PARTIALLY AUTOMATED GRADING: CONSTRUCTION PROCESS INNOVATION

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ABSTRACT: The innovativeness of the construction industry has been both defended and debated. Innovative solutions to construction challenges have occurred, however, despite many hurdles. The partial automation of earthmoving equipment using laser-guided controls, one such advancement, is the subject of this paper. This latest generation of a fragmented family of construction laser applications is a cost-saving, productivity-enhancing aid to earthwork operations. This paper contrasts the former methods for fine grading with the partially automated technology, describes the process of innovation for the advanced technology, compares this process with a model of innovation in the construction firm, and develops conclusions and practical applications based on this example of construction innovation.

INTRODUCTION

Despite the many criticisms of the construction industry as technologically complacent, there are many examples of advancement that brought significant benefits. This paper describes one such successful innovation in a construction firm. This technology for the partial automation of grading equipment using a laser alignment system improved the productivity of fine grading operations and increased the contractor's flexibility in managing his equipment fleet. Both of these benefits substantially decreased cost. The development and use of this technology involved the joint efforts of a grading contractor and a laser system supplier. The process of innovation for this advanced technology illustrates both the myriad problems and the major potential benefits.

The purpose of this paper is to describe the process by which the laser-aided grading system came about, including the technological advancements made and the forces behind its success, to compare this example to a previously developed model of the innovation process, and to develop practical applications and conclusions for increasing the rate of innovation in construction.

Fine grading is bringing the surface of a cut or fill to the finish elevation defined on the plans. It is required for roads, parking lots, building slabs placed on grade, and other portions of site development. The partially automated grading system is a process innovation because it results in a technology that produces a greater output for a given input (Rosenberg 1982). It is also an example of an innovation developed within a construction firm for use on multiple projects, as contrasted with a technological advancement made in response to the demands of a specific project.

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Note. Discussion open until August 1, 1988. 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 April 20, 1987. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 114, No. 1, March, 1988. ©ASCE, ISSN 0733-9364/88/0001-0019/$1.00 + $.15 per page. Paper No. 22238.

Construction technology, as used in this paper, is the combination of construction methods, resources, work tasks, and project influences that defines the manner of performing a construction operation.

This paper will first review laser applications in construction. Next we will describe the previous technique for fine grading and its inherent inefficiencies, and contrast this to the laser-guided method. We then describe the process by which this advancement came about and compare this with a previously developed model of innovation within the construction firm. This results in practical applications and conclusions regarding the insights gained from this example of construction innovation.

Laser Applications in Construction

The word laser is an acronym for "light amplification by stimulated emission of radiation." This beam differs from ordinary light in that it contains only one wavelength (e.g., the color red) of the whole light spectrum. The rays in the laser beam tend to stay parallel to one another; this property of coherency makes it an ideal alignment device. Although laser beams were originally generated from solid crystals, today most are of the gas type. Helium and neon, contained in a cylindrical tube, are electrically stimulated to form a neon glow. By means of mirrors at each end, the light is reflected back and forth, gaining in intensity until it breaks through the forward mirror, which is not fully silvered. The resulting continuous stream of red light is visible and remains straight without appreciable scattering (Klauminzer 1984; Weber 1982).

Modern alignment lasers are inexpensive (approximately $3,000 for a simple device) and are relatively harmless at an average 0.002-watt output. The beam is accurate up to a distance of approximately 1,000 ft (300 m) before its divergence exceeds 1 in. (25 mm) (Spectra-Physics 1984). Laser sales for applications in agriculture and construction totaled approximately 23,000 units in 1984 (Hitz 1985). These consisted of the helium neon and diode types that are used to define straight lines for reference points and for distance measurement.

The challenges of dredging and aligning the Bay Area Rapid Transit (BART) tubes next to the San Francisco Bay Bridge produced an early application of lasers in construction (Davidson, personal interview, October 31, 1986; Day 1973). A motorized prism projected the laser beam vertically to strike a horizontal member of the dredge, while another prism rotated a second beam horizontally to strike an adjacent vertical ladder. This established references for dredging in a straight line at the correct depth.

Point devices for the alignment of sewer pipe, a subsequent laser application, marked the first generation of marketable construction lasers. By 1970, several companies were producing these laser devices. Other applications developed in the next five years included aligning turbine components, boring tunnels and shafts, aligning stakes for airport paving and striping, setting posts for highway median barriers, and laying railway track (Barry 1973).

The laser then evolved into interior construction uses, such as leveling computer floors and suspended ceilings. The penta prism was added to bend the beam at a 90° angle, easing its use as a height reference. The beam

was still manually rotated around the room and pointed as needed. The addition of a motor to spin the laser, creating a horizontal reference plane, brought further applications. These included aligning concrete formwork and accurate trenching to allow laying drainage lines at nearly flat slopes. In 1974, another problem-based application took place. After observing Arizona farmers attempt to cut vast areas at dead level to allow efficient flooding of the soil, a laser supplier mounted the device on tractor-towed scrapers. This open up the laser-aided land-leveling market.

Other specific uses were attempted, such as paving machines and bulldozing, but these did not grow into major applications. There was no concerted effort to systematically develop or market the device. One exception was a venture by a laser supplier and a small grading contractor in the San Francisco Bay area. Their pioneering efforts to develop partially automated grading technology, which began in 1976, provided an important foundation for the current use of laser-aided grading. This paper describes the process of innovation. To start, it is useful to review the technology that the partially automated system replaced.

Manual Methods of Grading: Old Way

Obtaining a flat, planar surface is a key design requirement for many building sites, runways, and drainage systems. Contractors must employ the most skilled operators of motor graders to cut the finish grade to within a 1/8-in. (3-mm) tolerance over a 10-ft (3-m) span. These "blue-top" operators, those who can scrape a dime off a finish grade stake with a motor grader, command premium wages.

Difficulties in controlling these grading operations result in both differences from design grades and variations in the quantities of materials required. For example, the specifications may require a 6-in. (150-mm) minimum thickness of expensive base course material. If the fine-grading techniques used by the contractor only allow controlling the thickness to ±1 in. (25 mm), then he must place a 7-in. (175-mm) thickness of the material to assure meeting the specifications. This 17% increase in material cost indicates an opportunity for substantial improvement.

The work tasks to prepare the base for a typical 100-ft × 100-ft (30-m × 30-m) concrete slab on grade illustrate the problems in using conventional technology. Because earthwork is still somewhat a "seat-of-the-pants" field adaptation of the site plan, these steps do not imply a standard technique; each project is a unique challenge that requires a specific procedure:

1. The layout/survey crew sets the reference stakes for rough grading. This requires approximately four hours, with an experienced crew and drawings that matched the existing conditions.
2. Depending on the amount of cut and fill required, the next crew and equipment spread consists of either dozers or scrapers, or a combination. The crew places fill in loose layers up to eight in. (300 mm) before compaction. The compactors may have a dozer blade attached to spread the fill, possibly eliminating the need for a separate piece of equipment. Water sprayed from trucks maintains adequate moisture content and controls dust.

3. Once the site is leveled to rough grade, the layout crew returns to check the grade. If it is within one in. (25 mm) of final grade, they place the blue-top stakes. The tops of these blue colored hubs are driven level with the final grade; they are placed in a grid at approximately 10-ft (3-m) intervals. If the site is not to grade, the crew replaces the offset stakes. Resetting is also required whenever these survey stakes are accidentally knocked by the construction crew, an all too common occurrence.

4. To obtain final grade, the layout crew remains on site, while an experienced grader operator makes a series of passes over the pad, slowly cutting and filling to achieve required tolerances. The grader is used because of its greater flexibility (as compared to a dozer), its tighter controls, and its faster speed (resulting in increased production); however, it does not have the dozer's earthmoving or cutting power, so it may find only sporadic use prior to the final grade work (Day 1973; Nunnally 1977). Final grading make take several hours to several days, depending on the crew's capabilities, the weather, and the soil type.

The operations to prepare a pad, as just described, present several inefficiencies and frustrations. Many of these also apply to other types of finish grading:

1. It takes several pieces of equipment to complete even small projects. At a minimum, a dozer, a grader, a compactor, and a water truck are needed, and "just-in-time" scheduling is too risky; all equipment stays with the job until complete. The last inch of fine grading is especially labor and equipment-intensive, and productivity is low.

2. Despite strong efforts to schedule and coordinate the operations, it is generally not possible to avoid having the survey/layout crew and the construction crew spend time waiting for each other, especially on smaller projects such as that described. Accidental jarring of reference stakes can cause delays for resurveying or, worse, for rework if the change is undetected.

3. The existing conditions are often not consistent with what is shown on the contract documents. Because of the long lead time and the amount of survey work required to document this discrepancy, the contractor frequently makes field adjustments in grades as he is laying the project out, and revises cut and fill requirements accordingly. He may not be aware of these discrepancies until well underway, which also makes it even more difficult to obtain compensation from the owner/designer.

4. The operations are restricted to areas and conditions of good visibility, both for surveying and for placing fill in accordance with the reference stakes.

5. The operator's experience required for final grading makes this operation very costly. It also makes the contractor highly dependent on this one person to be at the project when his skills are needed. Even for an experienced operator, about six to nine passes over the same area are necessary to meet the tight tolerances.

These problems and inefficiencies substantially increase the cost of fine grading. However, a poor final grade, resulting in such consequences as poor drainage or uneven (and inefficient) engineered fill thicknesses, is

more costly. Not meeting the grading tolerances can lead to surface failure and expensive rework.

Laser-Aided Grading Alternative

By using a laser beam to guide the blade's cutting edge, a laser-aided grading system overcomes several of the inherent inefficiencies of previous methods. These laser systems, which are offered by several specialty manufacturers, not only speed-up grading operations, but also allow greater quality control. Decreased cost results from increased productivity, lower material usage, a shorter weather-dependent time window, and less equipment hours. The laser systems are an important part of the state-of-the-art in the automation of mobile construction equipment (Paulson 1985).

The advanced grading technology uses a laser and a control system to provide a reference elevation over the entire surface to be graded and help control the blade to cut the soil to this elevation. The system includes a laser transmitter, a mast receiver on the grading equipment, a microprocessor, a visual grade indicator, and a hydraulic control system for the blade (see Fig. 1). The transmitter is a rotating laser adapted for construction and powered by an automotive battery. It sits on a tripod and projects a light beam approximately 1/4 in. (8 mm) in diameter as it spins at approximately 600 rpm. This defines a reference plane parallel to the design grade. This plane may be horizontal or inclined, and is generally set at an elevation between 3–10 ft (1–3 m) above grade in order to clear the equipment body.

All other parts of the system are aboard the earthmoving equipment. The receiver is a 6-ft (2 m) mast with a laser-sensitive zone of approximately one ft (0.3 m). It is mounted on the cutting structure, such as a dozer blade, a grader mold board, a scraper bowl, or a backhoe arm. The point at which the laser beam strikes the mast is transmitted to the microprocessor, which calculates the difference between the desired and actual blade elevation.

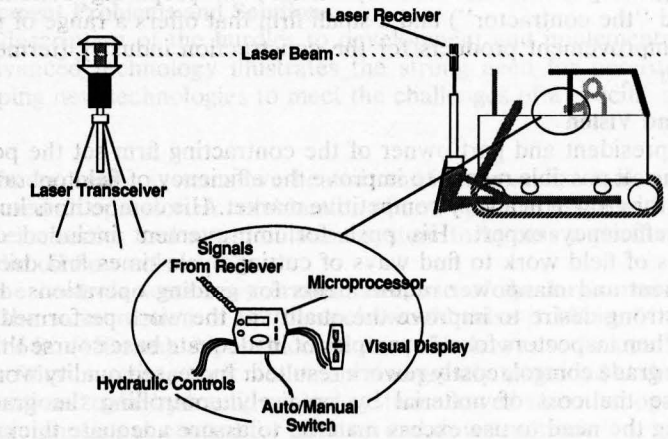


FIG. 1. Schematic of Laser-Aided Grading System

The microprocessor then commands, at a frequency of three times/sec, the hydraulic control system to raise or lower the blade to maintain the design grade. The microprocessor also activates visual signals indicating the variation of the cutting edge from the reference plane. Supplementing the other operator-directed controls for the machine, this electro-hydraulic system positions the cutting surface to remove enough material to meet the design grade. Applications of the control system include small crawler-tractors, compactors, scrapers, and presently the most popular, motor graders.

The crew sets up the transmitter and calibrates the elevation of the instrument. They also attach the microprocessor, the supplemental hydraulic system, and the control mast to the machine, if it is not already installed. This setup normally takes approximately 1/2-hr at the start of the shift or when changing surface planes.

Then the operator sets the system to the desired grade and selects either the automatic or the manual operating mode. In the automatic mode, the laser and hydraulic systems control the blade elevation and amount of cut. The operator's role is to set the machine speed, blade angle, and cross slope, and drive the grader over the surface to be graded. In the manual mode, the operator controls all of the blade functions, using a readout of flashing lights which indicates the need to raise or lower the blade, based on the reference point established by the laser plane. This mode of operation has proven very valuable in training operators to avoid the natural tendency to overcontrol the blade, and also when the cut amount is too great to scrape off in one automated pass. A small switch on one of the standard control levers allows rapid mode changes.

Road to Success: Process of Innovation

The process that brought about this construction innovation provides a very interesting example of how a contractor can advance construction technology. It also highlights the determination and hard work required to make it happen. This example of innovation involved the interaction of a small grading contractor that specialized in preparing building sites (termed "the contractor") and a small firm that offers a range of productivity improvement products for the construction industry (termed "the supplier").

Need and Vision

The president and part owner of the contracting firm set the policy of pursuing all possible means to improve the efficiency of field operations as a basis for growth in a very competitive market. His competitors knew him as an efficiency expert. His push for improvement included detailed analysis of field work to find ways of cutting cycle times and decreasing equipment and manpower requirements for grading operations. He also had a strong desire to improve the quality of the work performed by the firm. When inspectors found examples of inadequate base course thickness or poor grade control, costly rework resulted. Increased quality would also decrease the cost of material by precisely controlling the grade and avoiding the need to use excess material to assure adequate thickness.

Despite the failure of others to successfully apply the laser technology to fine grading, the simplicity of the concept made it very appealing to the

contractor. His firm performed highly repetitive grading operations on a large number of projects, and he strongly believed that the laser control system would work and would greatly improve both quality and productivity.

Development of Technology

The contractor was aware of the growing use of laser technology in other construction applications, and he attempted to interest the manufacturers of large earthmoving equipment to adapt it for automated control of their machines. These manufacturers did not believe that the small market for this specialized equipment justified the development cost for this "unique" application. So the contractor did it himself.

Convinced that laser controls could greatly improve grading productivity, he located suppliers and set out to adapt both the lasers and the existing hydraulics systems to the requirements of his grading operations. The contractor also discussed laser-controlled grading with competitors who had attempted to use the technology in fine grading. Each of these efforts had failed, but this experience offered valuable information about the problems and the attempted solutions. He located a supplier who was beginning to develop laser alignment devices for the agricultural industry. This supplier had experience in the use of lasers in building construction and saw the grading and sloping of farm land for efficient irrigation as an opportunity for further use of this technology. The supplier and the contractor joined forces to continue development of the technology for application to fine grading.

Based on his belief in the potential improvements, the contractor made investments in equipment and laser systems which strained the small capitalization of the firm. For example, he spent an extra $18,000 to add the capability for blade tilting to a small crawler tractor because he felt this hydraulic system would be easier to integrate with the laser controls. Using this equipment for fine grading opposed convention but supported the development of the advanced technology.

Development Problems and Solutions

The description of the hurdles to development and implementation of this advanced technology illustrates the strong need for persistence in developing new technologies to meet the challenges of a specific application:

1. The hydraulic systems overheated, and in one case, a tank exploded and injured an operator. A combination of new system design with greater use of electronics and a recirculation system to bypass a portion of the hydraulic oil flow solved this.
2. The controls were very erratic. Because of the large mass of the blade, the same motion of the controls would raise it 1/8 in. (4 mm) or lower it 6 in. (150 mm). Also, since the dozer blade was so far out from the crawler fulcrum point, track movement was greatly magnified at the blade. Modifications to the hydraulic control system allowed smoother operations and more consistent control for both up and down motion.
3. Stands for the laser equipment were not rigid enough to meet field conditions, such as wind and vibration from equipment operating close by.

Stronger stands, designed for outdoor use, replaced those originally supplied and solved the problem.

4. The lasers were not self-leveling and therefore required up to an hour for initial setup in the field, and equal time if jarred during operation. The supplier later added the capability for self-leveling.

5. The receivers picked up stray laser signals from building reflections or adjacent operations; field experience and adjustments avoided this mysterious problem.

6. Failures in the control system caused expensive rework on many projects. When the system failed to operate properly, the correction of inaccurate grades often cost more than initially grading the area using conventional techniques. And because most breakdowns occurred in remote areas, repairs were time consuming and costly.

7. Experienced equipment operators (approximately eight years of training and practice are required to develop a fully skilled grader operator) considered the new technology a slap in the face and refused to use it. The contractor responded by assigning apprentice operators instead. When they achieved production rates of up to four times those of the highly skilled operators, acceptance of the technology followed. The contractor also donated a set of the laser equipment to the apprentice training program run by a union local.

8. Laser-controlled grading is especially beneficial if the design grades involve large surfaces of unchanging inclination. The contractor occasionally attempted to convince the designers to make the relatively simple changes required to fully implement the automated grading and obtain both improved quality and lower costs. This proved difficult. Because paving and grading is generally bid based on complete drawings, the contractor had little chance to inform the designer of these benefits. On one project, the contractor paid the cost of redesign, decreased the contract price to the owner, and still substantially improved his profit over what it would have been if he had used the conventional method.

9. The unwillingness of certain suppliers to expand their scope outside of a specific discipline or product was a major problem in the early development of this technology. "They gave us the equipment and ran." This included the lasers, the hydraulic control systems, and the earthmoving equipment. Specific manufacturers ignored the continued development necessary to use their product in construction. This required an unusual amount of coordination from the contractor to get the individual components to work as a system and to withstand the construction environment.

In short, the contractor, the supplier, the mechanics, and the operators conducted a field testing program to bring the combination of laser and hydraulic technology to a satisfactory level of performance.

Once the partially automated systems proved successful on crawler-tractors, the contractor expanded innovative use of the technology. He applied it to graders and gained increased flexibility and capability. He used it to control the bowls of multiple-towed scrapers for accurate cutting and filling in large-scale operations. He even put a control system on a compactor to allow this machine to rough grade an area at the same time it is compacting the soil to the specified density. He also adapted the

system to control trenching for drainage lines that required a specific slope. Each of these applications successfully extended the technology.

Results of Innovation

The results were well worth the effort. The partially automated grading brought about the expected improvements in productivity as well as several unexpected benefits.

Improved Performance

The average daily production of a single grader and operator increased from 30,000 ft^2 (3,000 m^2) to 200,000 ft^2 (20,000 m^2). The cost of fine grading decreased from approximately \$0.08/ft^2 using conventional methods to approximately \$0.02/ft^2 using the laser control system (\$0.86–\$0.41/m^2). As an example of the impact, a standard approach to grading lots in a housing development would require a crawler-tractor with a dozer blade, a self-loading scraper, and a grader to make an average daily production of eight lots. With only a scraper and a crawler-tractor equipped with the laser system, 15 lots can be completed per day. The contractor now uses eight laser systems on an average workload of 50 active projects.

The system also met expectations for improved quality. Using the laser controls on several types of equipment, operators could consistently meet grade tolerances. This lowered material cost by limiting the cushion of surplus fill needed to ensure specified minimum thickness.

Other Benefits

The successful use of this technology also led to several unanticipated benefits for the contractor. First, he developed the ability to perform fine grading with small crawler-tractors. This increased flexibility and decreased cost because fewer pieces of equipment were required for individual jobs. Second, with his laser-controlled bulldozer blade on a compaction machine, he greatly improved filling operations. The operator could shape the fill to a rough grade while compacting it, again decreasing equipment needs and costs. Adaptation to trenching and pipe-laying equipment brought similar benefits.

By using the laser for earthwork alignment and grade checking, operations could continue at high efficiency even during times of darkness. High-intensity light requirements are reduced, and production increased, thus improving flexibility and decreasing cost.

Operator training was a further unanticipated benefit from the system. Even experienced operators overcontrol grading equipment. By operating in the manual mode and using the laser grade indicators, the control system became a valuable training aid. This even allowed operators with extensive experience to improve their techniques.

Competitive Advantage

The contractor gained a major competitive advantage from the partial automation of grading equipment. This advantage contributed to the contractor's growth from an annual volume of \$500,000 in 1976 to over \$50,000,000 in 1984. This occurred in a declining and very competitive market. Surprisingly few of the contractor's competitors have made the

same use of the laser-control technology. Possible use of the partially automated system is now a major consideration in bidding a project at this firm. The managers and estimators seek projects for which the site conditions and the design grades allow use of the laser systems.

With this success behind him, the contractor continued his push for innovation in other areas. He became involved in developing further advantages in computer applications, such as automated quantity takeoff systems and computer-aided dispatching of men and equipment. Although these other important advances helped, the contractor attributes a major part of his impressive success to the partially automated grading.

As expected in a growing firm, the contractor is now branching into other types of projects. Some of these, such as small dam construction, have provided an opportunity for further use of automated grading technology. The contractor's approach to these opportunities is to consider any possible means to improve the efficiency of the project operations. He frequently tries alternate management approaches along with the new technologies. He is also aware that as his competitors become more innovative, they will push him harder.

Plans for Continued Development

The contractor and the supplier are continuing their development of the technology for partially automated grading. The contractor was a test site company for the supplier's sonic tracker and cross/slope control system, a new device for control of grading using existing pavements or curbs as references.

The contractor and the supplier share an ambitious vision for an integrated earthwork system. They see the use of a unified data base to prepare the design, plan and estimate the job, and finally control the equipment in the field. Currently, the designer first defines the required grades, frequently using a CAD data base, and produces a drawing. The contractor, to bid the job, builds another electronic data base for quantity takeoff and estimating. In executing the work, the field forces use neither data base to set the laser and partially automate the machine in cutting the grades.

This process is inefficient for two reasons. First it involves multiple data entry. Second, further automation of the field operations could improve productivity. Common data bases, if competitive and liability concerns allow, will solve the first problem. For the second, new technologies are needed. The contractor must capture the as-built configurations of features that actually govern grading in the field, such as high and low drainage points. The final grades must tie into these items, regardless of the "theoretical" design elevations. Also, for the control system to handle other than single-plane surfaces, it must monitor the location of the machine. To set the blade to the design elevation on a superelevated curve, for example, the system must know the x and y-coordinates for the location. The contractor is assisting the supplier in developing systems to solve these problems and further automate fine-grading operations.

Insights from This Example of Innovation

The description of this innovation offers important implications for industry professionals seeking to increase the rate of innovation in

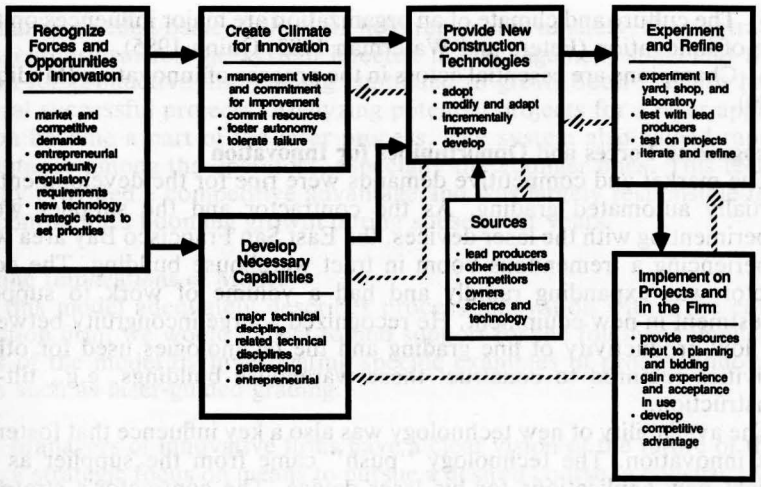


FIG. 2. Innovation in Construction Firm

construction firms and researchers trying to understand the process. We will next compare this innovation with a general description of process innovation in construction. This results in additional insights regarding the development of the partially automated grading system and suggestions to improve our understanding of innovation in construction firms.

A model or description of process innovation in construction, developed as a part of the Stanford Construction Innovation Project (Tatum 1986), includes the following major steps, as shown in Fig. 2: (1) Recognizing the diverse forces for innovation and the opportunities to improve even when there is no apparent problem; (2) creating an appropriate climate for innovation including a vision of the future of the firm, commitment of adequate resources, fostering autonomy, and tolerating failure; (3) developing the necessary technical and entrepreneurial capabilities within the firm; (4) providing new construction technologies; (5) experimenting and refining; and (6) implementing on projects and in the firm (Tatum 1987). These steps both describe an overall process and suggest specific implications of the model.

This model is based on findings from prior innovation research and other examples of innovation in construction. The key concepts from the background research that influenced the model are:

1. The process of innovation is iterative, messy, unpredictable, opportunistic, tumultuous, and interactive (Peters and Waterman 1982; Quinn 1985).
2. Innovations stem from many unexpected sources (Drucker 1985).
3. The mechanisms of "technology push" and "market pull" are both important for the innovation process (Mowery and Rosenberg 1982).
4. Incremental improvements in new technologies frequently bring about greater gains in productivity than the innovation itself (Rosenberg 1986).

5. The culture and climate of an organization are major influences on the rate of innovation (Peters and Waterman 1982; Quinn 1985).
6. Champions are essential actors in the process of innovation (Madique 1980).

Recognizing Forces and Opportunities for Innovation

The market and competitive demands were ripe for the development of partially automated grading. As the contractor and the supplier were experimenting with the laser devices, the East San Francisco Bay area was experiencing a tremendous boom in tract warehouse building. The contractor was expanding rapidly and had a volume of work to support investment in new equipment. He recognized a large incongruity between the low productivity of fine grading and the technologies used for other activities required to construct these warehouse buildings, e.g., tilt-up construction.

The availability of new technology was also a key influence that fostered this innovation. The technology "push" came from the supplier as he sought new applications for his laser device. The contractor's strategic focus was also critical for the successful innovation. His persistence brought together the laser engineers, hydraulics mechanics, electrical technicians, equipment operators, and others needed to solve the problems. As a team, they made it successful.

Create Climate and Capabilities for Innovation

The contractor was determined to commit the resources required for the innovation. As majority owner of the company, he had sufficient autonomy to pursue a wide range of alternatives in efficiency improvements, despite an occasional failure. The contractor also provided a strong technical and managerial base in civil construction. He not only had design, estimating, scheduling, cost control, and supervisory experience, but he was also known for his equipment-operating and field-surveying skills. This broad technical knowledge enabled the company to overcome the many obstacles and transform a series of components into a practical, working system.

Provide, Experiment with, and Refine New Construction Technologies

The use of laser alignment devices to partially automate grading operations brought about the improved technology. The main component, the transmitter, has not fundamentally changed since its first use as a planar alignment device in the early 70's. Despite this, several modifications and improvements were required to overcome many practical field problems and make the complete system operational. Through experimentation and testing in a highly iterative process, the contractor incrementally improved the technology.

Implement on Projects and in Firm

The contractor made sizable investments in laser-automated grading prior to successful implementation. But even after proving it's effectiveness, he had to overcome additional obstacles to get his firm to see the benefits. Four of his top operators left the company to protest the new development, and many technological "bugs" had to be resolved. Each potential operator had to be trained in the use of the laser, and the

mechanics needed basic skills in its field repair. Fortunately, the contractor's enthusiasm for the system infected his management staff, and the vision for productive fine grading continued to grow. Soon the firm had several successful projects. Analyzing potential projects for a laser application became a part of the laser process. The system also gained rapid acceptance among the operators, especially the younger ones. This technology provided a competitive advantage and was largely responsible for the contractor's booming growth during subsequent years.

Specific Implications of Model

If this model adequately describes process innovation within the construction firm, we would expect to find support for the following implications of the model by investigating specific examples of process innovations such as laser-guided grading:

1. Managers of innovative firms have a clear vision of the future of the firm, a strategic focus on means to pursue a desired course, a constructive discontent with current practices, and the ability to recognize opportunities disguised as problems. For the laser-controlled grading, the contractor's vision of growth for the firm was based in part on the expected advantage of the partially automated grading technology. He consistently probed the standard practices for operations such as grading to find improvements. His perseverance in developing the new technology was based on a strongly held belief that it would significantly improve productivity. He was right.
2. The climate within the firm supports innovation, as indicated by: (1) Committing resources for activities outside of projects; (2) allowing autonomy in performing these activities; and (3) tolerating creative mavericks who often fail. In this example, the continued efforts to develop the technology and the willingness to make the investments this required clearly demonstrated a commitment. The president of the firm was the maverick and the champion; he insisted on experimentation and improvement.
3. The firm displays technical depth and entrepreneurial capability. The technical depth includes all engineering disciplines associated with the technology. The entrepreneurial capability requires a mix of technical competence, business sense, and experience. For the laser-controlled grading, the contractor brought technical depth concerning grading operations along with an entrepreneurial attitude in experimenting with new technology. When he encountered problems in other technical areas, he brought in the supplier and other technical specialists to solve these problems.
4. Innovative construction technologies stem from many sources; therefore researchers should find evidence of many trials and failures, including unexpected sources. Many cycles through experimenting, refining, and implementing result in continued improvement of new technologies on each project. Firms that make process innovations include means to transfer new technology between projects, with incremental improvement as a part of this process. For the laser-controlled grading, once the basic system was defined, the major effort was focused on solving the practical problems of using it in the field. This required many refinements to specific

components and involved using the system on many different types of projects. Once the technology proved advantageous on bulldozers used in grading building foundations, the contractor applied it to other types of equipment and projects.

5. Innovative firms use new technology to gain a competitive advantage in bidding and negotiating new work; they seek a reputation as innovators. The initial use of the technology for partially automated grading gave the contractor a significant competitive advantage in his traditional lines of business. The firm then used expanded applications of the technology to penetrate other markets, such as highway construction and drainage system installation.

6. The process involves the following roles: senior management as executive champion, and engineer as technical champion. For the laser-controlled grading, the contractor's position as the major owner of a small firm initially enabled him to serve as both executive champion and technical champion. He provided the necessary resources and the commitment necessary to continue development of the technology despite many disappointments. The contractor later shifted the role of the technical champion to the supplier and to other members of his organization, but he continued his involvement in the resolution of serious technical problems.

Conclusions and Practical Applications

This description of the development and application of laser technologies for partially automated grading leads to conclusions concerning the opportunities for improvement of construction operations and the results of comparison with a description of innovation in the construction firm. In this section we also highlight practical applications for industry professionals seeking to increase the rate of innovation and insights for researchers who continue to investigate innovation in construction.

Opportunities for Improvement

Many factors contribute to the inefficiency of fine grading using conventional technology. The design requires precise dimensional control of frequently repeated operations. The conventional technology involves many types of equipment, highly skilled operators, and excess materials. The process of grading to meet the specified requirements is slow, and labor and equipment intensive and uncertain. Each of these problems provides incentives for new technology to accomplish fine grading. They also offer insights regarding the characteristics of existing construction technology that encourage innovation.

This innovation resulted in many types of improvements for grading. The new technology increased efficiency by lowering the equipment and operator hours required per unit of work completed. Laser-aided grading also allowed using existing equipment in new ways, such as small crawler-tractors for fine grading. It lessened the need to have men and equipment wait for the completion of one operation before they could work on another. There were also other unexpected benefits such as improved operator training and more efficient fleet management.

The success in partial automation of grading operations described in this paper suggests many additional applications of laser technology in con-

struction. These include further automation of excavation and grading operations, paving operations, and installation of both buried and exposed piping. This technology should benefit any construction operation that requires high precision, involves special skills, or demands increased flexibility to improve efficiency.

The example of partially automated grading illustrates the potential to significantly improve a specific construction operation despite long-term evolution of the existing technology. Just when it appears that "we have gone about as far as we can go," a new technology such as the laser can make a revolutionary improvement. Then the process of incremental improvement starts all over again. Using the laser to aid in the control of fine grading was a revolutionary improvement. Following this, developing the new technology to perform in the demanding environment of field construction required a series of evolutionary improvements.

Comparison with Model

The example of partially automated grading conforms well to the model of process innovation in the construction firm. The contractor recognized the forces and opportunities for innovation and devoted considerable resources and personal energy to creating a climate for innovation and developing the necessary capabilities. The actual experience of developing the laser control system for partially automated grading included steps to provide the new technology, experiment and refine, and implement on projects and in the firm. Solving the practical problems of using the technology in the field made the process highly iterative.

Using the model provided some interesting insights regarding this construction innovation. Among these, the following can assist in further understanding the process of innovation in the construction firm:

1. The process of developing the technology was unpredictable, iterative, confusing, and very frustrating for those involved. The practical problems of using the laser system in a new environment and controlling a machine in a new way increased the uncertainty of success.
2. Because of the laser technology, the contractor was able to use existing equipment in unintended ways. This required thinking beyond the constraints of existing practices, which substantially increased the benefits of the new technology. Grading with a bulldozer on a crawler-tractor or a compactor was highly unconventional but the laser system allowed it.
3. The innovation produced unexpected benefits. The contractor sought improved productivity in fine grading operations. He gained this and more. Increased flexibility in equipment utilization brought more effective use of the overall equipment fleet. The laser system helped train less experienced operators so that they could quickly gain skills and high productivity levels.
4. The innovation required integration. The contractor and the supplier had to integrate the laser transmitter, the electronics components, and the hydraulics systems of the machines. Integration was essential because the vendors of individual components limited their involvement to their specific products.
5. Success with the laser-aided grading system soon highlighted opportunities to further improve productivity and overcome constraints based

on the design. For example, conventional designs for parking lots involve many planes and swales. This requires many laser set-ups and limits the effectiveness of the laser technology. Therefore, changes in design practices may be necessary to realize the full benefits of construction automation.

6. The improved productivity of the grading operations and the many other benefits of the partially automated technology gave the contractor important competitive advantages. The slowness of competitors in adopting the technology helped maintain this advantage.

7. The success of the laser-aided grading and the tenacity of the contractor spawned an innovation culture in the firm. They tried to improve all aspects of operations. Examples in the office included computerized quantity takeoff and dispatching. In the field, members of the firm continue to experiment, even with mounting a dozer blade on a water truck.

8. The contractor's insatiable desire to improve construction operations made him a champion for the new technology. This role was essential to the success of the innovation because of the many problems and skeptics.

Practical Applications

The development of partially automated grading presents several practical applications for managers seeking to increase the rate of technological innovation in construction firms. Successful innovation requires a long-term view of markets, the firm, and the potential for success of the innovation; in other words, vision and patience. Seek improvements in current operations even without apparent problems; the proven technologies may offer the greatest opportunity for improvement. To adopt new technology, you must be aware that its exists; "gatekeeping," an unfamiliar role in most construction firms, is essential. Involve all levels of the organization; field forces in construction can be a major source of good ideas. Innovations, even those with tremendous potential benefits, need a champion. Use the traditional "can-do" attitude of construction personnel to build a culture that makes innovation a practice in the firm. Expect many problem in developing new technologies and many unanticipated benefits. Seek major competitive advantages from new technology.

Insights for Innovation Research

The development of partially automated grading offers some insights for future innovation researchers. Many types of data are necessary to capture the process of innovation and the significant influences. Models provide a useful means to help gain an in-depth understanding of the complex process of innovation. However, the complexity and confusion of the process, as illustrated by this example, indicate a need to devise better means to capture iteration and feedback in a model. The differences in specific technologies and construction operations highlight the need to investigate many examples of innovation.

Acknowledgments

The research described in this paper is funded by the Structures and Building Systems Program in the Division of Mechanics, Structures, and Materials Engineering of the National Science Foundation under Grants

CEE-84-04352 and MSM-85-03431 and the members of the Stanford Construction Institute. Their support is gratefully acknowledged. We also greatly appreciated the willingness of Dan Lowry of GradeWay Construction Company, and John Fletcher and Rick Davidson of AGTEK Development Company to share their experience and insights regarding construction innovation.

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