CONSTRUCTION EQUIPMENT EMERGING TECHNOLOGIES:

FUZZY LOGIC CONTROLLERS

by
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CONSTRUCTION EQUIPMENT EMERGING TECHNOLOGIES:

FUZZY LOGIC CONTROLLERS

A Special Research Problem

Presented to

The Faculty of the Division of

Construction Engineering and Management,

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by

W. E. Bennett

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TABLE OF CONTENTS

Page

CHAPTER 1 Introduction and Background

CHAPTER 2 Fuzzy Defined

CHAPTER 3 Current Benchmark vs. Fuzzy Control

CHAPTER 4 Decision Matrix

CHAPTER 5 Decision Matrix Results

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 - INTRODUCTION AND BACKGROUND

1.0 State of the Construction Equipment Industry

Since World War II the heavy equipment industry has experienced numerous cycles of good and bad times. The average period of these cycles is 6 years (McKey 1987). In the mid 1970s, many "experts" were predicting that the demand for construction equipment could be plotted on an upward curve through the 1980s and even into the 1990s. Reasons for this optimism (U.S. Department of Commerce 1985) were:

1. Energy demand was expected to increase by 7% a year. This would prompt the continued construction of new power plants and supporting facilities.
2. Less developed nations expressing interest in rapid economic development.
3. Ownership of construction equipment was a good place for investors to shelter income due to tax credits and depreciation.
4. Rapid real estate appreciation fueled an active housing market.

Unfortunately, major events and trends in the early 1980s changed the picture dramatically, creating the following discouraging factors for construction equipment manufacturers (U.S. Department of Commerce 1985).

1. Excess production capacity ranging from 30% to 50%. (foreign and domestic manufacturers included)

2. Industry employment in the U.S. fell 57% in 3 years, 1981-1984.
3. High exchange rate of the dollar and high production costs caused U.S. exports from construction equipment manufacturers to fall from 50% to 30%.
4. Foreign imports made substantial inroads, both in the U.S. market and foreign markets previously dominated by U.S. manufacturers.
5. The increase in the price and demand of energy slowed dramatically and actually fell as the 1980s progressed.

The construction equipment market worldwide is fiercely competitive. The industry is considered mature and has entered an era of full-scale internationalization, in which a company's survival depends heavily on their success in overseas sales and production. Major manufacturers have generally established dealers and/or manufacturing subsidiaries in each major market. Fierce competition among the principal manufacturing countries - the U.S., Japan, and certain western European countries - has led to international cooperation, coupled with competition between three major international groupings: Hitachi-Deere-Fiat; Komatsu-Dresser; and Mitsubishi-Caterpillar. These groupings and the competition play a significant role in new product introduction and innovation, both positive and negative. Due to the grouping of Deere and Hitachi it does not come as a surprise that Deere is the first U.S. company to acknowledge that they are studying the use of advanced control techniques such as fuzzy controllers (Schofield 1995), which constitute the topic of this report.

1.1 Research and Development Funding

When considering innovation, and factors within the state of an industry that affect innovation, the first factor that may come to mind is research and development funding (R&D). On the average, construction equipment manufacturers tend to devote less than 5% of total sales to research and development. This percentage rose through the early 1980s as sales dropped and companies recognized the need for product innovation. Individual proprietary R&D efforts predominate throughout the construction equipment manufacturing industry. R&D consortiums, university-conducted R&D, and Federal R&D efforts play a nominal role in the continuing evolution of construction equipment. Competitiveness, as mentioned earlier, has made individual firms or partnerships less than willing to share information. Given the lack of, or slow innovation in the construction equipment market, coupled with the low R&D effort in general, it is not surprising that some of today's advanced new devices, such as fuzzy logic controllers are not being used in production models.

1.2 Advent of Electronics

The most significant innovation in construction equipment since the beginning of the 1980s is electronic control and monitoring systems. Today all earthmoving equipment is equipped with at least an electronic monitoring system. Some equipment, such as the front end loader (FEL) and especially the hydraulic excavator are heavily controlled by electronics to increase productivity and increase operator comfort.

It appears that the increased use of electronics on these pieces of equipment may have reached a peak in 1995 unless new control systems are developed. Today's control systems are constrained by their inability to recognize and control the complex, ever-changing work environment that construction equipment must operate in. Simply said, today's electronic controllers cannot handle the complex construction environment, work tasks in construction are too non-linear, complex and change too rapidly. This is often cited as a tremendous hindrance to automating this same equipment.

1.3 Background of Fuzzy Logic Usage

Since Professor L. A. Zadeh's original introduction of fuzzy sets and his subsequent rationale for a fuzzy controller, fuzzy control has emerged as one of the most active and fruitful areas for research. Table 1-1 summarizes the development of fuzzy control (Lee 1990).

Table 1-1: Summary of Fuzzy Control Development (Lee 1990)

1972	Zadeh	A rationale for fuzzy Control
1973	Zadeh	Linguistic approach
1974	Mamdani & Assilian	Steam engine control
1976	Rutherford et al.	Analysis of control algorithms
1977	Ostergaard	Heat exchanger and cement kiln
1977	Willaeys, et al.	Optimal fuzzy control
1979	Komolov et al.	Finite automation
1980	Tong et al.	Wastewater treatment process
1980	Fukami, Mizumoto and Tanaka	Fuzzy conditional inference
1983	Hirota and Pedrycz	Probabilistic fuzzy sets
1983	Takagi and Sugeno	Derivation of fuzzy control rules
1983	Yasunobu, Miyamoto et al.	Predictive fuzzy control
1984	Sugeno and Murakami	Parking control of a model car
1985	Kiszka, Gupta et al.	Fuzzy system stability
1985	Togai and Watanabe	Fuzzy chip
1986	Yamakawa	Fuzzy controller hardware system
1988	Dubois and Prade	Approximate reasoning

As of today, construction equipment has not begun to take advantage of fuzzy controllers. As mentioned earlier, John Deere just recently on fuzzy controllers for hydraulic excavator use (Schofield 1995). The essential part of a fuzzy logic controller (FLC) is a set of linguistic control rules related by the dual concepts of fuzzy implication and the compositional rule of inference. Experience has shown that the FLC yields superior results to those obtained by conventional control algorithms. In particular the FLC appears to be very useful when processes are too complex for analysis by conventional controller techniques. With these factors in mind it appears that fuzzy control has the possibility to have a tremendous positive impact on the construction equipment industry once the industry begins to use and develop these type of controllers for their machines.

1.4 Fuzzy Control Basic Background

In many industries a relatively new control technology is being used to overcome just the problems cited above for construction equipment. This new process involves fuzzy logic and uses fuzzy logic controllers (FLCs). Japanese companies have embraced this technology for years. In fact Japanese companies now hold thousands of patents on fuzzy controlled devices. It is the success of the Japanese in particular that is driving the current interest. Japan funded the Laboratory of Industrial Fuzzy Engineering (LIFE) beginning in 1988 for a period of 7 years at $24 million per year (Bezdek 1993).

Fuzzy controllers usually require less information than conventional controllers and fuzzy rules compartmentalize inputs and outputs by using independent rules so if one is wrong it does not produce drastically erroneous results. Fuzzy control has been shown to require one-tenth the information required of conventional controllers, a decisive cost savings during product development. conditioners that save 24% in cooling and 17% in heating over conventional PID (Proportional-Integral-Derivative) controllers. Closer to the construction equipment industry is Nissan's Automatic Transmission Controller (ATC) that reduces fuel cost by 12-17% and Nissan's Automatic Braking System (ABS) that senses 18 factors minimizing the uneasy feeling that conventional ABS systems sometimes provide the operator when ABS engages and disengages the brakes under conditions when the operator does not expect this action. It is this wealth of deployed, successful applications of fuzzy technology that is, in the main, responsible for current interest in the subject area (Bezdek 1993).

1.5 Problem and Scope

The construction industry is a highly competitive workplace. Future documented declines in the number of construction equipment operators, coupled with a changing job mix from heavy construction to light and residential construction, increases the pressure to increase equipment productivity and adaptability (USITC 1992). The introduction of fuzzy logic and FLCs may be beneficial to the industry by increasing productivity, reliability, maintainability, lowering costs and allowing unskilled operators to be as productive in most situations as a more experienced operator. Before the construction equipment industry fully embraces FLCs on construction equipment it must be qualitatively proven that the technology can provide the benefits mentioned above.

1.6 Research Objective

The primary objective of this research is to qualitatively define the expected impact of fuzzy logic on construction equipment. Succinctly, the following questions must be answered.

1. Is it maintainable?
2. Is it reliable?
3. Is fuzzy logic safe for the construction jobsite?
4. Is productivity increased?
5. Is an unskilled operator more productive with this type controller?
6. Is fuzzy logic control an economically viable alternative to today's controllers?
7. Are operating costs reduced?

Answering these questions for the equipment types studied will indicate if this technology warrants future implementation by construction equipment manufacturers.

1.7 Study Organization and Methodology

This study is divided into 5 chapters. This first chapter describes the background and introduces the problem of qualitatively describing the impact of fuzzy logic control of construction equipment. This is followed by a brief introduction of fuzzy logic, models and controllers, including examples of current usage related to construction equipment. This third chapter benchmarks current electronic control technology for earthwork equipment and compares this technology to fuzzy logic controllers. The fourth chapter describes a decision matrix that is used to qualitatively describe the impact of this technology and discusses each of the factors as to their importance to the decision making process. The last chapter completes the decision matrix and presents final thoughts on fuzzy controller impact.

"SOMETHING LIKE $100 BILLION WORLDWIDE HAS GONE INTO AI (ARTIFICIAL INTELLIGENCE) AND YOU CAN'T POINT TO A SINGLE AI PRODUCT IN THE OFFICE, HOME, AUTOMOBILE, ANYWHERE. WITH NEURAL NETWORKS, ITS APPROACHING $500 MILLION, AND YOU CAN'T POINT TO ANY PRODUCTS AND YOU PROBABLY WON'T BE ABLE TO FOR SOME TIME. FUZZY TECHNIQUES HAVE GOTTEN ALMOST ZERO DOLLARS FROM THE GOVERNMENT, AND YOU CAN POINT TO A LOT OF PRODUCTS, AND WILL BE POINTING TO A WHOLE LOT MORE."

BART KOSKO (Terano *et. al.* 1992)

Chapter 2 - Fuzzy Defined

2.0 Introduction

Today's fuzzy controllers and fuzzy logic owe their beginning to Professor L.A. Zadeh (Zadeh 1965) with his original paper describing fuzzy sets. From this inauspicious beginning, fuzzy sets have evolved into fuzzy logic and into fuzzy controllers. A basic understanding of the terminology is essential to this research. It is basic to Zadeh's propositions that we as humans all assimilate and act on fuzzy data, vague rules and imprecise information. A classic example is teaching someone to drive a car. The instructor does not tell the student to apply the brakes 74 feet before they need to stop or tell the student to remember their simple kinematics equations as they brake to a stop. The instruction is more likely to be "apply the brakes soon, or judge your speed to stop just before the sign without too much jerking action." This example illustrates that in many of our everyday human decisions precision is useless, yet we all seem to operate in the world in a more than adequate manner.

2.1 Fuzzy versus Conventional Sets

Conventional or crisp sets contain objects that satisfy precise properties. An example is the set of real numbers H from 6 to 8. This is a crisp set and H can be described by its membership function m_H .

m_H = 1: $6 \le r \le 8$

0: otherwise

The purpose here is to emphasize that crisp sets correspond to two-valued logic, which implies: is or is not, off or on, black or white.

Now to describe a fuzzy set F, assume our example is the set of real numbers close to 7. “Close to” is fuzzy, there is not a unique membership function for this set F. The modeler can then decide what the membership function, m_F , should be. There are at least three plausible solutions, normality ($m_F(7) = 1$), monoticity (the closer r is to 7, the closer $m_F(r)$ is to 1, and symmetry (numbers equally to the right and to the left of 7 should have equal memberships). As an example either of the figures below could represent m_F.

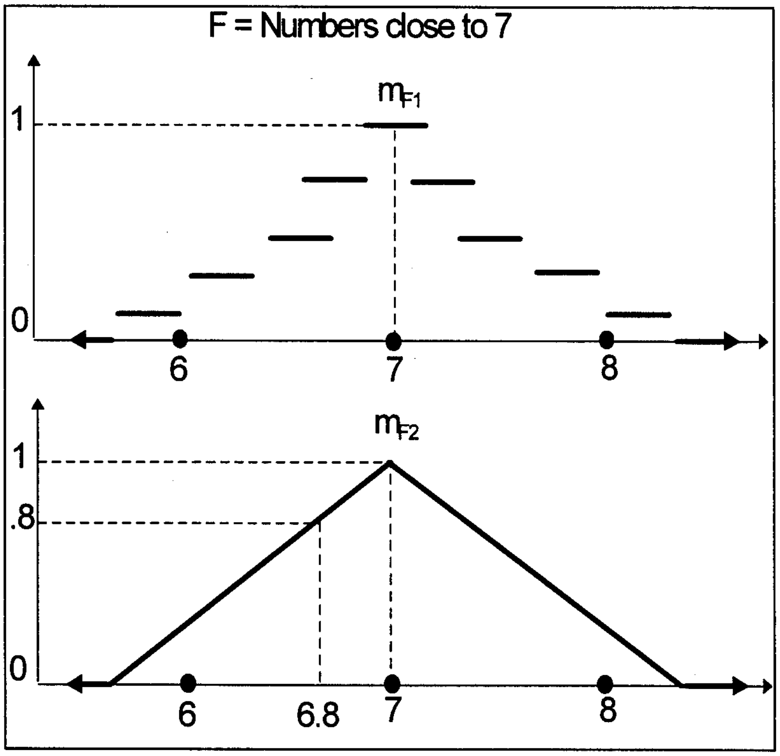


Figure 2-1: Fuzzy Set Membership (Bezdek 1993)

The point is, that the biggest difference between crisp and fuzzy sets is that crisp sets always have unique membership functions, but fuzzy sets have an infinite number of membership functions. This is both a weakness and a strength: uniqueness is sacrificed, but this gives a concomitant gain in terms of flexibility, enabling fuzzy models to be "adjusted" for maximum utility in a given situation (Bezdek 1993).

Fuzzy sets are always functions, from a universe of discourse (objects), as the figure following implies. The outstanding feature of fuzzy sets is the ability to express the amount of ambiguity in human thinking and subjectivity (including natural language) in a comparatively undistorted manner (Terano, Asai, Sugeno 1992)

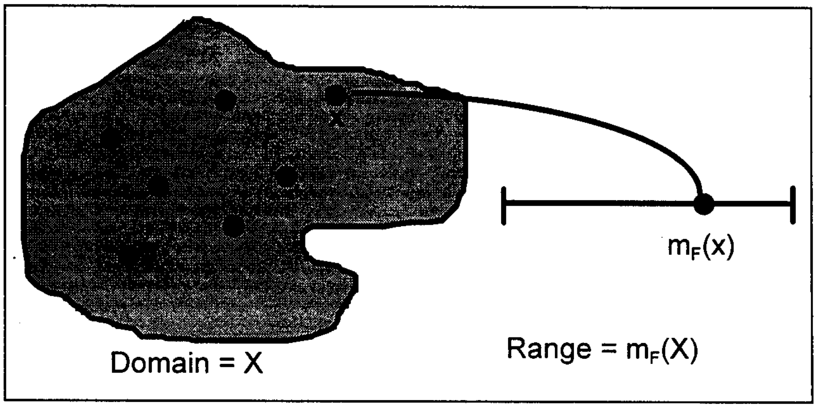


Figure 2-2: Universe of Discourse (Bezdek 1993)

2.2 Relationship of Fuzzy Versus Probability

Before fuzzy logic, probability was the only way in which mathematics recognized uncertainty. Probability however, deals with occurrence of phenomena. Fuzziness is a mathematical concept that takes in uncertainty also, but, fuzziness refers to the ambiguity of a concept or a word. Examples of fuzzy words are, close to, hot, cold, old, tall, small, etc.

An example best demonstrates that fuzziness is not probability and further illustrates the definition of fuzzy and crisp sets. Assume that the universe of discourse is all liquids and the fuzzy set is defined as potable liquids, L. Suppose in the desert there were two bottles marked A and B.

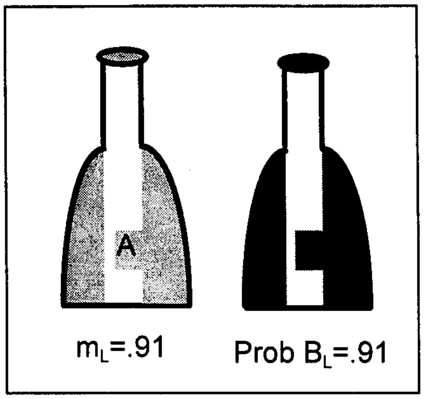


Figure 2-3: Fuzzy Logic versus Probability (Bezdek 1993)

For bottle A the fuzzy membership value is given as shown and for bottle B the probability of the liquid being potable is given as shown. The question is which bottle should you drink from. Since bottle A is of the potable membership, even if it is disgusting looking or smells bad it won't kill you, it is potable. However, bottle B has a probability of .91 of being potable. This means that 9 out of a hundred times it may be non-potable in which case the liquid would not be fit to drink regardless of its smell or looks. Therefore probability and fuzzy sets are not one in the same, and the same techniques and mathematics cannot be used or applied to fuzzy sets (Bezdek 1993).

2.3 Graded Membership

The question of how the membership functions of fuzzy sets are created is best described by an example that Zadeh refers to as graded membership. Take the word "tall" for example. Each of us has an idea or definition in our mind of what tall implies. When tall is used with crisp sets, there must be a cut off point as to when someone is tall or not. Recall that in crisp sets membership is either yes or no, 1 or 0. For example, take the list of men below.

Table 2-1: Fuzzy Membership Values

	Membership Value	
	Crisp	Fuzzy
Jim (6' 6'') is tall	1	.95
Jon (6'2'') is tall	1	.8
Ed (5'11'') is tall	1	.6
Bob (5'9'') is tall	0	.4
Bill (5'6'') is tall	0	.2

In the case of crisp sets we must have a cutoff point, for the example suppose the cutoff is 5'10'', therefore Ed, Jon and Jim are tall and have membership in the crisp set of "tall." For the fuzzy set all the men have membership, but each to a varying degree as shown in the table.

2.4 Linguistic Variable

The term linguistic variable is used at times to describe a fuzzy set. An example of a linguistic variable is the word "speed." If speed is interpreted as a linguistic variable, then its fuzzy set T(speed) could be defined as

T(speed)={slow, moderate, fast, very slow, more or less fast,...}

Where each term in T(speed) is characterized by a fuzzy set in universe of discourse U=[0,100]. Where "slow" might be 40 mph and "moderate" 55 mph and "fast" as 70 mph. The figure below is a graphical representation of this fuzzy set with these three terms “slow”, “medium”, and “fast.”

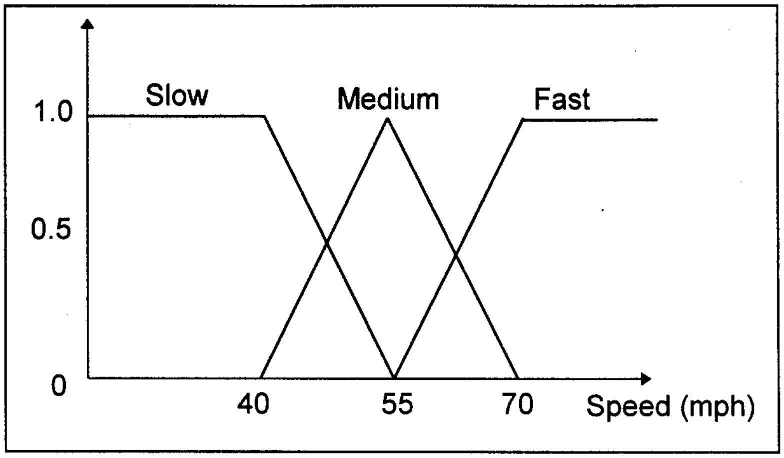


Figure 2-4: Linguistic Variables (Ross 1995)

Linguistic variables are used to make fuzzy rules for controllers. An example for the hydraulic excavator would be “bucket force.” Describing the force being exerted on the ground by the bucket a fuzzy set could use terms such as “hard,” “soft,” “medium,” “extremely soft,” etc.

2.5 Defuzzification Strategies

A defuzzification strategy produces a non-fuzzy control signal that best represents the inferred fuzzy control action. Presently there are three defuzzification strategies being used:

1. Max. Criterion Method (MAX) - The max criterion method produces the point at which the possibility of the control action reaches a maximum value.
2. Mean of the Maximum Method (MOM) - The MOM strategy generates a control action which represents the mean value of all local control actions whose

membership functions reach the maximum. This strategy yields the best transient performance.

3. The Center of Area Method (COA) - This methodology is perhaps the most widely used and it generates the center of gravity of the possibility distribution. This method yields superior results for steady state performance.

The figure below is a graphical interpretation of these three defuzzification strategies. The gray area represents the fuzzy inferred control area. The MAX value is at the tip of the control action and the COA and the MOM are found using similar procedures to find the center of area and maximum moment axis of any figure.

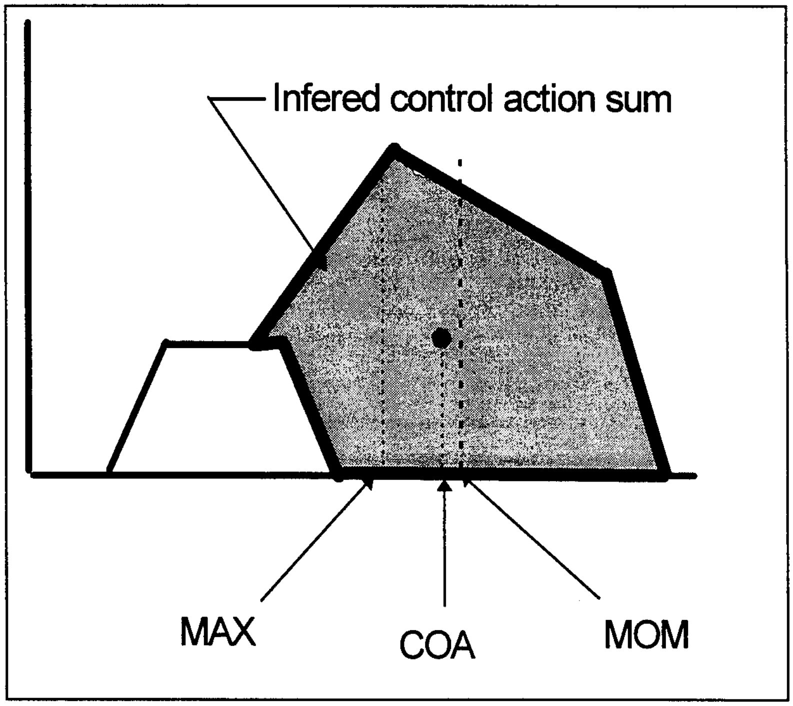


Figure 2-5: Defuzzification Strategies (Ross 1995)

2.6 Fuzzy Control Rules

Fuzzy control describes the algorithm for process control as fuzzy relations between information about the condition of the process to be controlled, x and y, and the input for the process z. The control algorithm is given in “if-then’ expressions, such as

If x is small and y is big, then z is medium

If x is big and y is medium, then z is big.

The statements above are called fuzzy control rules. The “If” clause is called the antecedent and the “then” clause the consequent. “Big and small and medium” are called fuzzy values and x and y are fuzzy variables expressed as fuzzy sets. Fuzzy controllers are constructed of sets of these rules and when the output from these rules is calculated, it is called fuzzy inference.

There are four structures that make up a fuzzy production rule system (Weiss and Donnel 1979).

1. A set of rules that represents the policies and heuristic strategies of the expert decision maker.
2. A set of input data assessed immediately prior to the actual decision.
3. A method for evaluating any proposed action in terms of its conformity to the expressed rules, given the available data.
4. A method for generating promising actions and for determining when to stop searching for better ones.

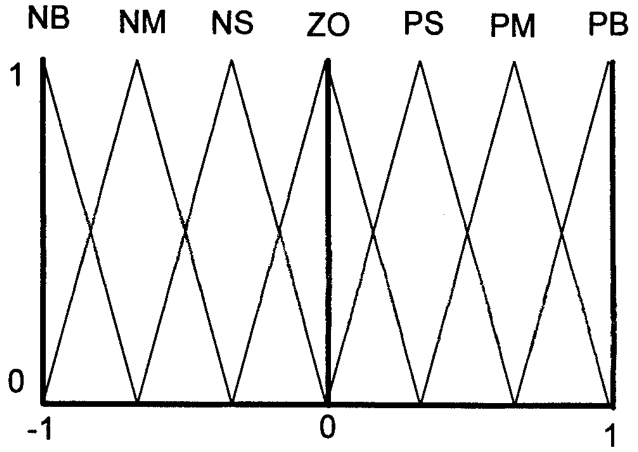
The input data, rules, and output action , or consequence, are generally fuzzy sets expressed as membership functions defined on a proper space. The method used for the evaluation of rules is known as approximate reasoning, or interpolative reasoning or fuzzy inference, and is commonly represented by composition of fuzzy relations applied to a fuzzy relational equation.

The control surface or decision surface is a time varying plane surface, which relates the control action u() to the measured state or output variables. It is obtained using these four structures. It is then sampled at a finite number of points, depending on the required resolution, and a look-up table is constructed. The look-up table can be downloaded onto a read-only memory chip constituting a fixed controller for the plant.

2.7 Fuzzy Variables

Fuzzy variables can be either continuous or discrete and examples are shown below. Discrete fuzzy variables are represented by a fuzzy look up table as shown below. Continuous fuzzy variables are functions, with each function given a linguistic definitions such as NB - negative big, or PS - positive small. Fuzzy tables have the advantage of being easily constructed, but in actual operation research has shown they increase the inference time. Continuous fuzzy variables while harder to construct than discrete fuzzy variables provide quicker more responsive fuzzy inference (Lee 1990). Figure 2-6 shows the continuous fuzzy variable memberships are expressed as a triangular function. Any type of function can be used, Gausian or Bell shaped functions are the other common type of continuous fuzzy variable function being used.

Triangular Continuous Fuzzy Variables



Discrete Fuzzy Variables

	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
PB	0	0	0	0	0	0	0	0	0	0	3	7	10
PM	0	0	0	0	0	0	0	0	3	7	10	7	3
PS	0	0	0	0	0	0	3	7	10	7	3	0	0
ZO	0	0	0	0	7	7	10	7	3	0	0	0	0
NS	0	0	3	7	7	7	3	0	0	0	0	0	0
NM	3	7	10	7	0	0	0	0	0	0	0	0	0
NB	10	7	3	0	0	0	0	0	0	0	0	0	0

Figure 2-6: Fuzzy Variables (Ross 1995)

2.8 Fuzzy Inference

Fuzzy controllers then are constructed of groups of fuzzy control rules, and fuzzy variables are described as either continuous or discrete and the output is calculated by means of fuzzy inference. Fuzzy inference is based on fuzzy logic. Mathematical procedures for fuzzy inferencing of "if-then" rules are implemented on a computer or within a microchip for processing speed and actual implementation. There are four methods used to perform this inference.

1. Max-min method with crisp inputs
2. Max-product method with crisp inputs
3. Max-min method with fuzzy set inputs
4. Max-product method with fuzzy set inputs

However to gain some insight into the mathematical process and as a way to check computer code, graphical methods have been developed that emulate the inference process.

To illustrate fuzzy inference, consider a dual-input and single output fuzzy system with two non-interactive inputs x_1 and x_2 and a single output y. The if-then statements become

If x_1 is A_{11} and x_2 is A_{21} then y is B_1

If x_1 is A_{21} and x_2 is A_{22} then y is B_2

where the A's are fuzzy sets with the pairs indicated and B is a fuzzy output set.

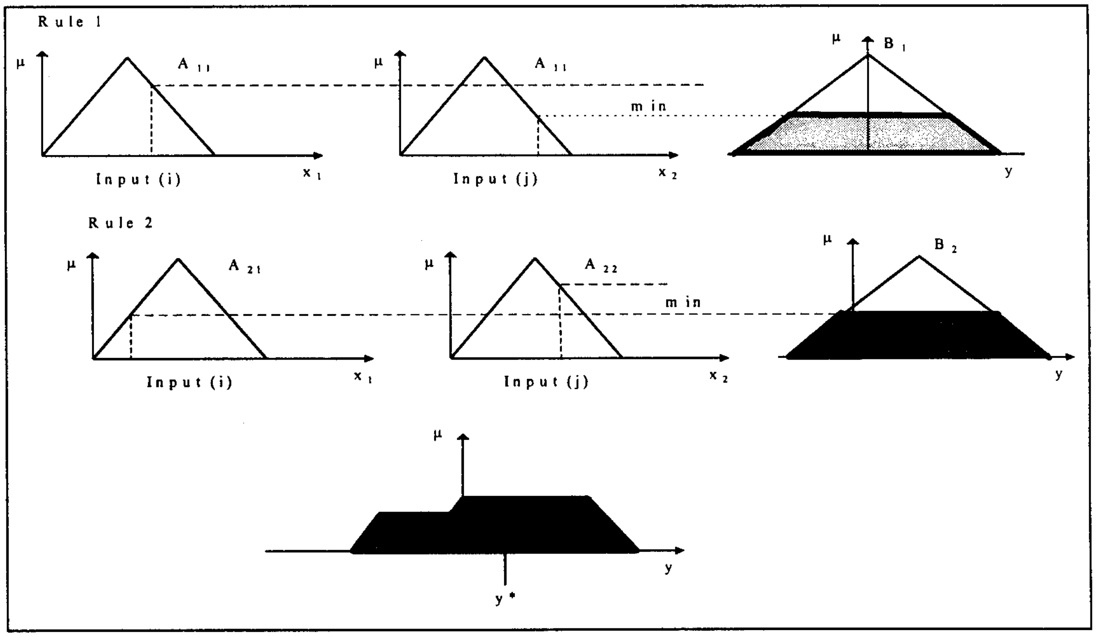


figure 2-7: Fuzzy Inference (Ross 1995)

As is easily seen from figure 2-5, the minimum from each input value of A1 or A2 fuzzy sets becomes the value of B. The two fuzzy values are then added and a defuzzification method is used to find the crisp output represented by y*. The inference technique used in this example was the Max-min method.

2.9 Planning Fuzzy Controllers

To design a controller involves determining the form of the control rules and writing them out concretely. The problem can be divided into two parts: (1) determination of the antecedents and (2) determination of the consequents. First, the input information for x_1, x_2, etc., which have to be used in the antecedents is selected: next is the determination of the fuzzy partitions of the input; ,and third is the determination of the parameters for the fuzzy variables. As far as the consequent is concerned, the output is generally the control input for the process, which is determined of its own accord. The only remaining problem is the fuzzy parameters. Therefore, determination of the consequents is not difficult, and the problem is wholly the determination of the antecedents.

Generally speaking there are three design methods used today. The first utilizes expert experience and knowledge, the second models operator processes and the last creates fuzzy models of the process.

2.9.1 Expert Experience and Knowledge

The experience of skilled operators and the knowledge of control engineers is expressed qualitatively in words, and if these were are put into logical forms as fuzzy control rules, a controller can be planned. With this design method the information input into the fuzzy controller becomes clear and is not a problem. The main concern is the fuzzy partitions of the input space, which must be determined through interviews with operators and by using the instincts of control engineers.

2.9.2 Operator Models

The operation of complicated processes is performed skillfully by experts, but it is not always easy to put their know-how into logical form. For example, experts may not be able to express their work in words. As with driving a car, or operating construction equipment, when an expert learns an operation with his or her hands and feet, it is next to impossible to express the skills in words. An effective design method in this case is a model of the functions carried out by the operator. This means working an input/output relation between the information used by the operator and his functional output. "if-then" form control rules can be written and used as a fuzzy controller. As with the expert model the input information presents little problem, it is the problem of identifying the fuzzy partitions that causes concern.

2.9.3 Fuzzy Models of Process

When the process does not have experts or operators a better method is based on a fuzzy model of the process. Here a fuzzy model means describing the features of the process using an "if-then" form that is the same as that of fuzzy control rules. The idea is to have one fuzzy rule correspond to each process rule.

2.10 Control System Overview

Before describing fuzzy control systems an overview or introduction into control systems in general is warranted. A control system is an arrangement of physical components designed to alter, to regulate, or to command, through a control action, another physical system so that it exhibits certain characteristics or behavior. There are typically two types.

Open loop - in which the control action is independent of the physical system output. An example is a toaster in which the operator sets the desired toasting range and the machine heats up to that setting only.

Closed loop - This is commonly referred to feedback. Here the control action depends on the physical system output. The thermostat in a home is a common example where the heating and cooling action depends on the actual output, i.e. room temperature.

The figure below is an easily understood schematic of a common simple feedback or closed loop controller.

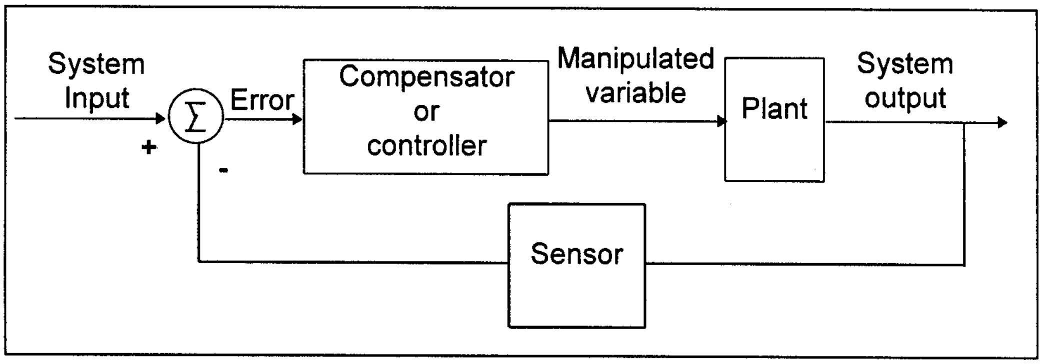


Figure 2-8: Simple Feedback Control (Ross 1995)

Controllers are also divided into two classes.

Regulatory - The object is to maintain a physical variable at some constant value even when disturbed. The thermostat in the home is an example.

Tracking - a physical variable is required to follow or track some desired time or distance function. The automatic aircraft landing systems are an example of this type of controller.

2.11 Control System Design Stages

Ross (1995) lists seven simplifying steps used in modeling a controller for a system, regardless of the type of controller these steps are beneficial to understand.

1. Large-scale systems are decentralized and decomposed into a collection of decoupled subsystems. For example, in construction equipment the hydraulic and engine systems can be decoupled. Even further, the engine system can be decoupled into transmission, speed control, suspension control, etc.
2. The temporal variations of plant dynamics are assumed to be "slowly varying." This assumption simplifies equations, but, for construction equipment this assumption is not valid in most cases.
3. The nonlinear plant dynamics are locally linearized about a set of operating points.
4. A set of state variables, control variables, or output features is made available.
5. A simple P (proportional), PD (proportional-derivative), PID (proportional-integral-derivative) (output-feedback), or state-feedback controller is designed for each decoupled system. The controllers are of regulatory type and are fast enough to perform satisfactorily under tracking control situations. Optimal controllers might also prove useful.
6. In addition to uncertainties introduced in the first five steps (in particular linearizing and time invariance), there are uncertainties due to external

environment. The controller design should be made as close as possible to the optimal one based on the control engineer's knowledge, in the form of input-output numerical observations data and analytic, linguistic, intuitive, and other kinds of information regarding the plant dynamics and the external environment.

7. A supervisory control system, either automatic or a human expert operator, forms an additional feedback control loop to tune and adjust the controller's parameters, in order to compensate for the effects of variations caused by unmodeled dynamics.

It is obvious then, that to design a controller the design process simplifies the process so it can be controlled. This points out the difficulty that arises in controller design and as shown below the fuzzy control system not only simplifies this design process, but in many ways the simplifying assumptions made above do not have to be made.

2.12 Assumptions in Fuzzy Logic Control (FLC) System Design

There are six basic assumptions (Ross 1995) commonly made whenever fuzzy logic based controllers are to be used.

1. The plant is observable and controllable: state, input, and output variables are usually available for observation and measurement or computation.
2. There exists a body of knowledge comprised of a set of expert production linguistic rules, engineering common sense, intuition, a set of input/output measurements data, or an analytic model that can be fuzzified and from which rules can be extracted.

3. A solution exists.
4. The control engineer is looking for a "good enough" solution, not necessarily the optimum one.
5. We will design a controller to the best of our available knowledge and within an acceptable range of precision.
6. The problems of stability and optimality are still open problems in fuzzy controller design.

Compared to the general controller design assumptions, FLC design assumptions point our some advantages of fuzzy control... "good enough,"... "acceptable range of precision"... "a body of knowledge exists" , all implying that fuzzy controllers are easier to implement and design.

2.13 Simple Fuzzy Logic Controllers

A simple fuzzy logic controller is depicted below.

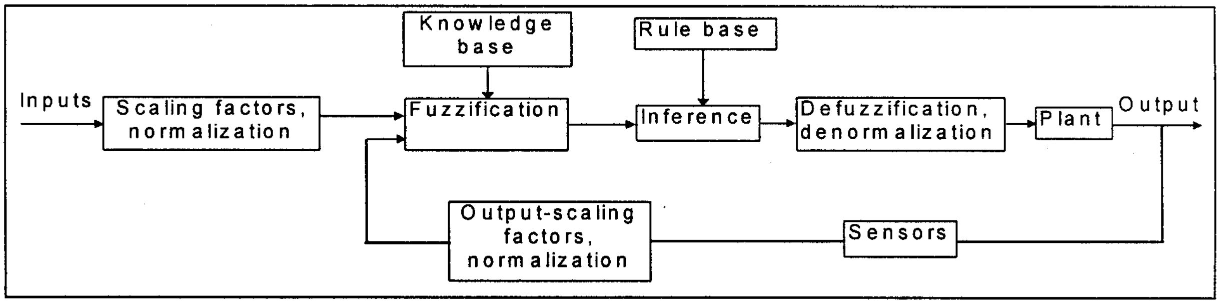


Figure 2-9: Simple Fuzzy Controller (Terano, Asai and Sugeno 1992)

The knowledge-base module contains knowledge about all the input and output fuzzy partitions/sets which are the fuzzy variables. It will include the term set and the corresponding membership functions defining the input variables to the fuzzy rule-based system and the output variables, or control actions to the plant under control. The rule base contains the "if-then" statements and corresponding solution methods are found in the inference block. These two blocks, the knowledge base and rule base, are sometimes referred to as the inference engine.

With the above diagram in mind, the steps to design this controller are as follows (Ross 1995):

1. Identify the variables (inputs, states, and outputs) of the system.
2. Partition the universe of discourse or the interval spanned by each variable into a number of fuzzy subsets, assigning each a linguistic label.
3. Assign or determine a membership function for each fuzzy subset.
4. Assign the fuzzy relationships between the 'inputs' or 'states' fuzzy subsets on the one hand and the outputs' fuzzy sets on the other hand, thus forming the rule-base.
5. Choose appropriate scaling factors for the input and output variables in order to normalize the variables to the [0,1] interval or the [-1.1] interval.
6. Fuzzify the inputs to the controller.
7. Use fuzzy approximate reasoning to infer the output contributed from each rule.
8. Aggregate the fuzzy outputs recommended by each rule.
9. Apply defuzzification to form a crisp output.

2.14 Characteristics of a Simple Fuzzy Controller

A simple fuzzy logic control system has the following characteristics (Ross 1995):

1. Fixed and uniform input- and output-scaling factors.
2. Flat, single-partition rule-base with fixed and noninteractive rules. All the rules have the same degree of certainty and confidence, equal to unity.

3. Fixed membership functions.
4. Limited number of rules, which increases exponentially with the number of input variables.
5. Fixed metaknowledge including the methodology for approximate reasoning, rules aggregation, and output defuzzification.
6. Low-level control and no hierarchical rule structure.

Therefore a simple fuzzy controller is easier to implement and design than the traditional PID controller, but is very fixed in nature. The real power in fuzzy logic is the ability to infer and almost think. This can be done using an adaptive or predictive fuzzy controller.

2.15 Adaptive Fuzzy Control System

The simple fuzzy control system is just an iteratively adjusting model. An adaptive system adjusts its control surface in accord with varying signal parameters. A truly adaptive fuzzy control system not only adjusts to time- or process-phased conditions but also changes the supporting system controls. Meaning that an adaptive system modifies the characteristics of the rules, the topology of the fuzzy sets, and the method of defuzzification based on predictive convergence metrics. The metric is simply a set of rules signifying when a rule set or inputs or output sets should be varied. An example of this type of system is shown in figure 2-10.

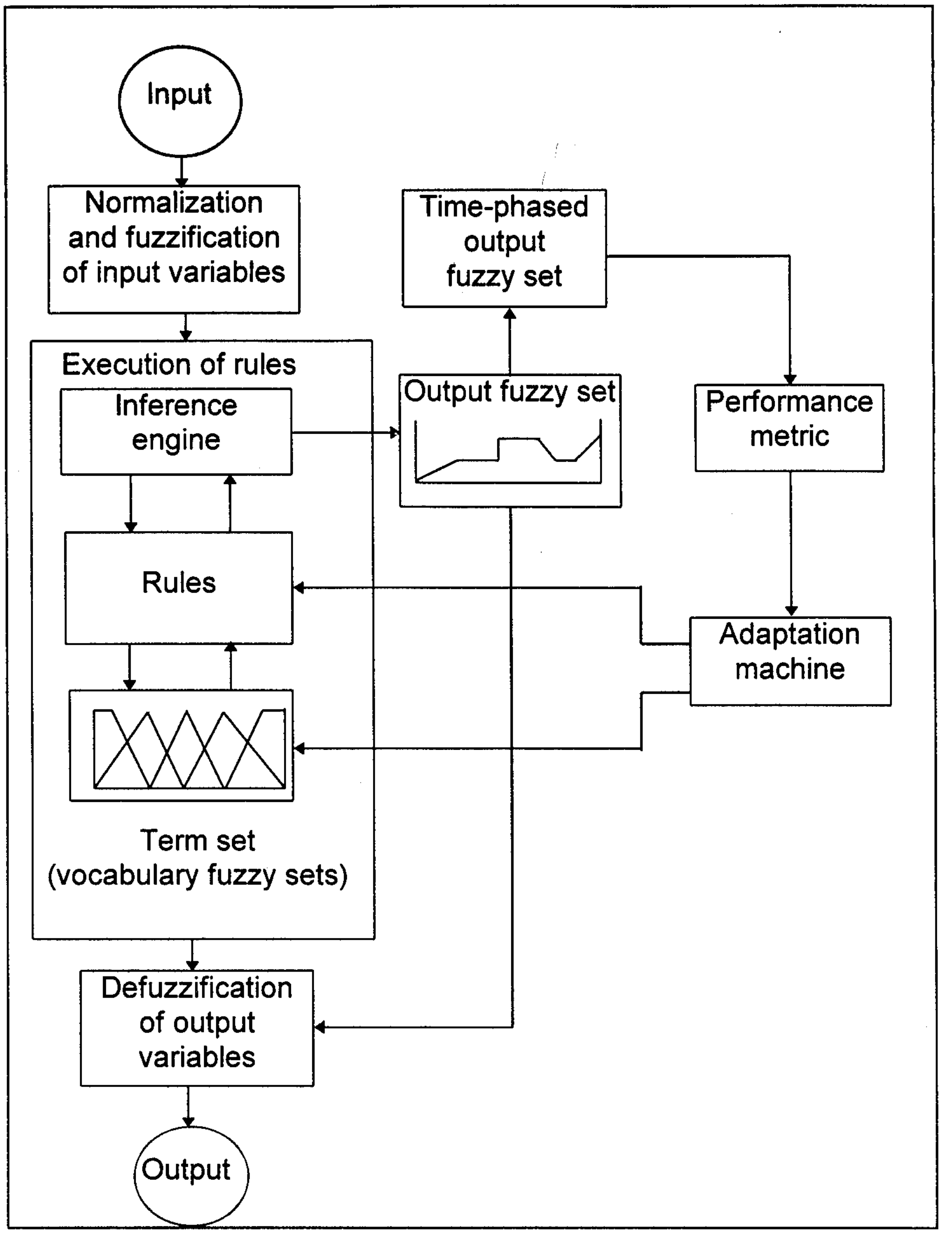


Figure 2-10: Adaptive Fuzzy Controller (Terano, Asai and Sugeno 1992)

As shown above the adaptive controller first performs a conventional fuzzy inference. The output of the inference is stored in a time-phased output buffer where they can be accessed. To produce a feedback signal to the fuzzy model a performance metric, usually an expert system or an algorithm that measures the change between sensor measurements sends a signal to the adaptation machine which decides which changes to make to the underlying fuzzy model.

2.16 The Steam Engine

Ebrahim Mamdani of London University in 1973 was perhaps the first to compare the characteristics of conventional control to that of a fuzzy controller. The object of the control was a steam engine. As the output or load on the engine increases inlet valves to the engine are opened to increase steam flow into the engine. The resulting increasing steam flow causes pressure to decrease. To control the engine and meet the new load demand, steam pressure must be increased. The fuzzy controller utilized in the experiments was just a simple fuzzy controller as described earlier, and the plot below depicts the performance characteristics of both controllers in the situation just described.

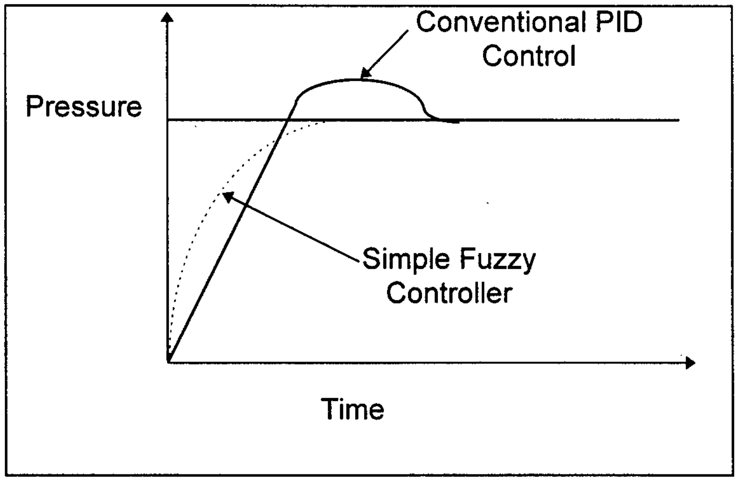


Figure 2-11: Steam Engine Control (Mamdani and Assilian 1975)

As the plot shows the fuzzy controller is more responsive and does not overshoot the pressure setpoint as the conventional controller does. Mamdani also varied some of the fuzzy rules and input sets and found that the system was very forgiving to an erroneous parameter, meaning that it is less sensitive to computational or programming errors than the conventional controller.

2.17 Conclusion

Through this discussion of fuzzy sets, crisp sets, fuzzy logic, FLCs and general controller design a number of distinct advantages of FLCs over conventional controls were discovered. These advantages are:

1. Easier to implement
2. Fewer instructions required
3. Insensitive to errors
4. Time responsive
5. No overshoot
6. Adaptive
7. Can model complex, non-linear processes using linguistic variables.

After discussing the state of today's electronic control technology in construction equipment, this information is used to qualitatively create a decision matrix to describe if these controllers are potentially beneficial for construction equipment.

Chapter 3 - Current Benchmark vs. Fuzzy Controller

3.0 Introduction

A review of manufacturers' brochures and other pertinent publications allows us to determine the time frame associated with the advent of electronic control. Each piece of equipment studied has varying degrees of electronic control and monitoring and their implementation timeframes were also different. However, it is clearly evident that this trend has been slow, with some equipment having only monitoring systems, even though electronics have been used heavily in the automobile industry for 20 years. The hydraulic excavator is the piece of equipment that has taken the most advantage of electronic control. As the starting point for our decision matrix on the adaptability of fuzzy controllers to the construction equipment segment of the construction industry it is first important to quantify the current usage of electronics for each piece of earthwork equipment. Then lastly, a fuzzy logic controller is adapted to the hydraulic excavator to demonstrate some of the advantages of this technology.

3.1 Dozers

There are currently 10 manufacturers of crawler dozers, supporting 123 models (Const. Equip. 1994). Dozers today range from 67 horsepower to the Guinness Book of World Records 1050 Horsepower dozer from Komatsu. In 1976 manufacturers recognized the need for easier shifting, both to reduce operator effort, but also to increase productivity. The power shift transmission became the norm. Basically powershift transmissions still involve the operator shifting, but a clutch is not necessary. At almost the same time both John Deere and Komatsu developed hydrostatic drive and torqueflow respectively. Both these transmissions use hydraulics, instead of mechanical clutch plates to shift engine torque. The end result with power shift or hydrostatic drive was to make shifting easier for the operator, unfortunately they are mechanically inefficient. Presently no dozer transmissions take advantage of electronic shifting capability. However, new for 1996, John Deere has introduced an engine monitoring system with the ability to maintain engine speed and provide a 12% power boost during backing operations.

After becoming standard in the late 1950s, hydraulic control of the blade has continued to improve. The volume of huge earthmoving projects in which the dozer plays a key role has been reduced, perhaps permanently. Manufacturers are working to adapt the dozer to a new role. Precision blade control, enhanced by pilot hydraulic valves introduced in 1981, has increased the usage of 6-way blade control which was developed around 1987. This enables the use of the dozer for its fine grading capability.

The dozer currently utilizes little, if any microcomputer controls. Caterpillar has recently begun to use diagnostic and monitoring systems that are basically an onboard computer that monitors various engine and hydraulic system parameters. The mechanic can then plug into the computer to track machine performance and trends that may denote problems with the machine.

3.2 Graders

Graders arguably have the longest usable life of any type of earthwork equipment. This is due to the constant maintenance necessary to keep the machine in top notch condition, which is imperative for it to complete its function. Grader operators very much resist new devices that hinder the "feel" of their work. As a result innovation is very slow. There are currently 11 manufacturers supporting 69 models of graders (Const. Equip. 1994). The articulated frame grader predominates, with 50 of those models. Grader size ranges from 35 hp to 210 hp and reach speeds up to 28 mph. While not yet heavily microcomputer controlled the grader does have gauges, monitors and an alarm system. Due to the number of levers in the machine, ease of operability is important and low effort levers are the resultant solution. John Deere has introduced electronically controlled four-wheel drive, but it has not caught on with the construction industry.

3.3 Front End Loader (FEL)

Front end loaders, especially the larger models, are expected to be operated 8-12 hours a day. This has driven manufacturers to address operator comforts as well as productivity and maintenance enhancing features. There are at present 23 manufacturers of 153 modes of FELs (Const. Equip. 1994). They range in size from 30 hp to 600 hp. Recently joystick controls were introduced on certain models. This is an effort to reduce operator fatigue from battling the steering wheel eight hours a day. Additionally, much like the dozer, easier transmissions have been developed, such as powershift and hydrostatic that require less operator effort. Single lever hydraulic control of bucket functions also reduces operator fatigue. Separated steering and hydraulic bucket functions increase safely by better ensuring the operator has control of the machine. Large models may have a ride control feature that automatically assist the operator in keeping the bucket level when filled during transit.

As early as 1981 microcomputer monitoring systems were available for power train pressures and temperatures. VolvoBM introduced an electromagnetically microcomputer controlled powershift transmission in 1987 that reduces jerk when shifting. Caterpillar in 1995 introduced a payload measurement system for the operator to use to maximize productivity.

3.4 Scrapers

There are only 4 manufacturers of scrapers, supporting 23 models (Const. Equip. 1994). 11 of those models are open bowl. They are manufactured with single and duel engines, ranging from 175 hp to 550/400 hp. Due to the demise of heavy earthwork projects in the U.S., smaller, more versatile scrapers are becoming the focus. Microcomputer controlled monitor and alarm systems for many engine and hydraulic functions became industry norm in 1987. Powershift transmissions were standard in 1981 and John Deere at the same time introduced microprocessor controlled transmissions to ensure maximum fuel efficiency.

3.5 Hydraulic Excavators

There are currently 27 manufacturers of hydraulic excavators making 259 models (Const. Equip. 1994). The systems have varying bucket sizes and operating pressures range from 2000# to 4500#. There are two manufacturers of telescopic excavators, Gradall and Badger. From 1987 to 1991 the number of excavators working in the U.S. went from 46,100 to 74,550, an increase of 62% (Stewart 1993). The hydraulic excavator is on its way to replacing the backhoe/loader as the first piece of equipment a new construction firm tries to purchase. The excavator is the only piece of earthwork equipment that has truly taken advantage of the microcomputer.

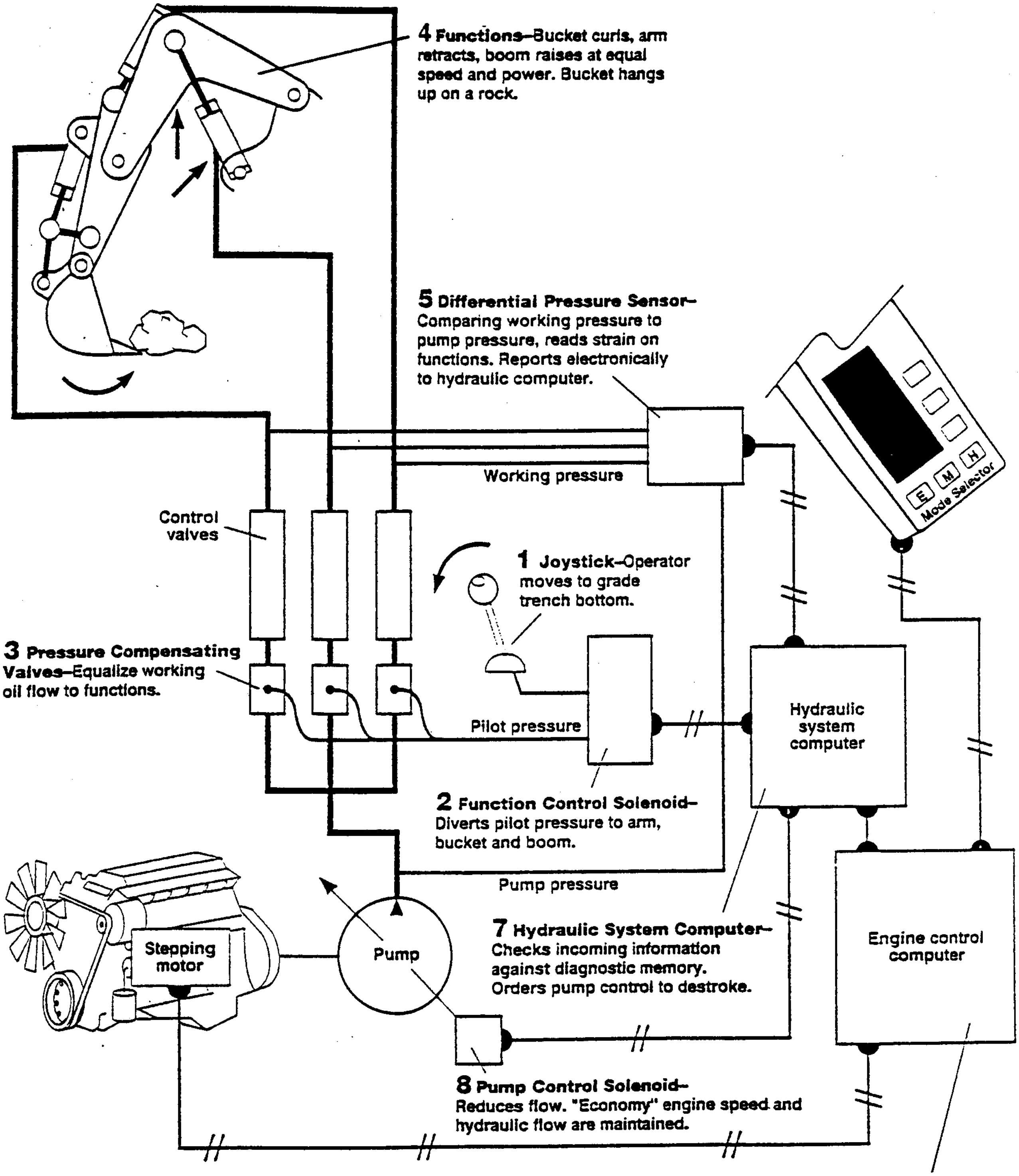
3.5.1 On-board Electronics

Few new excavators are built today without some type of electronic monitoring and sensing systems. This system performs two functions

1. Coordinates engine speed and hydraulic output to provide just the right amount of power.
2. Monitors various components and systems, providing alarms and reminders that something may be wrong with the machine.

Most new systems have work selection modes from which the operators can choose. Common examples are heavy-duty, standard and light duty. Some also have the deceleration function which automatically reduces engine speed when the machine is idle for a given period of time and a power up feature that allows the operator to activate an extra power burst.

To truly bring the excavator into the computer age two computers were needed. One for the hydraulic system, the other for engine control. Electronic sensors, instead of pilot hydraulic sensors are more accurate and the resulting electrical adjustments are faster. Being able to match pump output to load not only smoothes the machines movements and improves control of delicate operations, but also reduces horsepower requirements. Figure 3-1 illustrates how this two computer system works.



4 Functions—Bucket curls, arm retracts, boom raises at equal speed and power. Bucket hangs up on a rock.

5 Differential Pressure Sensor—Comparing working pressure to pump pressure, reads strain on functions. Reports electronically to hydraulic computer.

1 Joystick—Operator moves to grade trench bottom.

3 Pressure Compensating Valves—Equalize working oil flow to functions.

2 Function Control Solenoid—Diverts pilot pressure to arm, bucket and boom.

7 Hydraulic System Computer—Checks incoming information against diagnostic memory. Orders pump control to destroke.

8 Pump Control Solenoid—Reduces flow. "Economy" engine speed and hydraulic flow are maintained.

9 Function speed drops off as the flow decreases, but the load won't stall the engine. System working pressure never drops. Which means the functions will slow down, but if the excavator is powerful enough, it will eventually crowd the rock out of the trench.

6 Engine Control Computer—Notes drop in engine speed as stalled functions increase load on the pump and flywheel. Reports change to hydraulic computer.

Figure 3-1: Excavator Conventional Electronic Control (Stewart 1993)

3.5.2 Conventional System Operation

It is important to the discussion to understand the sequence of operations of the system shown in figure 3-1. The operator controls bucket and/or arm functions using a joystick as in step 1. IN step 2 a function control solenoid diverts hydraulic pressure to create the forces to make the arm and bucket movements desired by the operator. The hydraulic fluid is then equalized in step 3 by pressure compensating valves to equalize working pressures between each of the moving parts, this step helps ensure smooth rather than jerky motion of the excavator. In step 4 the bucket encounters a rock. This causes additional force against the bucket that is felt as strain in the hydraulic lines controlling the bucket. As the diagram indicates, in step 5 the electronic differential pressure sensor recognizes the strain and a signal is sent to the hydraulic system computer. At the same time the engine control computer is able to sense the engine stalling as the load increased and it sends a signal to the hydraulic system computer. The hydraulic system computer compares the signal against a diagnostic memory and sends a new order to the hydraulic pump. The end result in this example is that the hydraulic pump is controlled such that flow is decreased. However, pressure remains the same and forcing the bucket to operate slower. The end result is that if the excavator is powerful enough, it will be able to lift the rock. The combination of the two computers insures that the excavator will not stall and the best hydraulic pump and engine speed are maintained. The system operates extremely well. As these systems have been developed excavator productivity's have increased by as much as 100% from the early 1980s (Stewart 1993).

3.5.3 A Fuzzy Controller for the Hydraulic Excavator

The question then is, can fuzzy controllers be used in lieu of the two computer control system pictured in figure 3-1? The answer is yes, and it will be shown that one fuzzy controller can replace the two computers and can perform the same functions. Consider the two input, adaptive fuzzy controller shown in figure 3-2, with inputs being differential pressure from the same sensor as in figure 3-1 and engine speed from the same engine speed mechanism used in figure 3-1. The output as shown is to the hydraulic pump just as shown in figure 3-1.

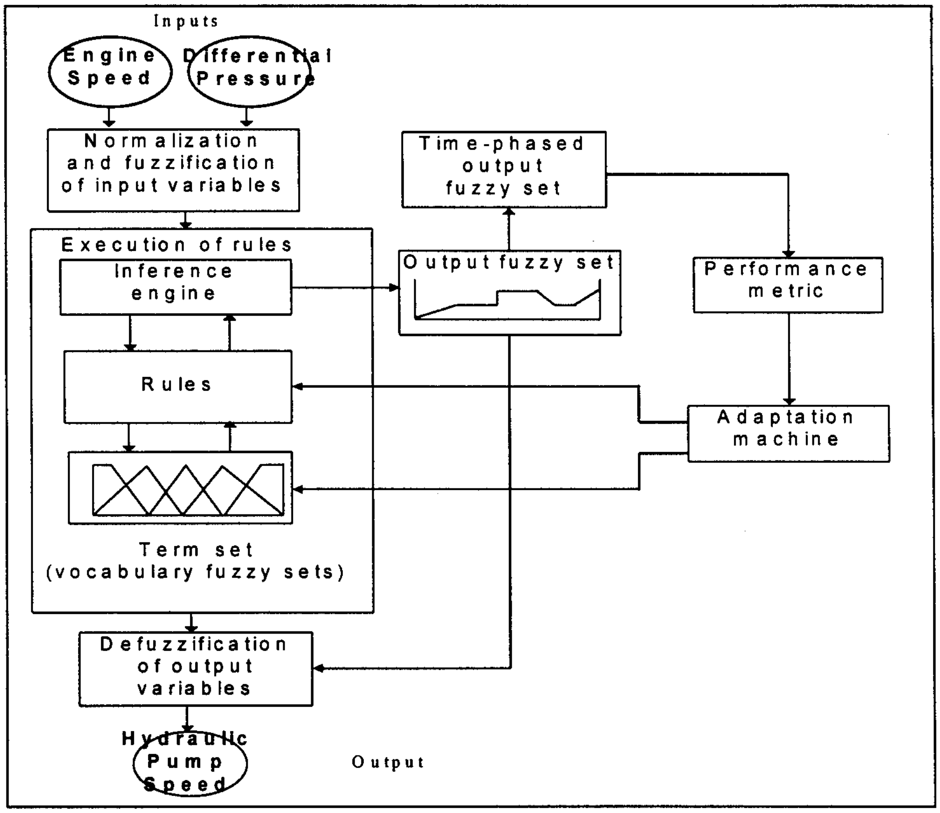


Figure 3-2: Adaptive Fuzzy Controller for Excavator (Terano, *et. al.*)

The continuous fuzzy set inputs and outputs for this controller are shown in figure 3-3.

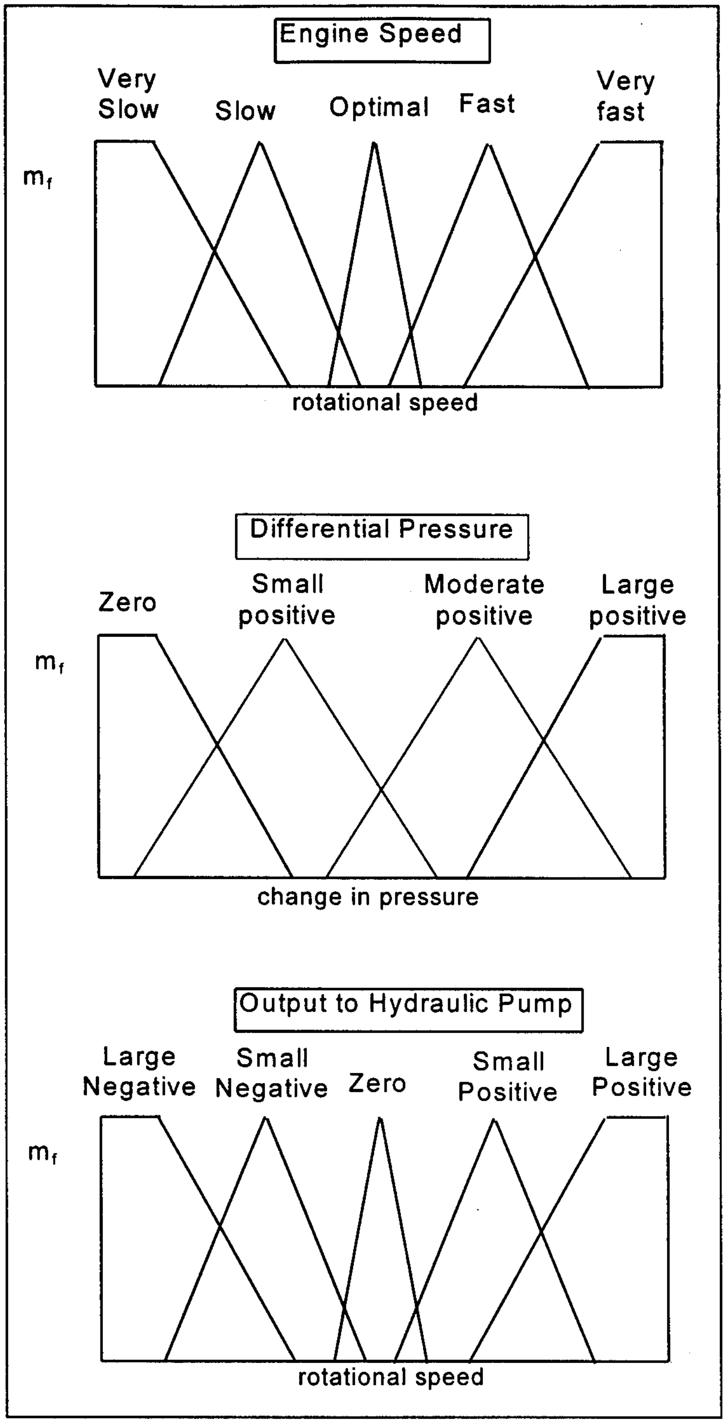


Figure 3-3: Fuzzy Inputs and Sets for Excavator

To put figure 3-3 into words we continue with the example of the excavator encountering a rock. The engine speed will decrease to very slow and the differential pressure will be zero or small positive, the control action then corresponds to large positive or perhaps small positive throttle position designating a large or small reduction in the speed of the hydraulic pump.

The adaptive feature of the controller can be implemented with the mode selector switch as in Figure 3-1 or the control system can be made totally adaptive on its own, meaning that the operator does not need to recognize the optimum mode to operate in under the given conditions on the job site. This incorporation is done using a simple weighting algorithm which the block diagram in figure 3-2 denotes as the performance metric.

Recall that the systems in use today compare the inputs to a diagnostic data base in the two computers. Obviously a continuous type function such as those shown in Figure 3-3 would provide more fluid, exact control of the excavator. The end result would be a machine always operating in the optimum range for the hydraulic and engine systems. This, of course, increases fuel efficiency and productivity. A similar system used to control automatic transmissions in cars delivers a fuel savings of 12-17%.

3.6 Conclusion

The benchmark of today's electronic control technology reveals that with the exception of the hydraulic excavator and to some extent the FEL there is little electronic control being used to actively control working functions of the machine. The reason for this lack of electronic control usage seems to be primarily driven by the market place...they haven't asked for it. Also, to a certain extent the processes that these machines are used in are complex and ever-changing, so conventional controllers are difficult to model and implement. As mentioned in chapter 2, fuzzy controllers can overcome these complexities. Finally, the hydraulic excavator is used as an example of how a fuzzy controller can be used. In this example a fuzzy adaptive controller replaces the two computers commonly used to control a hydraulic excavator. In the area of transmissions fuzzy logic has made in-roads in the car manufacturing industry and this is an obvious application of FLCs for each type of equipment studied here. Another application for construction equipment is FLC control of steering, braking and suspension functions. This area is just beginning to emerge within the car manufacturing industry and research has shown benefits in terms of reducing roll-over and excessive braking into turns. There is an obvious application to construction equipment that has safety and productivity implications. Each of these areas are investigated as a decision matrix, presented in the next chapter, which can be used to qualitatively determine the effect of the advent of FLCs on construction equipment.

CHAPTER 4 - DECISION MATRIX

4.0 Introduction

Before launching into lengthy and costly research it is imperative to know and understand what benefits fuzzy logic controllers could provide for earthwork equipment. With that in mind a decision matrix has been developed that qualitatively shows the expected effect of fuzzy logic controllers in a number of important areas. The decision matrix is shown in its entirety at the end of this chapter. Each area of concern is defined in the following sections and examples of applicable current fuzzy logic controller (FLC) technology and their benefits are discussed. These fuzzy controller technologies are used to form the basis of the decision matrix. As a summation aid, each decision matrix factor and the appropriate fuzzy logic controller technology identified as supporting this factor are listed in a table at the end of the chapter.

4.1 Maintainability

Maintainability refers to the on-site mechanics ability to diagnose, repair and maintain equipment using fuzzy logic controllers. This is a concern due to the increasing inability of today's mechanics to be able to diagnose and repair the electronic systems onboard today's construction equipment. Basically, coupled with a shortage of construction equipment mechanics, training in the often-proprietary electronic systems is not conducted, reducing the possibility that a construction mechanic will be able to diagnose and repair an electronic component. Today's equipment managers are being forced to rely on vender and specialty repair firms to perform these repairs. The industry is experiencing rising repair costs due to requiring specialty repair of electronic components (Stewart 1993).

4.1.1 Fuzzy Control versus Conventional Control Systems.

Recall the steam engine plot in chapter 2, Figure 2-11. Today's conventional controllers follow the pattern of overshooting the set point and then asymptotically approaching the set point. At times these controllers must hunt, meaning that they will successively overshoot and undershoot, as shown in Figure 4- 1 below.

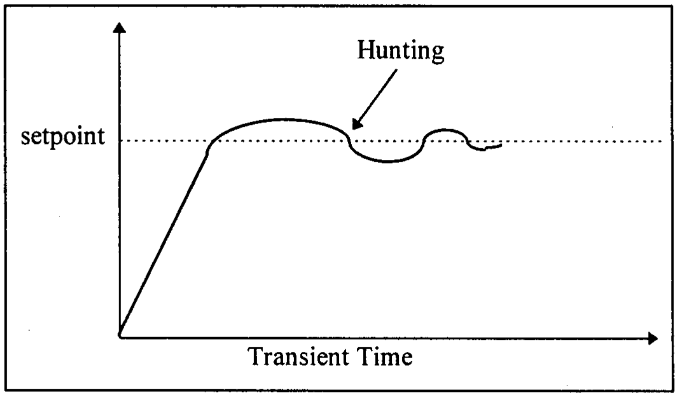


Figure 4-1: Conventional Controller Hunting

Imagine a hydraulic system operating at 3000 psi, the pressure variations at this pressure will create large cyclic stresses and strains in various components. Typically, hoses and fittings develop leaks that must be repaired. A FLC however, limits this hunting and will reduce cyclic stresses on hydraulic components. This is a positive effect on maintainability.

4.1.2 Affected Components

For engine components, transmissions, driveline, speed control units and units such as suspension systems, FLCs can provide the same steady control. This again reduces wear and tear on these components, increasing maintainability of the overall piece of equipment. Therefore each piece of equipment is studied with the effect of these factors on the overall maintainability of the unit.

4.2 Reliability

The reliability of construction equipment is an ongoing concern for construction firms. If new technology is to be used it must be highly reliable, meaning that with the exception of routine maintenance the machine will always be fully operational. This is an even greater concern today when equipment such as the hydraulic excavator and the front end loader are routinely expected to operate 8-10 hours a day. The reliability in question here is for the FLC controller itself. In the mid-to-late 1970's when electronic components began to become prevalent in cars their reliability was suspect, and rightly so at that time. Today's electronic components have proven themselves to be reliable under very arduous operating parameters. The same must be true for FLCs to be used. Therefore this category focuses on the reliability of the FLC.

4.2.1 Robustness of Fuzzy Logic Controllers

A subfactor in regards to controller reliability is the "robustness" of the controller. Controller robustness refers to how much the physical parameters in the control system can be changed. If a controller is to be considered "robust", it must still function adequately over widely varying system physical parameters. The classic example is the problem of balancing a stick of a given mass on top of an object such as a car hood, as shown below.

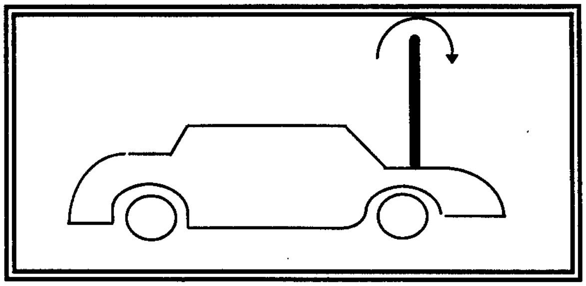


Figure 4-2: Stick Balancing Example (Lee 1990)

As the car accelerates the stick is subjected to forces to keep it upright on the car hood. This problem is easily solvable with conventional control or fuzzy logic control. However, with a conventional controller as soon as the mass or length of the rod varies, the solution, usually an eigenvalue/eigen function solution, is no longer valid. With fuzzy controllers however, the mass and length of the rod can be varied and the input fuzzy sets changed accordingly and the same fuzzy rule set provides an acceptable solution. This is an example of robustness (Bezdek 1993). This robustness helps the fuzzy logic controller in two ways: fewer lines of code are required, and less expensive microprocessors can be used.

4.2.2 <u>Faulty Fuzzy Sets and Rules</u>

Another factor of concern with fuzzy controllers, as well as conventional controllers, is how the controller reacts when lines of code become jumbled or, in the case of a fuzzy logic controller the parts of a fuzzy set become transposed. Mamdani (1973) in his famous steam engine control experiment varied inputs and transposed fuzzy set values. He found that due to the rule making structure and the defuzzification procedure and inference procedures, a fuzzy controller still provides acceptable control actions in these cases.

Hamaifar and McCormick (1995) noted that for the influence of faulty rules "in many instances, the rules surrounding a bad rule can override it when the output calculation is performed." Gurocak and de Sam Lazono (1995) felt it was apparent during their experiments that the dependability of the results obtained by the fuzzy system were excellent. In fact the 48 rule system achieved better results then the initial intention of the design.

4.3 Safety

While hard to quantify in terms of expense, safety is always an issue in construction. FLCs use fuzzy logic, fuzzy inference and defuzzification, which are new terms, and terms that imply less than exact control. For this issue FLCs are investigated from two points of view: can their outputs be trusted to provide the appropriate control (related to reliability), and are the operating characteristics of construction equipment using fuzzy controllers safer than machines using conventional controllers.

In general the issue of whether the fuzzy controller can provide safe outputs is again supported by Mamdani (1973) and the discussion noted above. So it can be assured that using FLC systems will not cause machines to provide potentially damaging outputs (as an example Audi 5000 cars with runaway transmissions of the early 1990's).

Beyond this issue however, we must look at the operating characteristics of machines using fuzzy controllers and determine whether fuzzy controllers are potentially safer than conventional machines. Below are examples of fuzzy logic controller research related to improving safety.

4.3.1 Transmissions

Tanaka and Wada (1995) investigated and experimented with fuzzy control of manual Transmissions. In this example FLC was applied to a 6-speed manual commercial vehicle transmission, similar to the type of transmissions used today on many machines. There are usually six factors important to successful clutch engagement.

1. Without engine stall
2. With minimum shock at the engage-start point
3. With minimum moving back for uphill start without assisting brake
4. With reflecting drivers will for quick or slow start
5. With reliable inching motion for riding over a barrier.

It is instantly recognizable that each of these factors above are safety related as well as performance related. Therefore a controller that performs these items better than current technology would increase the safe operation of the machine.

The controller used by Tanaka and Wada only utilized three inputs, accelerator pedal depression, engine rotational speed and clutch lever position. The fuzzy controller was tested on a 6-speed hydrostatic transmission and found to limit backward motion on a slope from 30 cm. to 2 cm. and reduce starting lag time by 65%. Starting lag time is the time from accelerator depression to throttle opening and vehicle movement. One only has to be on a jobsite for a few minutes to recognize that construction equipment operation is jerky, this is the result of starting lag time. These results are significant in that on the construction site, particularly smaller tightly spaced sites, the operator needs his equipment to respond to the accelerator accurately. Therefore this fuzzy controlled transmission has the potential to be a positive factor in improving jobsite safety.

4.3.2 Speed Control

Murakami (1983) applied a fuzzy controller to automobile speed control. This application may seem limited in this type of construction equipment, but it serves as an example of what a steady speed controller can accomplish. For FEL's or scrapers with long haul distances a speed controller might be useful in limiting operator fatigue over the course of a long day. This controller utilized just 4K ROM and 16K RAM and two inputs. The important implication from this controller was the absence of overshoot as the controller operated under various load conditions during actual road tests. As a mechanism to improve operator comfort and safety this type of control offers some promise.

4.3.3 Automatic Transmissions

Bastian (1995) studied the effects of fuzzy logic on automatic transmissions and their effect on operating characteristics such as breaking frequency and gear shifting. The system studied utilized the following inputs.

Driver's Intention	Vehicle's State
throttle opening (TO)	speed
rate of change in TO	acceleration
speed reduction due to braking	speed change
Road Condition	surplus engine torque
gradient resistance	lateral acceleration
winding rate of the road	steering wheel angle

Table 4-1: Automatic Transmission Fuzzy Inputs (Bastain 1995)

The researchers studied expert driver actions to write the fuzzy rules and construct fuzzy sets. The end result showed that the fuzzy system was able to:

1. Decrease the frequency of gear shifting and accelerator pedal depression on uphill winding roads
2. Decrease braking going downhill.

The impact to safety here involves less braking system wear and tear, reducing the chance of brake failure.

4.3.4 Project Trilby

Project Trilby (Schilke *et. al*. 1988) was a study focused on integrating man and the car. Specifically the research group was tasked to propose how today's cars would be different if microprocessors had been developed first, before the car. A pertinent result of the study was that coordination of braking and steering provides a number of benefits.

1. Improved path tracking
2. Shorter stopping distance
3. Improved robustness
4. Lower drive workload

5. Improved vehicle stability
6. Better utilization of the tire/road contact path

The system or method to employ this integration is fuzzy logic. Mitsubishi is in fact working on this integration today (Schilke, *et. al*. 1988).

4.3.5 Path Tracking

An example of improved path tracking is demonstrated by the figure below (Tanaka 1995).

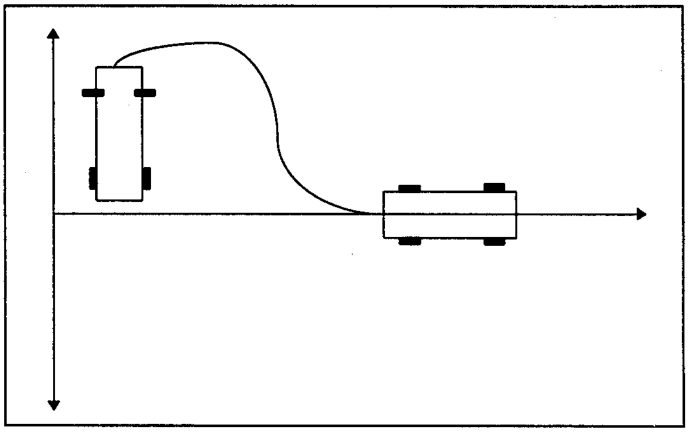


Figure 4-3: Path Tracking (Tanaka 1995)

The simulation showed that fuzzy control rules effectively realize trajectory stabilization of a model car along a given reference trajectory from all initial positions. This project supports the efforts of Project Trilby by demonstrating the better handling characteristics of a vehicle with integrated steering, braking and suspension systems.

4.4 Productivity

Productivity is always an issue with construction equipment. Even if FLC is safer, more reliable and increases maintainability, if FLCs do not increase or if they decrease productivity, then the industry will not use these controllers. At issue here are whether FLCs, due to their smoother control and more exact control nature, can increase productivity and whether the controller itself can make faster decisions than conventional controllers.

4.4.1 Examples

As a first example consider the fuzzy controlled manual transmission (Tanaka and Wada 1995) example previously discussed. While difficult to quantify, this transmission certainly would decrease operator fatigue which would increase productivity. The transmission control described by Tanaka and Wada also reduced starting lag time by 65%. This can be directly related to productivity as evidenced by reduced cycle times. Experiments would need to be performed to truly quantify the exact reduction in cycle times, but if a cycle time for a FEL includes accelerating from loading (8 sec) and accelerating from dumping (5 sec), then a 65% reduction would reduce the cycle time by 8.5 seconds. Over the course of a day this increase could be significant. If the machine also has speed control it would improve productivity by decreasing operator fatigue.

Tarng and Wang (1992) developed an adaptive fuzzy controller designed for steel cutting in the machine tool industry. The machine was found to respond to changing feed ratios of the material in 0.2 sec, while maintaining the constant turning force required in the cutting operation. The system also responded well to large turning force variations. The factor here that can be applied to earthmoving equipment is that faster response times were achievable with a fuzzy controller over conventional control.

4.5 Utilize Less Skilled Operators

A current issue in the entire construction industry is the lack of skilled labor, in regards to construction equipment the number of available operators has decreased, and aged considerably, in the past 15 years. Controllers that can enable unskilled operators to be productive will undoubtedly be accepted by the industry.

4.5.1 Results from Previous Examples

We have already looked at transmissions and speed control and stated that fuzzy controlled equipment would operate smoother and require less shifting and braking. This in itself would help less skilled operators by freeing them from worrying about speed and shifting. The less skilled operator can concentrate on the load and maximize bucket fill, blade push, etc.

4.5.2 Specific Productivity Examples

Fuzzy controllers on hydraulic systems can provide smoother operating characteristics which lends itself to helping less skilled operators to do precise tasks, such as trenching. As an example, the Automatic Train Operation in Sendia Japan (Hirota 1993) is related to the operation of a backhoe. The train is controlled by the notch setting of a speed controller, analogous to the joystick of an excavator. The system is constantly comparing notch position to the stopping point. Before installation the fuzzy control system for the trains was compared to conventional PID control and was found to reduce energy use by 10%, and most importantly for this discussion the average stop error was just 3.57 cm. This indication of precise control suggests that for fine work fuzzy controllers can enhance the skills of an inexperienced operator.

Another example is the Container Crane System (Hirota 1993). Here a container crane (overhead gantry type) must pick up a container from a ship and move the container to its place on the pier. The fuzzy system performs the task in 47 seconds while the human operator took 51.7 seconds. Also the fuzzy system was able to stop plus-or-minus 5 cm from the stop point versus plus-or-minus 10 cm for the human operator, and swing during travel was limited to 5.8 cm versus 10.8 centimeters. Again this example demonstrates that fuzzy controllers may be able to improve the accuracy of less skilled operators.

4.5.3 Fuzzy State Controller

A fuzzy state controller is simply a fuzzy controller set to maintain a certain system state. Obvious examples or applications to construction equipment include, scraper blade cut, grader blade cut and inclination and dozer blade orientation. Zhoe and Virvalo (1995) performed experiments on hydraulic position servo systems controlled by fuzzy state controllers. The controllers were found to be robust and were able to maintain position with an error less than 0.2 mm. The implication here is that this fuzzy state controller can be used to maintain constant cuts, depths, force, etc. a fuzzy state controller is complex to formulate, but virtually impossible with conventional control. The system is applied to a hydraulic piston type arrangement below, with the membership functions shown as a function of the distance of travel of the piston.

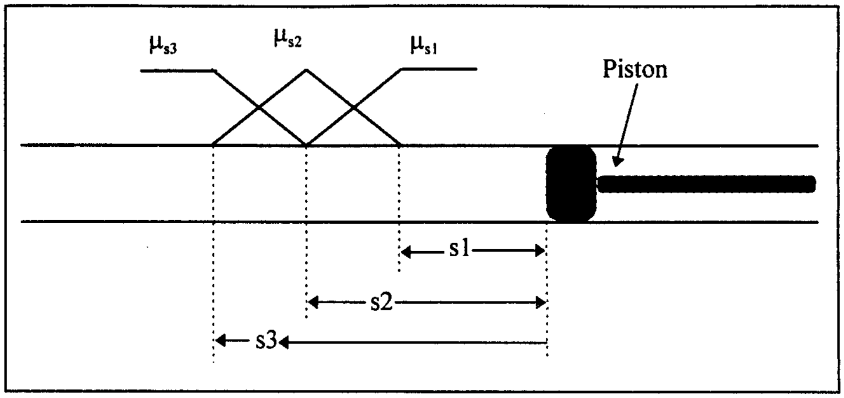


Figure 4-4: Fuzzy State Controller (Zhoe and Virvalo 1995)

4.5.4 Traffic Controller

A classic example of fuzzy logic providing a better solution was performed by Pappas and Mamdani in 1977. The focus of this study was the delay caused by a conventional traffic controller versus a fuzzy logic one. The fuzzy controller designed for this application was designed for random data inputs of number of cars per hour in two directions. As shown in the table below, the average overall delay per vehicle was found. These findings are applicable to construction equipment as a demonstration of the versatility of the fuzzy controller, and its ability to accept widely varying inputs yet still provide a solution. Imagine a less skilled operator versus a skilled operator. The less skilled operator is likely to make numerous adjustment to the controls, many more than the skilled operator would, the concern then would be how a fuzzy system would react to random inputs. Since the fuzzy system reacts faster the less skilled operator would be more likely to see the effect of his control action sooner and have additional time to make corrections. Specifically, this reveals that the previous concern of how an inexperienced operator would interact with an FLC is not a concern.

N -S traffic	E - W traffic	average overall delay (sec/veh)		Improvement (%)
		Vehicle-actuated controller	Fuzzy-logic controller	
360	360	7.2	5.7	+21
360	720	7.4	6.1	+18
360	1080	7.9	6.6	+17
360	1440	8.4	7.3	+13
360	1800	9.3	8.4	+10
360	2160	12.3	10.0	+19
360	2520	15.8	13.6	+14
720	720	9.7	7.4	+21
720	1080	10.8	8.8	+19
720	1440	12.7	10.9	+14
720	1800	15.9	14.1	+11
720	2160	21.8	18.5	+15
1080	1080	13.6	12.0	+12
1080	1440	17.9	15.4	+14
1080	1800	25.8	21.6	+16
1440	1440	27.3	22.9	+16

Table 4-2: Traffic Light Data Input/Output (Pappas and Mamdani 1977)

As stated, this example is for improvement of traffic flow using a fuzzy controller. On average the fuzzy controller was 15.6% more efficient than conventional control at reducing traffic delays. In this particular application, the stability of the system was defined as the condition of the system not getting saturated if subjected to a wider range of flow rates (Pappas and Mamdani 1977). As the data indicated the system remained consistent over a wide range of values.

4.5.5 Fuzzy Speed

Will Schrieber (Schofield 1995), senior program manager at Intel's Embedded Microcontroller Division indicates "going with fuzzy logic...might give a 10% performance boost." The fact here is that fuzzy controllers can make faster decisions than conventional control, improving productivity and helping less skilled operators perform more effectively.

4.6 First Cost

Equipment has become progressively more expensive, particularly with the advent of electronic controls. If FLCs drastically increase first cost then constructors will not accept the technology unless the productivity gains, reduced life-cycle costs, and other positive attributes outweigh this first cost. At issue then is the cost of FLC control versus today's electronic controllers.

4.6.1 Examples

The results of much research points to the fact that fuzzy controllers require less expensive hardware and implementation is less time consuming. For example, recall the hydraulic excavator example from chapter 3. In that example two microprocessors were replaced with 1 fuzzy controller.

Bartos (1995) relates the following fuzzy controller implementation case histories. American Ref-Fuel Company, Niagara Falls, NY, used fuzzy logic to solve a vexing pH control problem at a cogeneration plant. The senior instrumentation/control engineer with little fuzzy experience implemented the project in two weeks. Hochtief Corp., a major German construction company installed an anti-sway fuzzy logic controller on an overhead gantry crane used to transport 54,000 kg prestressed concrete parts. The strategy took two weeks. Productivity increased by 20% and a ground handler was eliminated. Another positive feature was resultant safety increase due to no loss time accidents from the tag line handler looking up as they walked. German Aerospace's automatic tunnel/sewage pipe inspection robots needed a control solution to ensure that constant tension was maintained on its control lines. The fuzzy logic solution required three months.

4.6.2 Sensors

First cost can also be reduced because fuzzy logic inference is frequently achieved using fewer, less expensive sensors. Note how each of the systems described usually involve only two or three inputs. This is due in part to the fact that fuzzy logic accommodates imprecision and uncertainty well (Smith 1994). Fewer sensors also means there are fewer parts to service and repair.

4.6.3 Fuzzy Rule Writing

The modeling of the system and writing of the rules for a fuzzy logic controller is less complicated and time consuming. Examples of the short implementation time were given above. This means that companies can decrease the product prototyping and development time. Matsushita's first fuzzy logic washer went from a design to a product in one year. Rockwell International Corp. applied fuzzy logic to the control of engine idling in a time interval that was on order of magnitude less than it took via conventional means (Smith 1994).

4.6.4 Hardware Requirements

Fuzzy logic control systems also enable inexpensive implementation of the technology, in terms of microprocessor and memory requirements (Smith 1994). A general rule is that fuzzy control enables a 10:1 reduction in memory requirements. The fuzzy washer mentioned earlier uses a traditional 4-bit microprocessor. The Sanyo Fisher USA Corp. used fuzzy logic in a video camera due in part because using conventional approaches would force a switch to a larger more expensive microprocessor (Smith 1994).

Schofield (1995) reports that there are U.S. customers doing great things with fuzzy logic, "one company implemented a control algorithm in fuzzy logic and was surprised at how compact and efficient the code was compared with previous C code. They went from using a 16-bit microprocessor to using a far cheaper 8-bit microcontroller (Schofield 1995)."

4.6.5 Saturn Case History

General Motors Corporation's SATURN division uses an automatic transmission fuzzy controller in many of its models. It reports the following benefits (Schofield 1995).

1. Accelerated research and development
2. Reduced time to market
3. Simpler solving of complex control problems

4. The ability to get more horsepower out of a given process.

4.7 Operating Costs

As with first costs, if FLCs drastically increase operating costs then any productivity gains and maintainability and reliability increases will be overshadowed. On the other hand drastically reduced operating costs might outweigh a small increase in first cost.

4.7.1 Transmission

The first and most obvious operating cost reduction for machines using fuzzy logic results from fuzzy controlled transmissions. A deterministic transmission is set to shift at certain torque settings. This method is satisfactory until the unit must operate on hilly terrain. Specifically, a deterministic transmission shift schedule gives rise to a hunting problem which results in excessive gear shifts and fuel consumption. Figure 4-3 is an example of this problem.

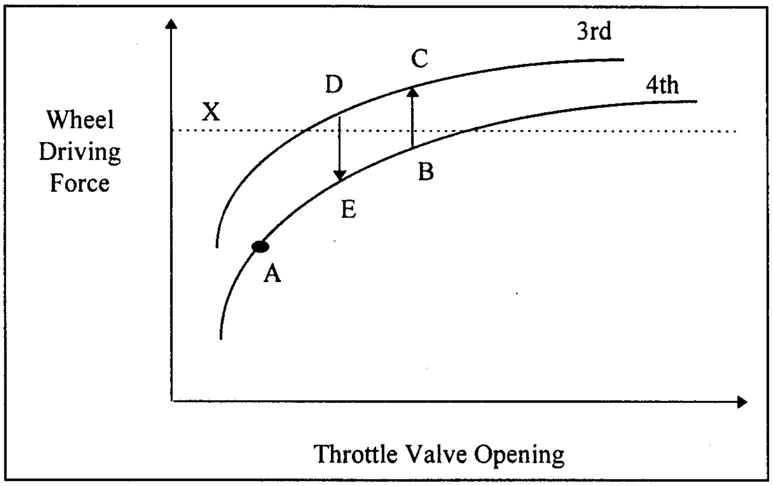


Figure 4-5: Transmission Hunting (Yamaguchi *et. al.* 1993)

The figure (Yamaguchi, Narita, Takahashi and Katou 1993) shows a vehicle operating in 4th gear at position A. Torque increases due to a gradient increase so the operator increases throttle valve opening and moves to point B. At this point the transmission shifts down to the next lower gear where the torque is higher, indicated by point C. Now the torque is too high, the operator closes the throttle valve opening and the operating point moves to D and then on to E as the transmission upshifts. Many transmissions today have an overdrive cancellation switch to limit this hunting if the operator remembers to use it. This type of hunting can be resolved if running resistance can be measured and input into a fuzzy controller. Engine speed can be the measure of running resistance.

The fuzzy reasoning program for this transmission was configured on a 8-bit microcomputer and installed in an experimental vehicle. During the actual testing the hunting problem disappeared and it was easier to maintain vehicle speed. The end result is fuel savings. Nissan now utilizes this same controller on its larger cars sold in the U.S. with a fuel savings of 12-17% (Bedzek 1992).

4.7.2 Energy Savings

The energy savings from using fuzzy controllers is well evidenced throughout literature. Recall that for the Sendai Automatic Train Operation the energy savings was 10%. Kirkwood Commutator (Bartos 1995) a maker of electrical insulators for high voltage applications, installed fuzzy controllers on its ovens in Cleveland, Ohio and the energy savings resulting from the finer control action was 23%. Mitsubishi Heavy Industries Ltd. reprogrammed an existing 8-bit microcontroller-based control system for an air conditioner and doubled temperature stability while reducing power consumption by 20% (Smith 1994).

4.8 Summary of Decision Matrix

The discussion of each decision matrix category included reference to experience form both industry and academic research. Most of these examples cross boundaries, meaning they affect more than one decision category, i.e. productivity and safety. To sum up the factors involved in each decision matrix, each category is listed in the following table with a brief discussion of how it impacts that category. This table is used to formulate the final decision matrix and recommendations presented in chapter 5.

Summary Evaluation of Each Decision Matrix Category Factors

Maintainability	**Productivity**
Hydraulic System Components	**Manual Transmission**
+ reduce cyclic stresses	+ decreases operator fatigue
+ reduce fitting and hose breakage and maintenance	+ reduce cycle times
Automatic Transmissions	**Speed Control**
+ reduce use of brake system	+ decreases operator fatigue
+ reduce wear and tear on all drive train components	**Machine Tool Positioning**
+ reduce shifting and wear and tear on transmission components	+ fine control enhanced
	Fuzzy State Control
	+ maintain position
	+ maintain constant load

Reliability	**Utilize Less Skilled Operators**
Fuzzy Set Reliability + satisfactory performance with values interchanged **Fuzzy Rules** + interchanged rules and still retained good performance **Measured Results** + better than designed for	**Manual Transmission** + decreased shifting **Speed Control** + decrease shifting **Automatic Train Operation** + precise stopping **Container Crane Operation** + precise stopping **Fuzzy State Control** + maintain position + maintain constant load **Traffic Light Controller** + Accept random inputs with 15.6% better efficiency then conventional controller

Safety	First Cost
Fuzzy Rule Writing + ensured safe output **Manual Transmission** + reduced backroll from 30 to 2 cm + reduced starting lag time by 65% **Speed Control** + improved operator comfort **Automatic Transmission** + reduce braking + decrease shifting **Integrated Braking and Steering** + reduce rollover **Trajectory Stabilization** + reduce rollover	**System Modeling** + short implementation time **Sensors** + fewer required **Hardware** + inexpensive memory requirements + 10:1 reduction in memory requirements **Saturn** + reduced time to market and accelerated research

Operating Costs

Transmissions

+ shift more efficiently

Automatic Train Operation

+ 10% energy usage reduction

Furnace Control

+ 20% reduction

AC Control

+ 20% reduction

Table 4-3: Evaluation of Decision Matrix Category Factors

CHAPTER 5 - DECISION MATRIX RESULTS

5.0 Introduction

With the decision matrix factors evaluated it is now possible to make logical conclusions as to the effect FLCs could have for the dozer, FEL, hydraulic excavator, grader and scraper. This involves extrapolating the fuzzy applications discussed for each decision matrix factor from the table at the end of Chapter 4. More than a simple extrapolation, this is an important step because a logical decision as to the effect of using FLCs versus conventional controls must be completed before any R&D efforts begin. Since R&D efforts in the construction equipment manufacturing industry are usually proprietary, a company is not likely to pursue fuzzy logic controller R&D unless it is likely to prove profitable. Therefore using the decision matrix we propose to recommend or not recommend the development of FLCs for the equipment studied.

5.1 Dozer

Presently the most advanced dozers only include electronic monitoring systems. Therefore there is the potential for electronic control, both conventional and fuzzy logic.

5.1.1 Maintainability - **Unchanged**

In this decision factor the dozer's maintainability increases due to less wear and tear on brakes, transmissions, hydraulics, etc. Conventional electronic controls have tended to reduce maintainability, since electronic component repairs are done by specialty firms or dealers instead of on-site mechanics. Fuzzy controllers should be more reliable than conventional controllers, but they will still require maintenance that the normal construction firm cannot perform. So despite increased maintainability of mechanical systems the advent of electronic controls of any type decreases maintainability. Therefore for the dozer this decision factor probably offers no improvement from today's technology, since current FLC technology utilizes the same microchip technology as conventional controllers.

5.1.2 Reliability - **Increase**

Due to the inherent reliability of the FLC in terms of varied and erroneous inputs, bad rules, etc., usage of FLCs will increase reliability of these machines over machines utilizing conventional electronic control. Due to the limited electronic control being used today in dozers there is no baseline for comparison, however if FLCs are used vice conventional control reliability will increase.

5.1.3 Safety - **Increase**

FLCs offer the distinct probability of enhancing safe dozer operation above and beyond passive devices like back-up alarms and roll-over cages. Smoother transmissions which offer more responsive control and limited backroll can only ensure positive operator control, especially in tight working conditions. Also, the many applications that reduce operator fatigue can not be overlooked in terms of improving safety.

5.1.4 Productivity - **Increase**

The increase in dozer productivity is likely to be small, due to the speed and nature of dozer operation. As a result the positive productivity effects of FLC transmissions are not going to manifest themselves quite as strongly as with the other types of earthwork equipment. However, finer positioning control, especially in tight spots, increases productivity. Also, perhaps the most significant impact is in the area of state control. With state control the operator can maximize the effectiveness of each pass and minimize the number of passes required.

5.1.5 Utilize Less-Skilled Operators - **Yes**

The impact of FLCs is significantly positive in this area for all types of equipment. Decreased shifting, precise operation and stopping, state control and the FLC controller efficiency all enhance the less-skilled operator's productivity.

5.1.6 First Cost - **Increase**

Due to the minimal usage of electronic controls on dozers, fuzzy logic controllers as proposed here would increase first cost. A factor that would significantly effect first cost, other than the additional hardware, is that the conventional electronic control basis does not exist from which to easily transfer to fuzzy control. Subsequently, more R & D and longer product-to-market timeframes would be involved, again increasing first cost.

5.1.7 Operating Cost - **Decrease**

Fuzzy transmissions will reduce operating cost by reducing fuel consumption. Also, if the machine is more productive it will accumulate operating hours more slowly, reducing operating maintenance.

5.2 Front End Loader (FEL)

FELs are constructed with electronic monitoring systems and electronic transmissions and hydraulic systems. Next to the hydraulic excavator they are the most automated type of construction equipment.

5.2.1 Maintainability - **Increase**

Unlike the dozer, the FEL, due to its electronic controls and monitoring, already requires specialized maintenance practices. Therefore fuzzy controllers will not increase the maintainability in terms of electronic maintenance. However, smoother transmissions and hydraulic action will increase maintainability by reducing cyclic stresses. More important than with the dozer, reduced braking would certainly reduce brake repairs and maintenance as FELs frequently transverse slopes with and without loaded buckets.

5.2.2 Reliability - **Increase**

Due to the inherent reliability of the FLC in terms of varied and erroneous inputs, bad rules, etc., usage of FLCs will increase reliability of these machines as they replace conventional electronic control.

5.2.3 Safety - **Increase**

As with the dozer, FLCs offer positive safety increases and they are more than just a passive safety devices. Smoother transmission and more precise control inherently increase the safety of the machine. Reduced starting lag time and decreased backroll are two specific examples of safety increases that highly benefit the FEL. Integrated braking and steering is another area that has real promise, as does trajectory stabilization.

5.2.4. Productivity - **Increase**

Smoother operation, speed control, less braking and shifting has already been mentioned as a factor increasing productivity by reducing operator fatigue. This is particularly applicable for the FEL which is operated 8-10 hours a day. Even if these factors only reduced fatigue by 5% this would result in 24 additional minutes of productive work during an eight hour day. FLCs used as state controllers can be designed to increase bucket fill capacities which increase productivity. Reduced starting lag time has already been addressed as a productivity increase and depending on the conditions, cycle time, etc., could increase productivity by 5%.

5.2.5 Utilize Less-Skilled Operators - **Yes**

As with the other equipment, for the most part decreased shifting, better stopping, ect., all enhance the operation of this machine with less-skilled operators. Particularly with this machine fuzzy state control utilized such that bucket fill is maximized would immediately increase the productivity of a less skilled operator.

5.2.6 First Cost - **Lower**

As evidenced by the factors in the decision factor table, fuzzy logic controllers require less hardware and less expensive hardware, and programming costs are reduced. Since for the most part the systems described above are already on the machines as deterministic electronic controllers first cost with FLCs would be reduced.

5.2.7 Operating Cost - **Lower**

Without question the fuzzy transmission would increase the fuel efficiency of these machines. Due to the constant starting and stopping the savings would not be on the same magnitude of the Nissan figure of 17%, but may be closer to 8-10%, which is significant for a machine that operates as long, and daily as most FELs do.

5.3 Hydraulic Excavator

This machine is highly automated with conventional electronic control as described in chapter 3. However, there is room for improvement and this improvement is only possible through the use of fuzzy control.

5.3.1 Maintainability - **Increase**

As demonstrated in Chapter 3, the present electronic control of this machine can be accomplished with a single fuzzy adaptive controller vice two microprocessors. This reduces the electronic maintenance necessary. Some of today's largest excavators have hydraulic systems that operate in excess of 5000 psi (Const. Equip. 1994). Although fittings and hoses and O-rings have improved dramatically over the past 20 years these components are still the likely point of failure in the system. This failure is due to the cyclic stresses in the system as the electronic controllers "hunt." The reduction or elimination of hunting offered by fuzzy controllers should significantly increase the maintainability of these components.

5.3.2 Reliability - **Increase**

As discussed earlier, fuzzy logic controllers are more reliable than conventional controllers in that faulty fuzzy sets and rules are overridden by the adjacent rules and the fuzzification, fuzzy inference and defuzzification procedures. Since the fuzzy controllers are replacing conventional controllers reliability is increased.

5.3.3 Safety - **Increase**

Smoother transmissions and more precise control inherently increase the safety of the machine. During trenching operations the operator is often in the situation where he is being guided by the hand signals of either a laborer in the trench or from a spotter above the trench. Finer hydraulic control is a safety benefit for the operator helping to avoid hitting the laborer. Additionally, fine work around gas and electric lines is always potentially dangerous. With even finer control of the bucket an additional margin of safety is offered to the operator.

5.3.4 Productivity - **Increase**

Due to the excellent conventional electronic control on today's machines it is not likely that fuzzy controllers would provide double-digit productivity increases as they might in other machines. However, state control offers the operator the ability to ensure the highest bucket fill factors which would increase productivity, especially during blind excavation where the operator now uses experience and machine performance to judge bucket fill.

5.3.5 Utilize Less-Skilled Operators - **Unchanged**

Today's conventional electronic control is excellent. One of the factors that drove the development of these controllers was the popularity of the machines and the requirement that inexperienced operators be able to perform adequately. Therefore, while providing productivity increases and safety increases and other positive factors, fuzzy controllers are less likely to have a major impact in allowing contractors to utilize less experience operators.

5.3.6 First Cost - **Lower**

This point as already been alluded to many times. As demonstrated in Chapter 3 the hardware requirements for fuzzy control of an excavator are less, reducing first cost of the machine.

5.3.7 Operating Cost - **Lower**

Due to reduced hydraulic system wear and tear, operating maintenance costs should decrease. Each time the excavator loads the bucket is analogous to a car driving up a hill. Therefore more efficient , fuzzy engine speed control would increase fuel efficiency.

5.4 Grader

The grader has little electronic control, usually only electronic monitoring systems, but some models do have electronically controlled transmissions. The hydraulic control systems are void of electronic control.

5.4.1 Maintainability - **Lower**

Despite the lack of electronic control of the hydraulic system of the grader any electronic control is likely to have little impact on maintainability because the transients in the system are not large. The operator operates the blade in small precise increments. In terms of additional electronic controllers requiring maintenance, speed control is a possibility, as is blade state control. Obviously the advent of these systems would decrease maintainability.

5.4.2 Reliability - **Increase**

The increase here is small due to the little electronic control that fuzzy controllers can replace.

5.4.3 Safety - **Increase**

Smoother transmission control, less shifting and better stopping are all safety enhancements for this machine.

5.4.4 Productivity - **Same**

It is doubtful that fuzzy controllers will increase the productivity of these machines. In particular the operator usually visually maintains the blade in the correct position unless assisted by sonic or laser guidance. Basically the blade movements are not large enough to allow productivity improvements. However, fuzzy controllers used with guidance devices do offer the possibility of providing a productivity increase.

5.4.5 Utilize Less-Skilled Operators - **Yes**

As with most of the equipment the fuzzy transmissions which reduce shifting and braking most certainly assist operators. In regards to blade positioning, state controllers may be able to provide a certain measure of consistency for newer operators.

5.4.6 First Cost - **Increase**

Speed control and fuzzy transmissions would probably not increase first cost as they would be replacing the present electronic systems. However, any blade control fuzzy controller is basically starting from scratch and a significant first cost increase would result.

5.4.7 Operating Cost - **Lower**

As with all the equipment the fuzzy transmission would reduce fuel cost. Due to the manner in which the grader is operated the savings would likely be on the same magnitude as the Nissan example, 17%.

5.5 Scraper

The considerations for the scraper are similar to those grader in terms of its onboard electronics. Electronic monitoring is standard and some models offer electronically shifted transmissions.

5.5.1 Maintainability - **Lower**

Despite the lack of electronic control of the hydraulic system any electronic control is likely to have little impact on maintainability because the transients in the system are not large. The operator operates the blade in small precise increments. In terms of additional electronic controllers requiring maintenance, speed control is a possibility, as is blade state control.

5.5.2 Reliability - **Increase**

The increase here is small due to the little electronic control that fuzzy controllers can replace.

5.5.3 Safety - **Increase**

Smoother transmission control, less shifting and better stopping are all safety enhancements for this machine.

5.5.4 Productivity - **Same**

It is doubtful that fuzzy controllers will increase the productivity of these machines. In particular the operator usually visually maintains the blade in the correct position unless assisted by sonic or laser guidance. Basically the blade movements are not large enough to allow productivity improvements. However, fuzzy controllers used with guidance devices do offer the possibility of providing a productivity increase.

5.5.5 Utilize Less-Skilled Operators - **Yes**

As with most of the equipment the fuzzy transmissions which reduce shifting and braking most certainly assist operators. In regards to blade positioning state controllers may be able to provide a certain measure of consistency for newer operators.

5.5.6 First Cost - **Increase**

Speed control and fuzzy transmissions would probably not increase first cost as they would be replacing the present electronic systems. However, any blade control fuzzy controller is basically starting from scratch and a significant first cost increase would result.

5.5.7 Operating Cost - **Lower**

As with all the equipment the fuzzy transmission would reduce fuel cost. Due to the manner in which the scraper is operated the savings would likely be on the same magnitude as the Nissan example, 17%.

5.6 Final Recommendation

A summary of the discussion in the preceding sections are tabulated in Table 5-2. The table provides an easy-to-read matrix summing up the research and enabling final recommendations concerning the application of fuzzy logic controllers to these types of construction equipment. It is quite obvious from table 5-1 that both the front end loader and hydraulic excavator warrant immediate research investigating the application of fuzzy logic controllers. The grader and scraper, according to the analysis are not good candidates for immediate research into fuzzy logic controller applicability. The dozer is the piece of equipment for which a recommendation is not obvious. The answer with the dozer lies in investigating the current and future usage of the dozer. The trend is towards smaller projects, and contractors do not want equipment to sit idle. The dozer has the capability to do much of the work of the grader in certain applications, even though it could never totally replace the grader. A dozer in tandem with trucks and a front end loader or excavator can be an efficient method of moving earth in certain situations, eliminating the usage of the scraper in some instances. Therefore the research and development of fuzzy logic controllers for dozer applications is warranted as the dozer can become more versatile and in many applications replace the scraper and grader. These conclusions are summarized in Table 5-1 below.

Type of Equipment	Develop Fuzzy Controllers
Front End Loader	yes
Hydraulic Excavator	yes
Dozer	yes
Grader	no
Scraper	no

Table 5-1: Final Recommendations

5.7 Further Research

As the analysis presented in the final decision matrix indicates there are many areas in which fuzzy controllers could benefit earthmoving equipment. The next step is to design fuzzy controllers for these areas, similar to that designed for the hydraulic excavator in Chapter 3, and run simulations using fuzzy logic software simulation packages to truly quantify the results. Should the simulations prove that the device is successful and shows promise, a scale model controller and device should be tested to finally determine the applicability and resulting performance characteristics.

In particular the state fuzzy controller may have the most benefit for construction productivity and should be thoroughly studied. Applications of state controllers are especially evident in the performance of many earthwork activities, such as:

1. Smooth level cuts
2. Maximizing blade capacity (reduce cycle times)
3. Maximize bucket fill
4. Maintain straight paths for certain work
5. Recognizing hidden objects (increased force on the bucket)

State control can potentially enhance each of these operations, with the end result being increased productivity, evidenced by shorter cycle times or increased capacity of earth moved.

Obviously FLCs can be used in other types of construction equipment than those studied here. Specifically the following pieces of equipment or categories of equipment warrant feasibility studies:

1. Backhoe Loader
2. Trenchers
3. Microtunneling equipment
4. Central and batch plants (concrete and asphalt)
5. Cranes (all types)
6. Power Shovels.

Initially, as in this study, a current benchmark of control technology is needed. Then an adaptability and feasibility study is required to determine if fuzzy control of this equipment is warranted and FLCs should be pursued.

In the area of construction equipment automation fuzzy logic controllers seem to be the answer to the complex control problems that have been difficult to overcome using conventional controller design. Recall that one of the methods to model fuzzy controllers is by characterizing expert operator actions. This at first glance seems to be the prime model that could be used to design fuzzy controllers for construction equipment. This methodology is similar to work done by Sugeno and Nishida (1985, 1992), where they modeled car parking and fuzzy control of cars by observing "experts." Standard, off the shelf software is available to model fuzzy systems. Therefore the first step is to utilize these software packages to design and validate FLCs for automated earthwork equipment application. Again, once computer models are validated then research needs to move into the practical application, utilizing scale systems such as automated excavators and radio controlled miniature construction equipment.

Finally, there is a tremendous amount of research available on fuzzy logic and FLCs. However, there has been little effort to apply these concepts and FLCs to construction equipment. This research is a first attempt to utilize the present state of FLC research and apply these results to construction equipment. Continued research is needed to further detail the applicable fuzzy logic controller technology available and applicable to construction equipment applications.

Equipment Type	Maintainability	Reliability	Safety	Productivity	Utilize Less Skilled Operators	First Cost	Operating Cost
Dozer	same	increase	increase	increase	yes	increase	lower
FEL	increase	increase	increase	increase	yes	lower	lower
Hyd. Exc.	increase	increase	increase	increase	same	lower	lower
Grader	Lower	increase	increase	same	yes	increase	lower
Scraper	Lower	increase	increase	same	yes	increase	lower

table 5-1

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