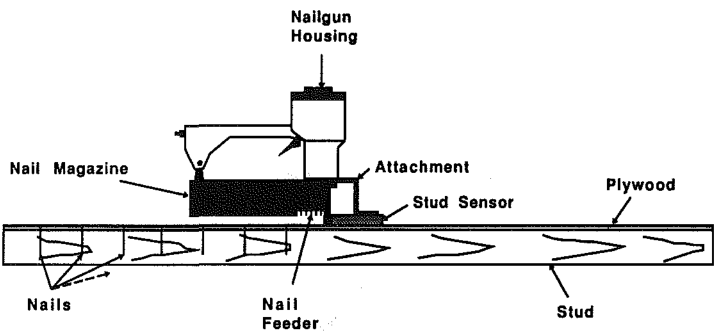

FIG. 1. Sensor-Integrated Nailer

gun. The angles were held together, and the stud sensor attached, through the use of friction plates.

The attachment to the ATRO nailgun was designed to perform for different plywood and stud thicknesses. It had to be flexible enough to allow easy connection to the nailgun, and sturdy enough to withstand the shocks generated by nailing with compressed air. In addition, the sensor had to be positioned close to the gun's point of nail discharge. This was necessary for two reasons. First, the effectiveness of the system depends on its ability to place a nail at the point where the sensor locates a stud. Secondly, in order for the sensor to operate, it must be on the surface of the plywood because the sensor operates by actuating light emitting diodes (LEDs) when a change in material thickness is detected, such as would be caused by a stud.

The aforementioned system was subsequently fabricated. The next step was to test the feasibility of the sensor-integrated nailer under laboratory conditions.

Laboratory Testing of Sensor-Supported Nailgun

The practical effectiveness of the sensor-integrated nailer was tested and evaluated with an emphasis on two general areas of interest: accuracy of the sensing device, and achievable nailing productivity under laboratory conditions.

Based on this, three specific objectives were specified for laboratory testing:

1. Prove the feasibility of the sensor-integrated nailer.
2. Measure the sensitivity of the system as related to differing thicknesses of studs and sheathing.
3. Establish a quantitative basis to evaluate the productivity and quality of nailing with the new system.

Based on these three objectives a series of laboratory test procedures was developed.

Test Procedures

The established test procedures were designed not only to address the three aforementioned objectives but also to simulate actual field operations as closely as possible. Both the selection of lumber to be nailed and the physical execution of the nailing was controlled by simulating field situations. The types and sizes of standard wood materials used in laboratory testing were as follows:

1. Plywood, 4 by 8 ft with thicknesses of 3/4 in., 5/8 in., and 1/2 in.
2. Waferboard, 4 by 8 ft, 1/2-in. thick.
3. Studs, 2 by 2 in., 8-ft long; 2 by 4 in., 8-ft long; and 2 by 6 in., 8-ft long.

All test sheets of plywood were set up in the same way. The appropriate studs were cut, and then glued to the underside of the plywood using Elmer's wood glue. This insured that the exact placement of the studs was not known. One of the many tests performed in the laboratory is presented next.

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Single-Shot Nailing Test

Single-shot nailing was an accuracy test designed to evaluate the sensor's ability to accurately "sense" studs while using the sensor-integrated nailer. The test was accomplished by sliding the nailer from the edge of the plywood towards the middle until the sensor located a stud. At this point a nail was fired and the nailer was subsequently moved back to the plywood's edge. This process was repeated 50 times for each of four tests. Two 2-by-8 ft sheets of 5/8-in. plywood and four 2 × 4 studs were utilized in the testing. This insured that all four tests had the same reference point, namely an edge at the right or left side of the stud from which each nailing cycle started. The results of the four tests can be seen in Figs. 2, 3, 4, and 5.

In tests 1 and 2, the left edge of the plywood was used as a starting point for the sensor-integrated nailer. The grouping of the nails, as shown in Figs. 2 and 3, is "left skewed." In tests 3 and 4, the right edge of the plywood was used as a starting point for the nailing. The grouping of nails in these two tests, as shown in Figs. 4 and 5, is "right skewed." The reason for this lies in the nature of the operation. Because the sensor's LEDs light the moment the stud is found, and not when the center of the stud is found, the nails tend to end up at one side or the other. By comparing the graphs it can be observed that the grouping of nails becomes more regular as the tests progress. This trend seems to be related to the learning effect of the operator since it became apparent that by watching the sensor's lights switch on and off the center of the stud could be approximated. From the overall analysis of the single shot tests presented in Figs. 2, 3, 4, and 5, the following conclusions can be drawn:

1. In test 1, 80% of the nails entered the stud and 20% fell to the left.
2. In test 2 and 3, 100% of the nails were successfully placed in the stud.

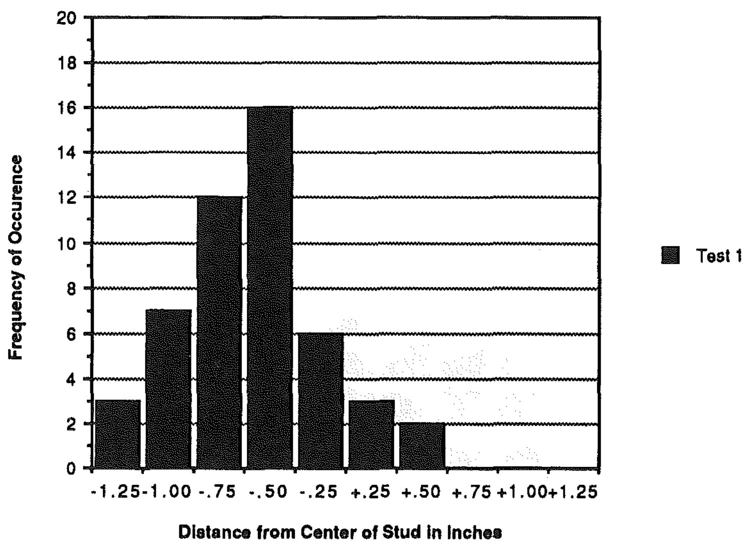

FIG. 2. Range of Nail Placement—Test 1

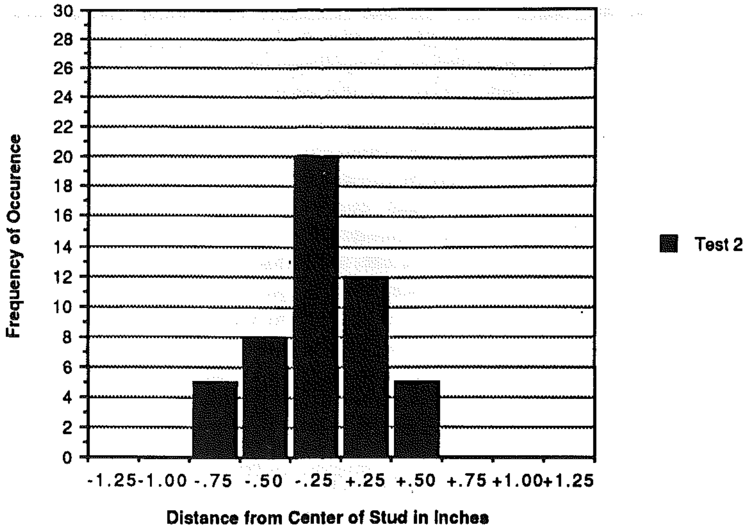

FIG. 3. Range of Nail Placement—Test 2

3. In test 4, 98% of the nails entered the stud, while 2% fell to the right.
4. Overall, 94.5% of the nails fell into the stud, and the success rate in tests 2, 3, and 4 was 99%.
5. Based on the improvement in the percentage of nails that found the stud from test 1 to test 2, it can be concluded that the learning time is very short.

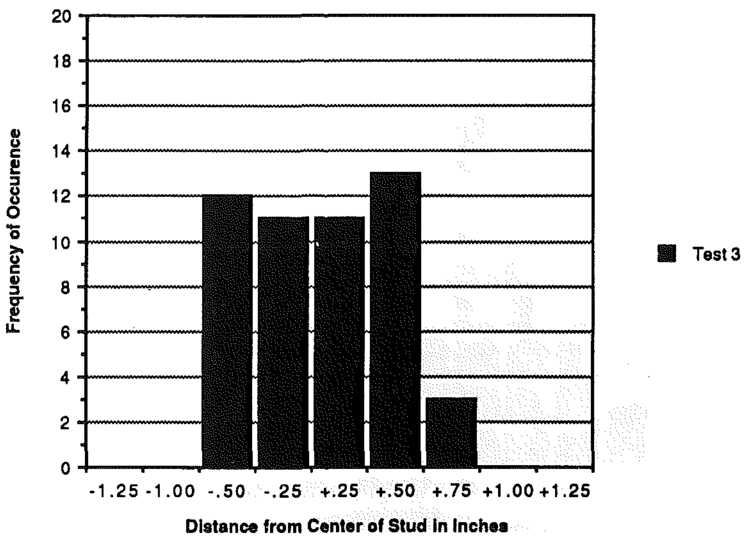

FIG. 4. Range of Nail Placement—Test 3

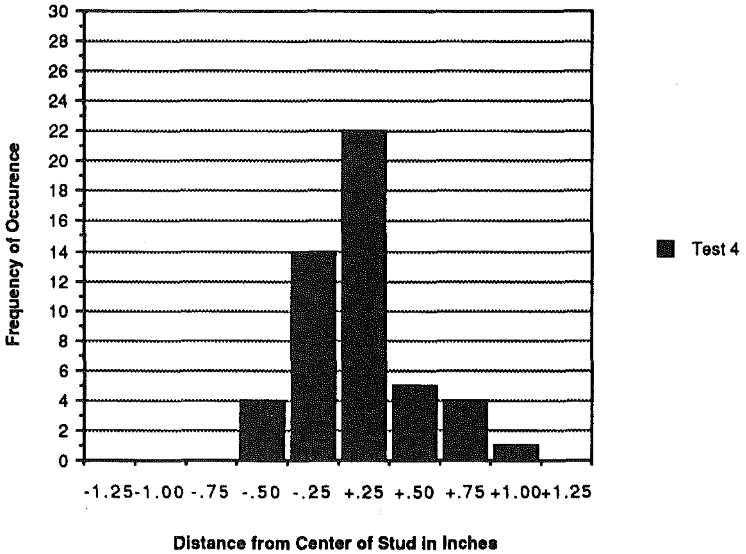

FIG. 5. Range of Nail Placement—Test 4

Other tests were performed in order to assess the sensor-equipped nailer's effectiveness under a variety of conditions. Because of limited space, only a short summation of the tests is presented here. However, the results are discussed in detail by Miller (1989).

Thickness variation tests evaluated the prototype's performance under standard stud and plywood sizes. Thickness variation tests were also performed with saturated woods in order to see if the sensor would operate under damp conditions. The sensor-integrated nailer's effectiveness under differing motions in both the vertical and horizontal direction was also evaluated. These tests included the patterns of down a row of studs, down a continuous stud, across a row of studs, and across a continuous stud.

Conclusions of Laboratory Testing

With regard to the three objectives set for laboratory testing, the following overall conclusions can be drawn:

1. The evaluation of the prototype system has shown that the proposed concept is technically feasible.
2. The sensor-integrated nailer was able to operate in every situation that it would likely encounter on a job site. In addition, the learning effect played a role in the speed and accuracy with which the operation being tested was completed.
3. In the laboratory testing 1,858 successful nails/hour productivity was achieved for vertical walls. 3,038 nails/hour productivity was achieved for horizontal surfaces such as a floor deck. Both these values represent straight productivity levels (e.g., no supporting work or breaks taken into account).

Based on the encouraging results obtained in laboratory testing, it was decided to take the new nailer into the field and have it operated by construction workers. The goal was to determine if the system would survive under field conditions and to measure nailing productivity. The following section will present the results of this part of the study.

Field Testing of Sensor-Integrated Nailer

Description of Testing

As stated earlier, the stud or joist is hidden from view most often during the application of sheathing to the wood frame house. For this reason, and because of the wide application of sheathing in the residential construction industry, the operation of sheathing attachment was selected for field testing of the sensor-supported nailgun.

The attachment of sheathing for the residential wood frame house is needed in three main areas: (1) Floor deck; (2) roof deck; and (3) vertical wall surfaces. The attachment of roof deck sheathing is performed on a sloped plane. The major difficulty during the operation is obtaining and setting the sheathing in the required position. The use of the pneumatic nailer with its weight, in addition to reaction forces present during firing, creates an additional difficulty for the inexperienced worker because a special effort is required in order to maintain balance due to the pitch of the roof. For these reasons the attachment of roof deck sheathing seemed to be the operation that could most benefit from the guidance offered by a sensor.

Design of Observation Methods

The process of roof sheathing attachment was broken down into three main work tasks: (1) Setting up; (2) positioning and tacking; and (3) pneumatic nailing (with or without the sensor).

1. Setting up consists of supporting work, such as obtaining tools and hooking up power cords, which must be performed before the task can begin.
2. Positioning and tacking consists of additional supporting work that must be performed in order to set the sheathing in place. This includes carrying, measuring, cutting, and temporarily nailing or "tacking down" the sheathing.
3. Pneumatic nailing is purely productive. It consists of permanently nailing down the sheathing to the rafter or truss.

Both positioning/tacking and pneumatic nailing are repetitive tasks that provided an opportunity to observe improvements during the operation. It also allowed the research analyst to compare the traditional operation with the sensor-supported nailing on the same roof.

Data-Collection Procedures

Two sources were used to establish a baseline productivity for comparing the new tool. First, field operations of roof sheathing with the use of the traditional nailgun provided productivity data for direct comparisons. Secondly, these figures were compared to those of similar studies done by the National Association of Home Builders (NAHB) (Fisher 1978). These two sources provided quantitative measurements against which the productivity

TABLE 1. Field Study Summary Results

Roof system (1)	Roof Fastening SMM/SF: Fastening method (2)	Set up (3)	Position and tack (4)	Fastening (5)	Total (6)
NAHB Study	Pneumatic—traditional	0.010	0.164	0.041	0.215
Saddle Creek	Pneumatic—traditional	0.025	0.397	0.083	0.505
Glen Port	Pneumatic—traditional	0.016	0.296	0.054	0.366
Glen Port	Pneumatic—sensor	0.013	0.309	0.071	0.393

data of the new nailer could be compared.

Nailing productivity was measured using the group timing technique, a method of work measurement that is frequently used by the NAHB in productivity studies. The group timing technique (GTT) as proposed by Maynard (1971) is a work-measurement procedure for multiple activities that enables the observer to make a detailed time study of two to 15 men. Continuous observations are made for each element at predetermined intervals and recorded on a form listing the elements of the job. Elements that vary in time due to worker performance may be leveled. This is accomplished by identifying a worker, who in the observer's opinion is working at a normal skilled pace, and comparing the others to him. For example, if one worker can only drive eight nails in the time it takes the "normal" worker to drive 10, he is working at 80% effectiveness. His time will be multiplied by 0.8 in order to adjust or "level" it to the "normal" workers. This results in normalized or adjusted time. Standard man minutes (SMM) are obtained by adding allowances for unavoidable delays and fatigue (which are taken as 20%) to normal man minutes (NMM). Resulting times in SMM represent typical labor times for each operation and are used in the analysis of operations.

Productivity Assessment of Roof-Sheathing Attachment

Task durations for each roof element were recorded using GTT. Observations were recorded at 1-min intervals, totaled, and subsequently adjusted based on each worker's performance rating. Work not related to the study was recorded but eliminated for the purpose of comparison. Idle time, personal time, and other delays were also eliminated and a standard factor of 20% added to obtain standard man minutes (SMM).

The three houses that were selected for field testing were all single-family two-story dwellings, varying in size. The roof area studied for the unit in the subdivision of Saddle Creek, located in Burtonsville, Maryland, was 390 sq ft. The roof areas studied for the second and third units in the subdivision of Glen Port, located near Manassas, Virginia, were both 840 sq ft. Trusses and 1/2-in. plywood were used in all three cases, with trusses spaced 24 inches on center. All systems were time studied from set-up through final completion. The results of the studies to compare labor time measured in standard man minutes for traditional pneumatic fastening with sensor-integrated nailing are presented in Table 1. The comparison of the two production rates for fastening at the Glen Port site shows that it has taken 0.017 SMM longer (0.071–0.054) to pneumatically nail the roof sheathing using

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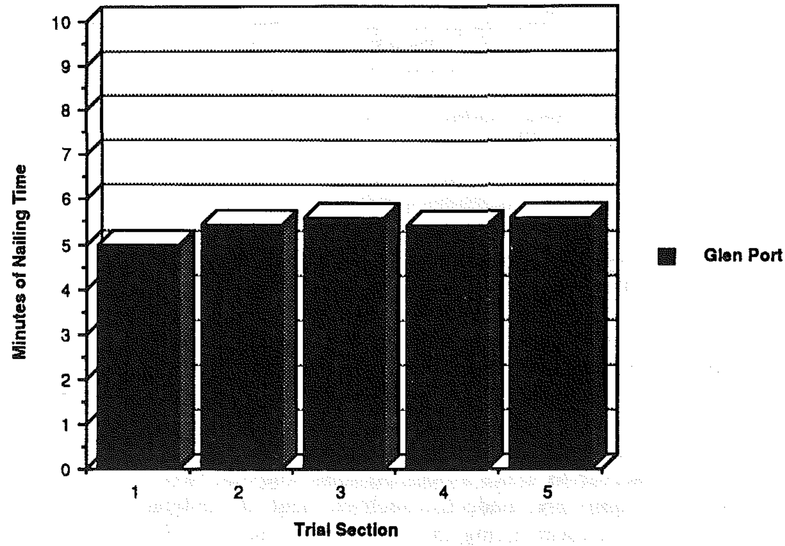

FIG. 6. Traditional Nailgun for Glen Port Study

the sensor-supported nails. This may lead to the conclusion that the innovative nailer has failed in its objective of improving productivity. However, to strictly compare the two SMM/SF results would be misleading. The sensor-integrated nailer is a new tool to the construction worker, and therefore the learning effect, which was observed in laboratory testing, must be taken into account.

In order to collect more detailed observation data, the roof systems at Glen Port and Saddle Creek were broken down into sections of 144 sq ft (approximately 787 nails) and the time required to pneumatically nail each section was recorded. The result of these studies are presented in Figs. 6 and 7.

Fig. 6 shows the observations from Glen Port, where a traditional nailgun was used by an experienced craftsmen. The maximum productivity (minimum time) achieved nailing 144-sq ft sections is about 5.5–6 min due to physical limitations such as the ability to move about on the roof surface.

Fig. 7 shows the observations from Glen Port, where the new nailer was used by a carpenter who had little to no experience with a nailgun. The time required to attach the plywood sheathing with the prototype tool drops from 14 min for the first section to only 6 min for the fifth section, at which point the sensor-integrated nailgun is about as effective as the traditional nailgun. A reduction in the time required to pneumatically nail each subsequent section with the sensor-supported nails has shown that there is a learning effect by which the prototype tool's effectiveness is strongly influenced.

Overall results of the more detailed study indicate, then, that the sensor-integrated nailer will not help to increase the productivity of skilled craftsmen using a traditional nailgun. However, the time it took for the sensor-integrated nailer to reach the productivity level of the traditional nailgun operated by a skilled workman was very short. Traditionally, becoming pro-

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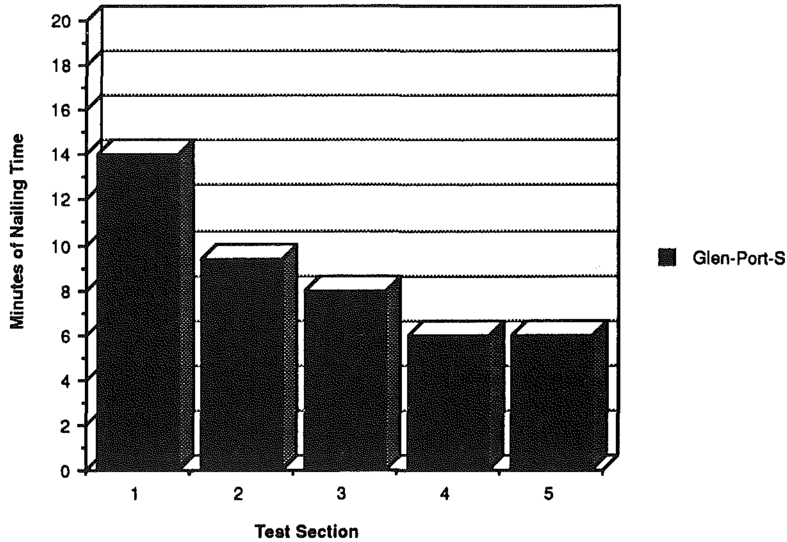

FIG. 7. Sensor-Integrated Nailer for Glen Port Study

ficient at "seeing behind" sheathing with an ordinary nailgun is a process that takes an apprentice considerably more learning time than a half-hour. This means that a worker who has only limited experience with the nailgun can become as productive as a skilled carpenter by nailing down about 720 sq ft of sheathing with the sensor-equipped nailer. When one considers the proportion of unskilled workers typically found on a construction site, this reduction in learning-curve time becomes very crucial for increasing productivity.

From the results of this study, the actual reduction in learning time can be found to be over 50%, which was used as a basis for comparison against the traditional nailgun in the next section. The "quality" of nailing, which can be expressed in the percentage of pneumatic nails that missed the joist, was about the same for both the sensor-integrated nailer (average 0.05% per 144-sq ft section) and the traditional nailgun (average 0.07% per 144-sq ft section).

Comparisons of Learning Time

The time it took a workman who had never used the innovative nailer to nail down 144 sq ft of roof sheathing was 14 min, as shown in Fig. 7. Based on five years of on-the-job experience, a reasonable time estimate for an apprentice to pneumatically nail down 144 sq ft of roof sheathing for the first time without the aid of a sensor is also about 14 min. A standard learning curve equation is $Yn = Kn^{-x}$, as discussed by Parker and Oglesby (1972), Cunningham (1976), and others is applied where: Y_n = effort required for the nth unit; K = effort required for the first unit; n = the nth unit; and $-x$ = the improvement factor, which is = -0.322 for an 80% curve (standard learning percentages range from 70 to 90% in the construction industry).

Based on the aforementioned learning curve shown, the time required for

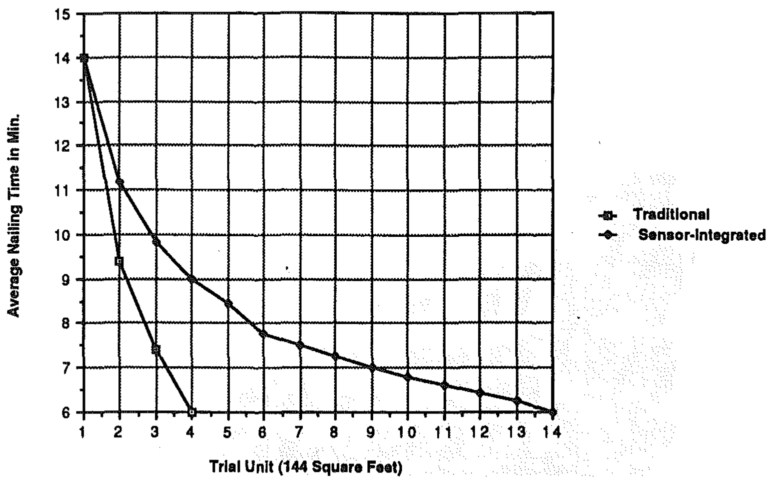

FIG. 8. Comparison of Nailing Time

the apprentice to nail down 144 sq ft of roof sheathing will not reach the optimum of 5.5–6 min until the 14th unit, as shown in Fig. 8. The learning time is a smooth curve with only modest improvements in productivity at each unit.

Fig. 7 shows the same graph for the sensor-equipped nailer's time data, obtained in the field. In this case, a large improvement in productivity occurs with the nailing of each unit. The location of the rafter is easily identifiable, and the workmen can concentrate more on keeping his balance. It takes the sensor-integrated nailer only 4 units of 144-sq ft areas to reach the optimum time of 5.5–6 minutes. Theoretically, according to Fig. 8, it would take another nine units at an average of 6 min each to reach this level of productivity using the traditional nailgun. The learning time has been reduced by over 50%.

Overall Study Conclusions

Several overall conclusions can be drawn from the discussed study. First, laboratory testing established confidence that the concept of sensor-integrated nailing was technically feasible (i.e., was able to survive and operate under field conditions) and that an increase in sheathing nailing productivity could be expected.

Second, field testing showed that the time required to become efficient at roof sheathing attachment with the innovative nailer was less than one-half that of the traditional nailgun, and therefore the laboratory tests, which suggested that an increase in the productivity of less skilled labor could be expected, were supported. It was shown that this is directly related to the learning effect.

Third, because the sensor-supported nailgun is a prototype tool with much room for improvement, further increases in productivity may be expected. A more durable casing for the sensor, such as one made of steel would most likely reduce the time necessary to reinitialize the current plastic-encased prototype. (The sensor must be initialized to the thickness of the sheathing before it will accurately locate the stud or joist. Due to the shocks generated by compressed air nailing, the sensor can become "disoriented" and require reinitialization. This time was included in the study results for both laboratory and field testing.)

Lastly, the sensor-integrated nailer can be adapted for other applications such as the attachment of interior trim or drywall where even greater productivity increases may be expected due to the difficulty of the operation for skilled craftsmen. The sensor-integrated tool in other forms, such as a sensor-integrated screwgun, may have the capability to increase worker productivity in any operation where the stud or joist is obscured from view.

In addition to the benefits already mentioned, the new concept may be able to help certain craftsmen whose skill level has reached a peak short of the ideal for some reason (e.g., lack of coordination), attain the productivity levels identified in this study. More testing is needed in order to evaluate this possibility.

Appendix. References

Anderson, M. (1974). *Design of experiments*. Marcel Dekker, Inc., New York, N.Y.

Bernold, L. E. (1986). "Automation and robotization in construction: The search for potentials." *Proc. 10th Triennial Conf. of CIB/86,* International Council for Building Research Studies and Documentation, 1,073–1,082.

Bernold, L. E. (1987). "Automation and robotization in construction: A challenge and a chance for an industry in transition." *Int. J. Project Mgmt.,* 5(3), 155–160.

Cunningham, J. (1976). *Using the learning curve as a management tool.* McGraw-Hill, Inc., New York, N.Y.

Fisher, L. (1974). *Comparative cost study of fastener corporation's screw-fast screwdriver powered by Black and Decker's motor unit versus the conventional hand-fed screwdriver with magnetic tip.* Nat. Association of Home Builders, Upper Marlboro, Md.

Fisher, L. (1978). *Comparative in-place cost of floor and roof sheathing fastened with power fastening equipment versus manual fastening tools.* Nat. Association of Home Builders, Upper Marlboro, Md.

Kangari, R., and Halpin, D. W. (1989). "Potential robotics utilization in construction." *J. Constr. Engrg. and Mgmt.,* ASCE, 115(1), 126–143.

Maynard, H. B. (1971). *Industrial engineering handbook.* McGraw-Hill, Inc., New York, N.Y.

Miller, M. (1989). "Study on the integration of a stud sensor and nailgun for use in residential wood construction," thesis presented to the University of Maryland, at College Park, Md., in partial fulfillment of the requirements for the degree of Master of Science.

Parker, H. W., and Oglesby, C. H. (1972). *Methods improvement for construction managers.* McGraw-Hill, Inc., New York, N.Y.

Stern, E. G. (1959). *Better utilization of wood through assembly with improved nail fasteners.* Virginia Polytechnic Institute, Blacksburg, Va.

Tatum, C. B. (1989). "Organizing to increase innovation in construction firms." *J. Constr. Engrg. and Mgmt.,* ASCE, 115(4), 602–617.

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