A Laboratory Study of Force-Cognitive Excavation

Darcy M. Bullock[1]
Intec Controls Corp.
Walpole, MA, 02081

Irving J. Oppenheim
Departments of Architecture and Civil Engineering
Carnegie-Mellon University
Pittsburgh, PA, 15213

ABSTRACT

Excavation is characterized by the development of unmodelled forces between the bucket and the soil; the subsurface conditions are generally uncertain, and the development of these forces is only revealed during the very act of disturbing the medium. A human operator typically exerts control to keep such forces within limits created by the combined constraints of equipment, geometry, and task. This research effort developed and tested a *supervisory control* approach of discrete adjustments to the digging trajectory in response to forces encountered during excavation-- essentially constructing a device which can dig by *feel.* A laboratory manipulator was configured with four actuated degrees of freedom to approximate a backhoe. The motion sequence is represented symbolically as *swing-sweep-scoop-raise-swing-dump*, with the *sweep-scoop-raise* motions comprising the actual digging trajectory. Simple rules for supervisory control were programmed and tested in laboratory studies of sand excavation, and were effective in adjusting the digging actions to maintain forces within the target envelope.

1. INTRODUCTION; PROBLEM STATEMENT

The act of digging appears simple only to the most casual observer. On closer inspection, it is extraordinarily complex and difficult. The subsurface conditions, which include soil density, cohesion, internal friction, inclusions and discontinuities, are clearly unknown, and most digging is accomplished without explicit knowledge or study of them. In fact, the influence of such conditions is generally evidenced only in the very act of irreversibly interfering with the medium while digging. A man digging with a spade adjusts his angle of attack, depth of penetration, and angle of removal in response to these varying characteristics; those adjustments are essentially done by feel. Moreover, the man with a spade also adjusts his digging mechanics to the force envelope within which his muscles, joints, and limbs can work. As a result, he has extraordinary efficiency in being able to match a very limited work envelope to arbitrarily large excavation tasks. In addition, he processes all the spatial implications of reach and stability, and he embraces the span between an immediate (tactical) objective, which is the next spadeful of soil, and the overall

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[1]Formerly graduate student, Department of Civil Engineering, Carnegie-Mellon University.

(strategic) objective, which is the target geometry such as a trench. This study addresses force-cognitive excavation, digging by feel, which captures collectively all the features mentioned above except for those purely spatial in their origin.

It is instructive to examine machine excavation and to observe that the same issues still apply, and that the human-in-the-loop as operator provides a level of *supervisory control* for those same purposes. A machine that is very strong, stiff, and heavy may be able to "eat through" many materials without great concern for the forces encountered, but it would not be turned loose without human control; moreover, it remains reliant on its operator for satisfaction of stability, which is itself a force-domain decision. Accordingly, the reader is asked to accept a problem statement giving a manipulator excavation tasks which will challenge its intrinsic mechanical limits, forcing reliance on some operator to accomplish control in the force domain. The research effort then seeks an autonomous system to replace that operator.

This capability is needed before any reasonable excavator could be developed for automated use. While a mechanically robust device will no doubt be used for that purpose, and while actual supervisory intervention will be less frequent than in this experimental study, it is argued here that the best mechanism for developing this capability is study of a system in which force-cognition is highly demanded. Moreover, if we consider extra-terrestrial applications it is fairly certain that the excavator will be light and of limited strength, thereby requiring the same force-cognitive capabilities needed by the spade-user and by the manipulator used in this research program.

In the proposed approach at a low level the manipulator is commanded under position control in its digging motions. Force are sensed and processed at a higher level, where there exist computational objects which create the *supervisory control* and which alter the intended digging trajectory. The updating of trajectory plans at the higher level can be considered a *tactical planner* which is sensor driven and which interacts with the ongoing position control of the device.

2. EXPERIMENTAL SYSTEM

Manipulator system:

An experimental manipulator of modular design was constructed in the laboratories of the Civil Engineering Department. Six actuated rotary joints were fabricated; each joint is a DC motor driven by a power amplifier, turning a harmonic gearing with a potentiometer as a rotation sensor. A number of end plates and fittings permit rapid assembly into different experimental configurations and rapid link changeout. Figure 1 depicts the manipulator as the 4-DOF system used in this research effort. It corresponds to a backhoe at one particular vehicle position. The link denoted L2 corresponds to the "boom" and the link denoted L3 corresponds to the "stick" of the backhoe; in this laboratory form the length L3 is 16 inches. Viewed as a robotic manipulator position control exists for the four joint rotations. In a real excavator various candidate locations for force sensing include pressure in hydraulic cylinders, boom and stick strains, axle loads, and so on. In this research effort force sensing was accomplished by strain sensing on the manipulator links. A sandbox was assembled and a medium used in sand blasting was placed as the excavation material; it is a poorly graded sand, with 100% passing a U.S. #10 sieve, 65% passing a U.S. #20 sieve, and 1.1% passing a U.S. #40 sieve.

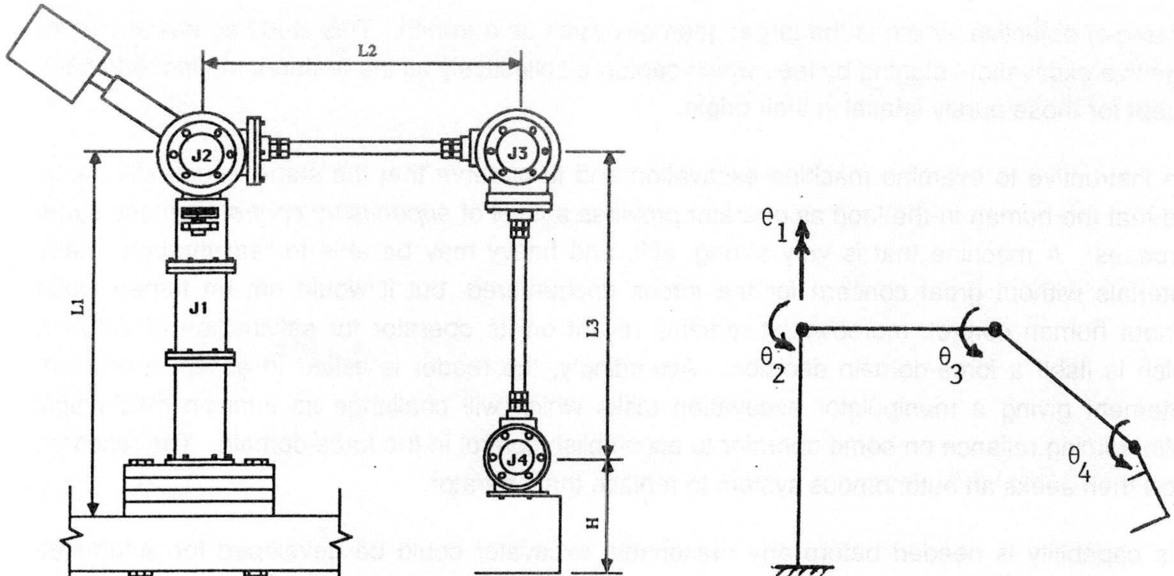

Figure 1: Excavator

Computing system:
Digital control of joint position was programmed on a Motorola VMEbus development system used for real time control, and strain signals were processed by a MicroMeasurements 2100 strain conditioning device. Significant research effort was then directed at extending a Smalltalk-80 environment for manipulator modelling, control, and task planning. Full description of this effort is well beyond the scope of this paper. The object-oriented programming environments have been recognized for their potential in rapid prototyping of systems, and for their capabilities in symbolic (high level) programming, but they have not been well suited for interfacing with real-time control. In an earlier effort a Smalltalk environment was implemented as a concurrent process on the VME system; in this research effort a Smalltalk environment running on a Sun-3 was extended to achieve serial line communications with the VME system. All manipulator and path modelling was performed in Smalltalk, producing joint space position commands for transmittal to the VME system. Supervisory control approaches were programmed as appropriate classes, objects, and methods within the Smalltalk environment. Symbolic programming was sought, in which the full sequence of excavation is characterized as *swing-sweep-scoop-raise-swing-dump*, with appropriate arguments (ie, bucket positions) for each motion in the sequence. For instance, the *swing* motion includes the rotation in θ_1 about the vertical axis; the first *swing* motion in the sequence would take the bucket from the dump position (truck location or spoil pile) back to the point in space at which the next digging cycle is to begin. Actual digging occurs within the *sweep-scoop-raise* portion of the sequence.

3. EXPERIMENTAL RESULTS

Experiments without supervisory control on strain:

The *intended* digging trajectory is the *sweep-scoop-raise* sequence. The full experimental *sweep* is a 30° rotation in θ_3 about a center of rotation which produces an arc approximately 12 inches long with about 2 inches of penetration into the medium. Figure 2 records the motion of a single point on the blade; the bucket itself and the manipulator links are not shown, and an approximate sand level is shown. Digging proceeds from right to left. The individual joint motions were recorded (not shown) and reveal the *scoop* motion (a 60° rotation in θ_4) to commence near bottom dead center of the trajectory, and the *raise* motion (a 2° rotation in θ_2) to complete the path. This trajectory can be considered an *intended unit of excavation*; given an excavator sufficiently strong, stiff, and properly positioned, this trajectory could be completed under position control, and the supervisory control exerted by the operator would be limited to the proper geometric sequencing of the motions. However, these experiments were chosen to demand significant supervisory control on internal forces. In principle the system could operate on several concurrent channels of force sensing (joint torques, link strains, axle/outrigger pressures, etc.); three channels were examined in this laboratory study, and the strain in link 3, the backhoe "stick," was observed to be an effective overall surrogate.

The link 3 strain signal as a function of blade position is recorded in Figure 3. Zero physical strain occurs at a strain signal of 2048 and the desired strain range is +/- 1050 units, corresponding to a desired signal range between 998 and 3098. In this experiment the strain signal violated that limit shortly into the *sweep*, after only 5 inches of blade motion. (The signal subsequently went completely out of range of the strain conditioning device.) In this experiment the system is "stiff" with respect to blade position and the desired strain range is very "tight," creating an extreme test for force-cognitive excavation.

Experiments with supervisory control on strain:

A series of experiments were conducted in which various force-cognitive tactics were programmed at the supervisory level of control. The most effective was supervisory control on both *sweep* and *scoop* motions, producing experimental results shown in Figures 4 through 7. Referring to Figure 4, the trajectory begins as a *sweep* but is overriden at the supervisory control level after approximately 6 inches because of excessive link 3 strain. The *scoop* motion commences but supervisory control then shortly demands a partial withdrawal of the bucket (approximately 1.5 inches of *reverse sweep*) during the *scooping*, again because of strain observations. The remainder of the motion is the completion of the *scoop* and the *raise*. Figure 5 records the strain signal and demonstrates that force-cognitive tactics have accomplished a complete excavation cycle while maintaining the strain signal within its desired range. Figure 6 records the joint rotations and Figure 7 the strain as functions of time. Referring to Figure 6:

- θ_1: There is no rotation about θ_1 during the *sweep-scoop-raise* sequence; it varies only during the *swing* motions.
- θ_2: Rotation about θ_2 is observed near the end of the experiment, after 50 seconds, and corresponds to the *raise* motion.
- θ_3: This rotation is the *sweep* motion. During the first 20 seconds it occurs incrementally, with brief pauses in which the strain signal is processed and supervisory control is considered. Approximately 12° of rotation are completed when

supervisory control ceases the *sweep* and commences the *scoop* motion 20 seconds into the record. At 25 seconds, while the *scoop* motion is underway, there is a reversed rotation of θ_3, corresponding to partial withdrawal of the bucket.

- θ_4: This corresponds to the *scoop* motion, commencing at 20 seconds and continuing to 50 seconds.

4. DISCUSSION OF RESULTS

Supervisory control on *sweep* and *scoop* actions constitutes a robust demonstration of force-cognitive excavation. The laboratory manipulator will make appropriate adjustments to its digging trajectory to accomplish excavation while maintaining force (strain) conditions within a desired range. Experiments demonstrated that capability over many trials, and the experiment recorded in Figures 4 through 7 displays a rather complex behavior, ably reproducing the role of an equipment operator. For example, note that the stiffness of the excavator-soil system at the start of digging is much higher in Figure 5 than in Figure 3. (This is evidenced by the greater slope to the portion of the record at the right in each Figure.) This could be caused by a sharper angle of attack, by an upslope to the soil surface, by compaction, and so on; it is noteworthy that the force-cognitive control is insensitive both to the origin and to the form of such conditions.

There is considerable significance to the use of supervisory control and this work is an early robotic demonstration of that concept. Similarly, the use of a Smalltalk programming environment is noteworthy, as is the hardware and systems development undertaken, as is the programming of manipulator modelling, manipulator kinematics, and trajectory modelling that were addressed in this study. All of these matters remain beyond the scope of this paper, but a succinct observation surfaces when examining the Smalltalk programs (not shown) which implement supervisory control. The program for the digging sequence is only 18 lines long, and the difference between versions with and without control on strain is restricted to minor changes in two of those lines. The environment was highly effective as a device for rapid prototyping, and was used in just that capacity in this investigation.

ACKNOWLEDGEMENTS; REFERENCES

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1. Bullock, D. M., *Supervisory Control for Cognitive Excavation*, M. S. Thesis, Department of Civil Engineering, Carnegie-Mellon University, August 1988.

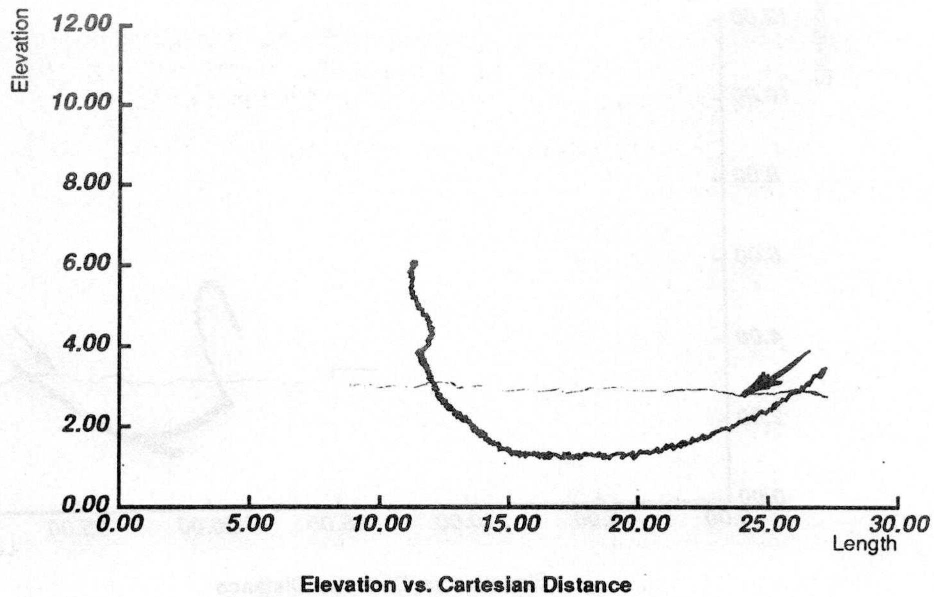

Figure 2: Excavation Path, No Supervisory Control on Strain

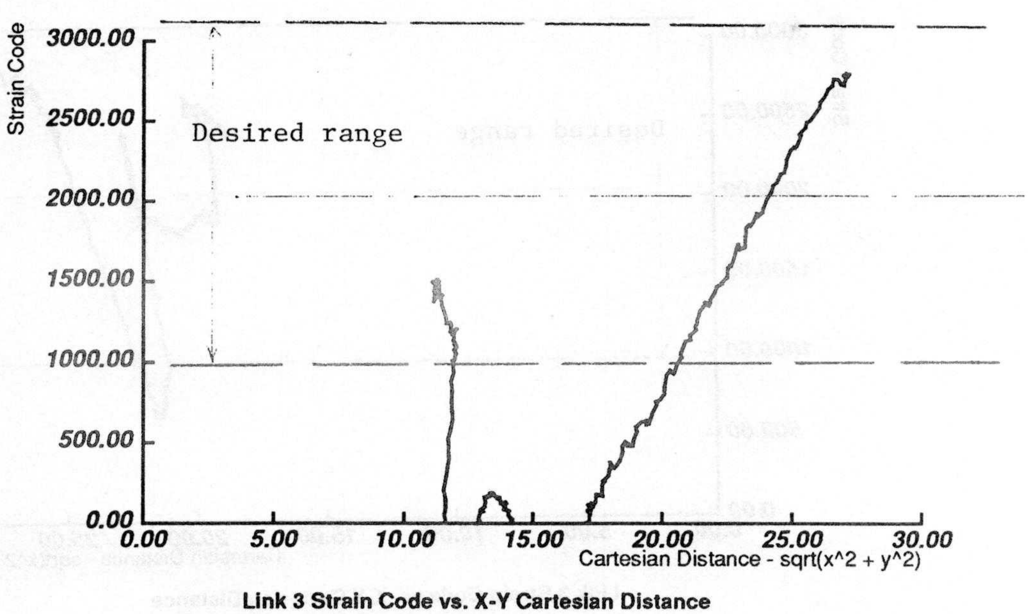

Figure 3: Link Strain vs. Blade Position, No Supervisory Control on Strain

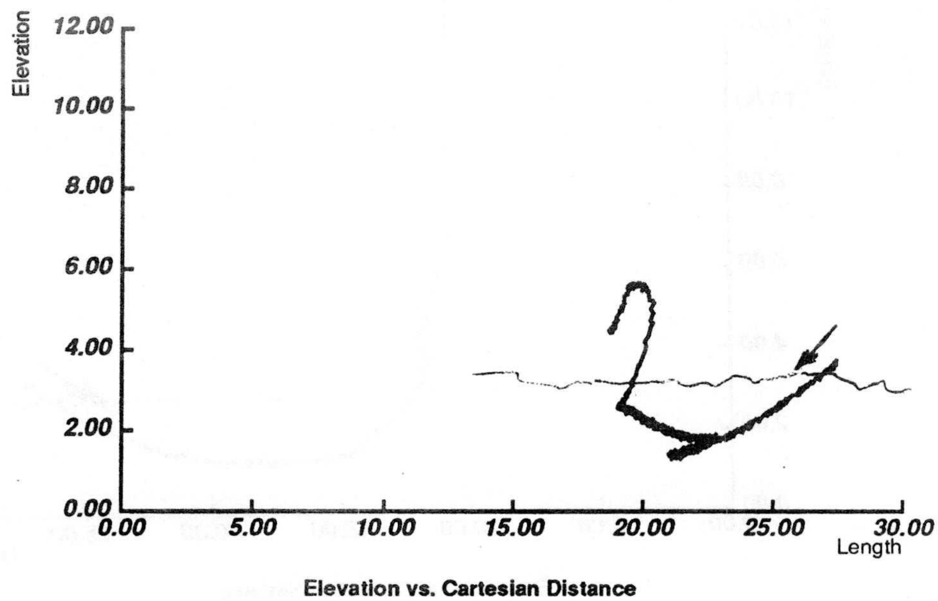

Figure 4: Excavation Path, Supervision on Sweep and Scoop Actions

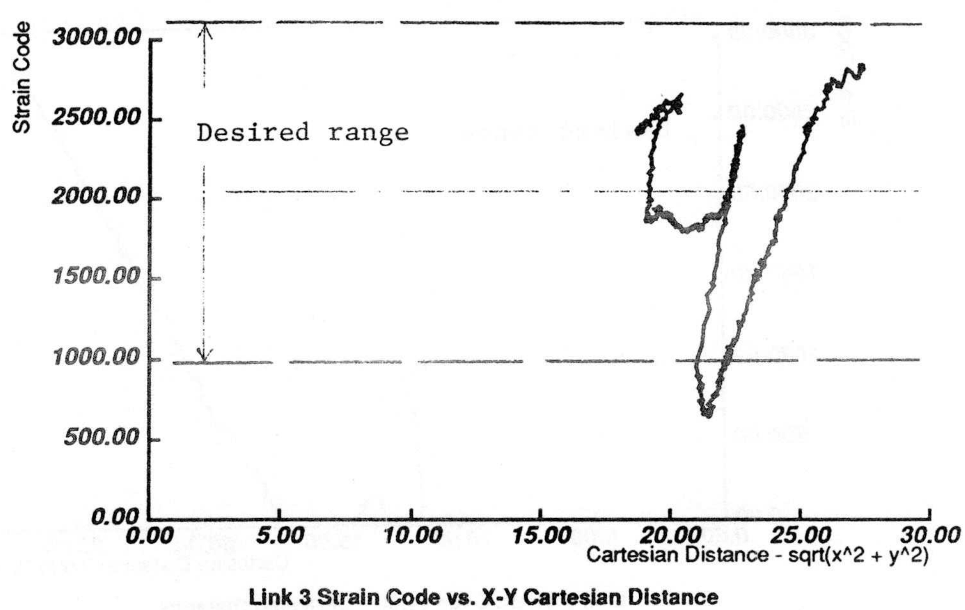

Figure 5: Link Strain vs. Blade Position, Supervision on Sweep and Scoop Actions

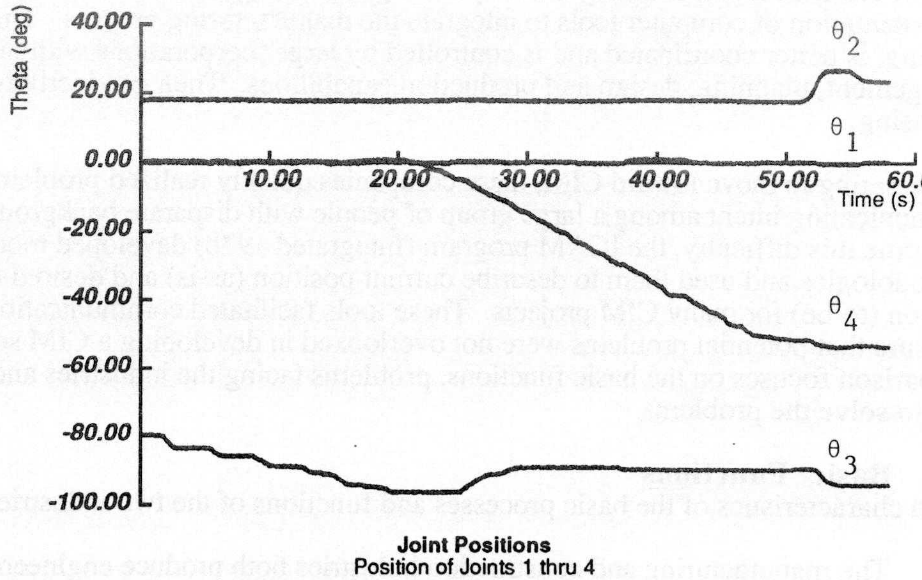

Figure 6: Joint Motion, Supervision on Sweep and Scoop Actions

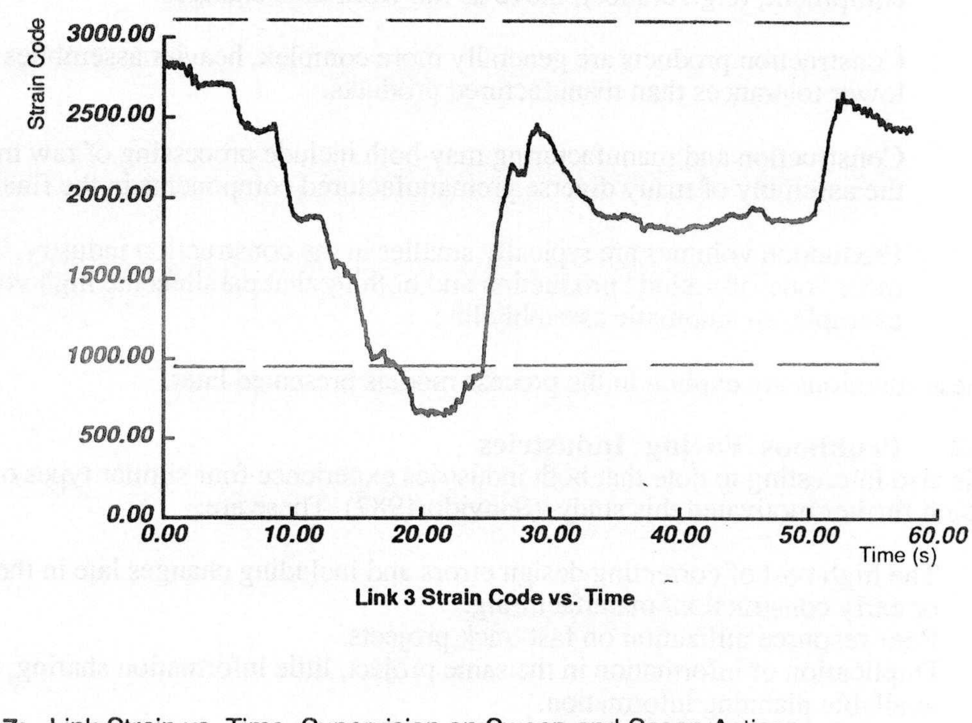

Figure 7: Link Strain vs. Time, Supervision on Sweep and Scoop Actions

Parts of the U.S. manufacturing industry have gone through a successful, extensive implementation of computer tools to integrate the manufacturing process. This industry is growing, is better coordinated and is controlled by larger corporations with in-house management, planning, design and production capabilities. Their productivity is increasing.

In attempting to move toward CIM, these companies quickly realized problems in communicating intent among a large group of people with disparate backgrounds. To overcome this difficulty, the ICAM program (Integrated 1978) developed modeling methodologies and used them to describe current position (as-is) and desired future position (to-be) for many CIM projects. These tools facilitated communication and helped to ensure that potential problems were not overlooked in developing a CIM solution. The comparison focuses on the basic functions, problems facing the industries and techniques used to solve the problems.

2.1 Basic Functions

Broad characteristics of the basic processes and functions of the two industries are:

1. The manufacturing and construction industries both produce engineered products that provide a service to the user.

2. Manufactured products are typically made in a facility and shipped to their final use area, while construction products are built in place. Hence the manufacturing environment is well controlled when compared to construction's.

3. The location of manufacturing process equipment, material paths, and the physical work area remain fairly constant throughout the production of one product. The construction work face changes as each component product is installed in place. This requires that process equipment, (e.g., concrete forms), and material handling equipment, (e.g., cranes), move as the work area changes.

4. Construction products are generally more complex, heavier assemblies built to lower tolerances than manufactured products.

5. Construction and manufacturing may both include processing of raw materials and the assembly of many diverse premanufactured components in the final product.

6. Production volumes are typically smaller in the construction industry. There is a more "one-of-a-kind" production and nothing that parallels the high volume of, for example, an automatic assembly line.

These functions are explicit in the process models presented later.

2.2 Problems Facing Industries

It is also interesting to note that both industries experience four similar types of problems which further motivated this study. (Sanvido 1987) These are:

1. The high cost of correcting design errors and including changes late in the design stage or early construction/ manufacturing.
2. Poor resource utilization on fast track projects.
3. Duplication of information in the same project, little information sharing, and lack of available planning information.
4. Poor efficiency in moving information from design to construction/ manufacturing.