Fuzzy Logic Based Coordinated Control of a Cable-Driven Clamming Device

BY

KEVIN L. ROBBINS

A Thesis

Submitted to the Faculty of Graduate Studies

In Partial Fulfillment of the Requirements

For the Degree of

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*****

Department of Mechanical & Manufacturing Engineering

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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

*****

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For all those who have helped me on the road of life

Abstract

This thesis presents the design and experimental evaluation of a controller for the purpose of closed-loop coordinated control of a cable-driven clamming device that is used for removing water-borne debris at hydroelectric generating stations. Currently, experienced operators control cable-driven clamming devices and are required to judge the tensions in each cable and smoothly coordinate their motions in real time. This requires the operator's constant attention. The goal of this thesis is to develop a control strategy to partially automate the operation of the system, therefore alleviating the mental burden on the operator. In the proposed control system, the operator simply uses one single-axis joystick to impart a desired speed to the system while the controller handles corrections required to coordinate the motion of the cables. This way, the operator would no longer be required to balance the loads on each cable during ascension and descension. The proposed control strategy cooperatively incorporates conventional proportional and integral control and a novel fuzzy logic based integral-type controller. It allows for smooth control of the winch speeds from multiple inputs, i.e. load state and speed error, by determining the small incremental corrections that are required to coordinate the motion of the cables. The developed control approach is experimentally evaluated on a test rig that operates in a manner similar to the actual clamming device used by Manitoba Hydro for clearing trashes from its many generating stations throughout the province. The experiments, consisting of both simple and advanced case studies of specific segments of typical trash removal operations, demonstrate the feasibility and the promise of the technique.

Acknowledgements

I would like to acknowledge the support and wisdom of Dr. Nariman Sepehri. Throughout this project he has been there when times got tough to keep me on track. Without his help and guidance this project surely would not have been completed.

Thanks are also due to Al Lohse for his bits of advice, the use of his tools and machining skills, and to Irwin Penner for the use of the machine shop and for machining some of the more delicate parts.

This thesis would not have been completed without the help of some fellow graduate students. Mark Karpenko's help has been invaluable for the past several years. His help with everything from C++ programming to soldering control boards is greatly appreciated. Dr. Roshdy Abo-Shanab's knowledge of control theory helped me through some mental blocks, while Farshid Najafi's design advice greatly influenced components of the experimental test rig.

Many thanks are given to Manitoba Hydro and to NSERC for their financial support. Thanks to Mr. Gary Gusberti and Mr. Paul Softly for allowing me to visit the McArthur Falls generating station to get a feel for the actual system.

Thanks to my Dad for giving me the skills to build and wire up the test apparatus, and to my Mom for all the discussions on the grey areas of life, certainly an important building block in designing a fuzzy logic controller. And also thanks to Robin for the lunches, support and rides to work over the last two and a half years.

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Chapter 1

Introduction

Removing debris from large trash racks (which are about 5 meters wide and 20 meters high) is an ongoing challenge at Manitoba Hydro's generating stations. Water-borne debris, consisting of dead animals, tree stumps or large logs which could weigh up to 3 tons, often get jammed between the racks or accumulated in front of them, 20 meters below the surface of the water. Hydraulic boom cranes equipped with cable-driven claw-type grapples (called clamming devices) are used for removing the debris. Presently, the operator lowers the clamming device until it reaches the bottom of the dam or hits an unknown obstacle. He/she then closes the claws of the clamming device to collect the trashes and lift them out of the water by continuously controlling the tensions and speeds of the two cables. The debris is delivered to a truck by maneuvering the crane manipulator to hold the clamming device directly above the truck and opening the clamming device. The whole process relies on the operators' judgment and experience, as he/she must be familiar with crane's configuration and capabilities, as well as the operation of the clamming device. Currently, these configurations are not user friendly with respect to ergonomics and logistics, and result in unintentional errors and subsequently undesirable machine reactions, including tip-over of the entire crane.

Within the context of the trash removal operation, Manitoba Hydro has identified a number of issues that require attention. One important issue is the improvement of the operation of the cable-driven clamming device. The current task of lowering/lifting and loading/unloading the clamming device is extremely difficult and requires constant attention from human operators to continuously coordinate the tensions and speeds of the two cables that hold the clamming device.

The objective of this thesis is to design a method for coordinating the control of the cables that operate the clamming device through the use of fuzzy logic. This will reduce the mental effort required from the operator by having the control algorithm make the necessary corrections to the speed and therefore the tension of the cables. The final product will consist of embedded supporting systems that will perform advanced control of the clamming device when combined with the traditional supervisory man-in-the-loop operation.

1.1 Problem Statement

There are many engineering applications in which the operators are required to be directly involved in performing every detail of a given task. One particular application is the operation of trash removal from the trash racks at hydroelectric generating stations. Boom cranes, equipped with cable-driven clamming devices, are employed to remove debris from the McArthur Falls, Great Falls, Pine Falls and Seven Sisters generating stations on the Winnipeg River in Manitoba. The crane and its clamming device at the McArthur Falls generating station on the Winnipeg River are shown in Figure 1.1.

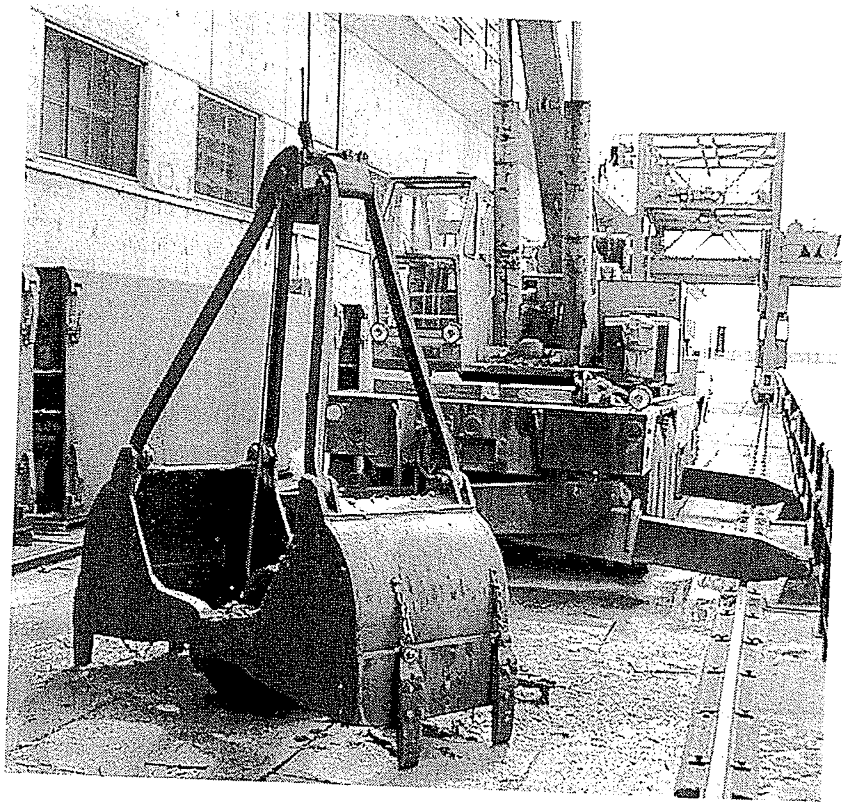


Figure 1.1 – Typical clamming device and crane.

Currently, the operation of both the crane and the claw-type clamming device face many challenges. With respect to the operation of a clamming device, the operators need to control two independently driven cables, referred to as Cable 1 and Cable 2, to coordinate motion in four distinct operating modes: up closed (ascending with the claws closed), up open (ascending with the claws open), down closed (descending with the claws closed), and down open (descending with the claws open). The operation of the cables is coupled, however. Figure 1.2 shows the details of the actual clamming device. The tensions in each cable are referred to as T_1 and T_2, for Cable 1 and Cable 2, respectively.

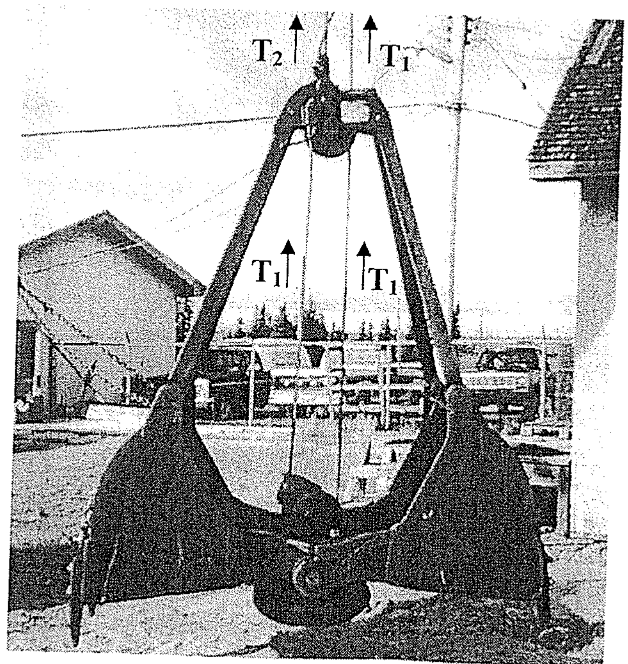


Figure 1.2 – Detailed view of the clamming device.

When the clamming device is fully open as shown in Figure 1.2, there is a minimum tension in Cable 1 and a large tension in Cable 2. The opposite is true when the clamming device is full closed; there is a minimum tension in Cable 2 and a large tension in Cable 1. For example, to lower the clamming device with open claws, Cable 2 carries the load of the clamming device while descending. Cable 1 only follows the motion of the Cable 2, with a minimum tension to keep coordination possible. If Cable 1 takes a significant part of the load, the clamming device will begin to close. If the tension in this cable declines to zero the cable will slacken and hang idle, causing serious problems during subsequent tasks. Opening the claws of the clamming device to release the debris is accomplished by holding Cable 1 stationary and lifting Cable 2. Holding Cable 2 stationary and raising Cable 1 causes the claws of the clamming device to close onto the debris both on and below the surface of the water.

The operators presently rely on their experience to manipulate the two cables by visually judging the tensions of the cables and observing the vertical speed of the clamming device. A major problem affecting the function of a cable-driven clamming device is the management of the coordination of the two cables. The current operation utilizes two separate joystick controllers, one for each cable. It then becomes the task of the operator to keep the two cables at proper tensions and speeds; this consumes most of the operator's attention. Previous valuable research on automation of heavy-duty forestry/mining/construction equipment has been aimed at coordinating the motion of the manipulator links using the concepts of coordinated-joint or rate controls [1,2,3] or navigation of the machines [4]. Much work has also been conducted on reducing the swinging of cable-suspended loads in stationary or shipboard crane operations [5,6,7]. There has also been a study to improve the operation of a cable array crane by optimally adjusting the tensions of four cables that hold the platform device for offshore loading/unloading of cargo ships [8].

1.2 Objectives and Scope of this Research

The general objective of this research is to develop an effective control strategy for coordinated-motion control of cable-driven clamming devices such that the *'movements in the control element and the intended changes in the considered object are logically coordinated'*. Achieving the above goal will provide solutions to some important challenges encountered in the current operation of cranes that carry cable-driven clamming devices.

The approach taken is to incorporate the concept of fuzzy logic into a novel controller for controlling the tensions and speeds of the cables that operate the clamming device cooperatively, in a manner similar to what experienced operators do. Fuzzy logic has been expanding in use since its initial applications in the area of control systems in the 1960's and 1970's by researchers such as L.A. Zadeh at the University of California at Berkley and E. Mamdani at the University of London, respectively.

Zadeh initially proposed fuzzy set theory in 1965 [9,10,11]. Fuzzy sets allowed for a more qualitative approach to control, where conventional control theory was more quantitative. Within fuzzy set theory, inputs are valued as a degree of membership between 0.0 and 1.0, not a crisp, absolute integer value of 0 or 1 as found in Boolean logic. This quantitative type of reasoning is intended to create digital computer based algorithms to control a process that has its roots in the human thought process [12]. Mamdani's work elaborated on the linguistic nature of fuzzy logic, applying it directly to control theory. One of the first attempts to control a system using fuzzy logic occurred in 1975, when Mamdani attempted to control a steam engine and boiler using linguistic-based rules derived from experienced human operators [13].

Presently, fuzzy logic finds applications in many areas of control, including the realm of heavy-duty machinery. Lever et al. designed a fuzzy logic controller at the University of Arizona to control a Puma manipulator fitted with a small shovel for digging in sand for potential applications towards lunar mining [14]. Sameshima and Tozawa developed a controller for heavy-duty excavation equipment where the controller itself was based on observations of human operators conducting the same task [15]. Ha and Rye proposed a controller where fuzzy logic was used in conjunction with other types of controllers, including sliding mode control, and task decomposition [16] for application in excavation and construction. Fuzzy logic control has also been used in discussions on automated road construction [17], and rotary crane control [18,19], as well as numerous other applications. However, as far as the coordination of the cable movements in clamming devices through the use of fuzzy logic control is concerned, this research is very new and not recorded in the literature.

The proposed controller coordinates the clamming device though the use of a combination of conventional PI control and the novel fuzzy logic controller designed for this research. Many researchers have investigated hybrid PID - fuzzy logic controllers, with much work focusing on controllers where the PID and fuzzy logic control signals are blended into a common control signal [20,21]. Information on the exact type of combination of fuzzy logic and conventional control used in the controller proposed in this thesis was not found in the literature, however, A.V. Patel proposed an integral type fuzzy logic controller, similar to the fuzzy logic portion of the controller proposed in this thesis [22]. Typically, fuzzy logic controllers operate by receiving an error signal and its time derivative as inputs [23], but P.J. Escamilla-Ambrosio and N. Mort, at the Universities of Bristol and Shefield in England, respectively, have investigated fuzzy logic controllers using multiple sensors [24]. With respect to the issue of selecting sensors and their placements for this research, measurement of the pressure differentials of the hydraulic motors indirectly assesses the cable tensions, while optical encoders indirectly assess the vertical speeds of the clamming device. This is believed to impose a minimum modification to the existing cranes. Thus, experiments will also be conducted to determine the feasibility of this approach within the context of the clamming operation.

The layout of this thesis is as follows. Chapter 2 describes fuzzy logic control in detail, including membership functions, rules and how to arrive at a crisp control output. These steps are referred to as fuzzification, fuzzy inference and defuzzification respectively. The scaled in-house clamming device is described in Chapter 3 along with the instrumentation added to the experimental test rig for this research. The design of the controller developed in this research is presented in Chapter 4. The specific membership functions for the inputs and outputs are detailed, along with the rules for various operating modes. Chapter 5 presents all of the results obtained during the experimental trials of the proposed controller, for individual as well as combined tasks. In Chapter 6, the contribution of this thesis is detailed along with comments for future work in this area of research.

Chapter 2

Fuzzy Logic and Conventional Control

The controller proposed in this thesis is a combination of conventional control and a novel fuzzy logic controller. While conventional control theory is well understood and widely used, fuzzy logic control is not. Therefore, an explanation of fuzzy logic control is presented in this chapter, along with a brief discussion of elements of conventional control used in this thesis.

Fuzzy logic is a powerful tool due to its simple, easy-to-use language-based nature. It is best suited for applications such as set-point control, discrimination or sorting, identification and image processing. Fuzzy logic performs well in cases where human knowledge and experience in controlling multivariable systems is required in a computer control algorithm, where it would be difficult to extend conventional control theory to a nonlinear system, or where the system is understood only qualitatively.

In the case of this research, an exact mathematical model of the clamming device is difficult to derive, but the dynamics of the system are known qualitatively, making a fuzzy logic control approach to this problem feasible. Fuzzy logic control allows for multiple inputs to be processed and for conclusions to be inferred based on a predetermined set of rules.

2.1 Fuzzy Logic Control Elements and Processing

The elements of a fuzzy logic controller are fuzzy sets, membership functions and fuzzy rules. Normally in conventional set theory, including digital logic, any particular input value leads to a full membership in one set only. This is shown in Figure 2.1.

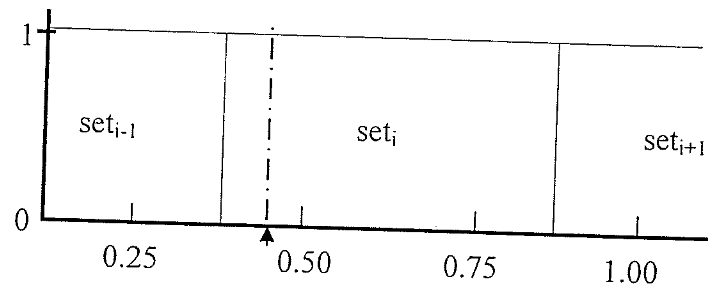


Figure 2.1 – Conventional sets.

Figure 2.1 shows rigid limits for each crisp conventional set. An input value of 0.45 would lead to full membership in set_i and zero membership in set_{i-1} and set_{i+1}, as shown in Figure 2.1. This classification is too strict to have many real life applications. Fuzzy set theory, as introduced by L.A. Zadeh [9], allows for degrees of membership ranging between 0.0 and 1.0, where a single input could co-exist in more than one fuzzy set simultaneously. Fuzzy sets allow for subjectivity to be applied to control theory. Terms such as 'almost' or 'partially' can be used to describe the regions under the lines, known as membership functions. For example, referring to Figure 2.2, an input value of 0.45 has partial membership in set_{i-1} and in set_i. The degree of membership of this value in set_{i-1} is 0.25 while its degree of membership in set_i is 0.75.

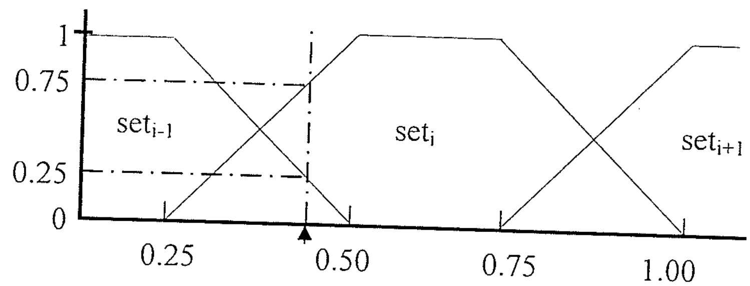


Figure 2.2 – Fuzzy sets.

Membership functions can use linear segments as shown in Figure 2.2 or can be constructed from more complicated functions such as curves, provided that at any input value the summation of the degrees of membership of the two or more co-existing membership functions is one. For example, referring to Figure 2.2, for an input value of 0.45, the two degrees of membership, 0.25 and 0.75, add to 1.0. These fuzzy regions allow a controller to deal with vague areas where crisp, exact classification is impossible or impractical.

The rules for a fuzzy logic controller are in the form of standard *IF-THEN* logic. A system can have a large assortment of fuzzy rules or relatively few, ranging from highly complex to straightforward in nature. These rules are commonly developed using human judgment and experience.

Fuzzy logic controller processing is broken down into two steps: fuzzy inference and defuzzification. Fuzzy inference involves evaluating the fuzzy rules. The rules infer conclusions based on the conditions of the rules and assign these conclusions a degree of membership. These conclusions are then summed together to create a crisp output value through the process of defuzzification. Several methods are used to defuzzify the rules, including the bisector method and the center of area (COA) approach.

2.2 Procedure for Application of a Fuzzy Logic Controller

There are seven steps for designing a fuzzy logic controller [25]:

1. check the applicability of fuzzy logic,
2. define the control objectives,
3. define input and output requirements,
4. create fuzzy logic membership functions,
5. create fuzzy logic rules of operation,
6. create pre- and post-processing logic, and
7. test and optimize the controller.

1 - Check the applicability of fuzzy logic – Fuzzy logic control may be used when:

- the process variables and qualitative relationships are well understood,
- the input-output relationships are known qualitatively but are difficult to model mathematically,
- the control problem is multivariable,
- conventional mathematical modeling methods do not work well, and

2 - Define the control objectives – Without at least a qualitative understanding of the system, a fuzzy logic approach would be very challenging. One must know what the system is intended to do, how much error is acceptable, what sorts of disturbances are expected, along with the capabilities and limitations of the physical system. In addition to these primary considerations, other objectives when using a fuzzy logic control approach are:

- to provide a self-correcting system using a hybrid fuzzy logic and classical control,
- to augment the operation of an existing control system by adding fuzzy logic,
- to provide an intelligent man-machine interface to convert human approximate "feelings" into control inputs,
- to design a control system that can perform discrimination based on inexact input from multiple sensors,
- to monitor the environment in which the control system is to be used,
- to ensure a high degree of maintainability,
- to minimize development and hardware costs, and
- to determine operator interface requirements.

3 - Define input and output requirements – There are five important factors to be considered when selecting sensors and actuators; technology, functional performance, physical properties, quality factors and cost. The technology of sensors may be electric, magnetic, mechanical, electromechanical, electro-optical, or piezoelectric, while the actuators may be electric, hydraulic, pneumatic, or thermal. Considerations to the functional performance of the sensors include linearity, bias, accuracy, dynamic range, and noise, while considerations of the functional performance of the actuators embodies maximum possible force, extent of linear range, maximum speed possible, power, and efficiency. Physical properties include weight, size, and strength. Quality factors consist of reliability, durability, and maintainability. Cost deals with expense, availability, facilities for testing and maintenance.

4 - Create fuzzy logic membership functions – Typically membership functions for both input conditions and output conclusions are broken down into a group of vague and imprecise terms, like positive large, positive small, zero, negative small and negative large. In some cases, more descriptive nomenclature is required. A typical group of membership functions is shown in Figure 2.2. When creating membership functions, the following guidelines are to be followed:

- an input value may co-exist in more than one membership function simultaneously to allow a total degree of membership of 1.0 at that point specific input point,
- each input condition must be able to be graphically defined,
- begin with equidistant triangles having 50% overlap (½ the base) when a smooth changing, continuous output is required,
- reducing the amount of overlap of the membership functions tends to result in a more step-like output,
- decreasing (increasing) the relative width of a membership function increases (decreases) the sensitivity of the system in that particular input range,
- translating the membership functions up or down the abscissa changes the input ranges to where the rules for the specific input terms will respond, and
- adjusting the relative shapes and sizes of the membership functions can "weight" the output rules unequally to provide a nonlinear output response where required.

5 - Create fuzzy logic rules of operation – The fuzzy rules relate the inputs to the outputs through a collection of *IF-THEN* statements, where conditions are compared and evaluated using standard logic (*AND* and *OR*). These rules take the form of:

IF (condition A) AND / OR (condition B), THEN (conclusion X)

The conditions are based on the inputs and the conclusion defines the output. The rules are a collection of knowledge of the physical system, and are determined through either experience or experimentation. When creating the fuzzy logic rules for a system, the following points must be considered:

- create rules so that there will be a non-zero conclusion from at least one rule at all times,
- where smooth control is required, input conditions and output conclusions should be developed so that a minimum of two rules always have non-zero conclusions,
- where precise control is required, define more input membership functions, each covering a small section of the input signal range,
- where precise control is not required, fewer input membership functions covering a broad signal range will be sufficient, and
- for two-input, one-output systems, a rule matrix can help create and document rules.

6 - Create pre- and post-processing logic – In order to properly evaluate the fuzzy rules, the pre- and post-processing logic must be defined. A rule is stated in the form of:

IF (condition A) AND / OR (condition B), THEN (conclusion X)

The logical *AND* operator utilizes the *MIN* function, or minimum value function. For example, if *condition A* has a degree of membership of 0.25 and *condition B* has a degree of membership of 0.75, *conclusion X* would then be evaluated as *MIN(0.25, 0.75) = 0.25*. In this case, *conclusion X* is only 0.25 true according to the fuzzy logic. In the case of a rule using an *OR* junction, a *MAX* function, or maximum value function, is used. These methods of evaluating conditions work equally well for Boolean logic and fuzzy logic. Once each rule for the system has been evaluated, a crisp output needs to be determined. An example of defuzzification is shown in Figure 2.3 by calculating the center of area (COA) of the output membership functions. There are other methods of defuzzifying the fuzzy outputs to determine the crisp output, such as the bisector method or the height method. The COA method, however, is the most commonly used.

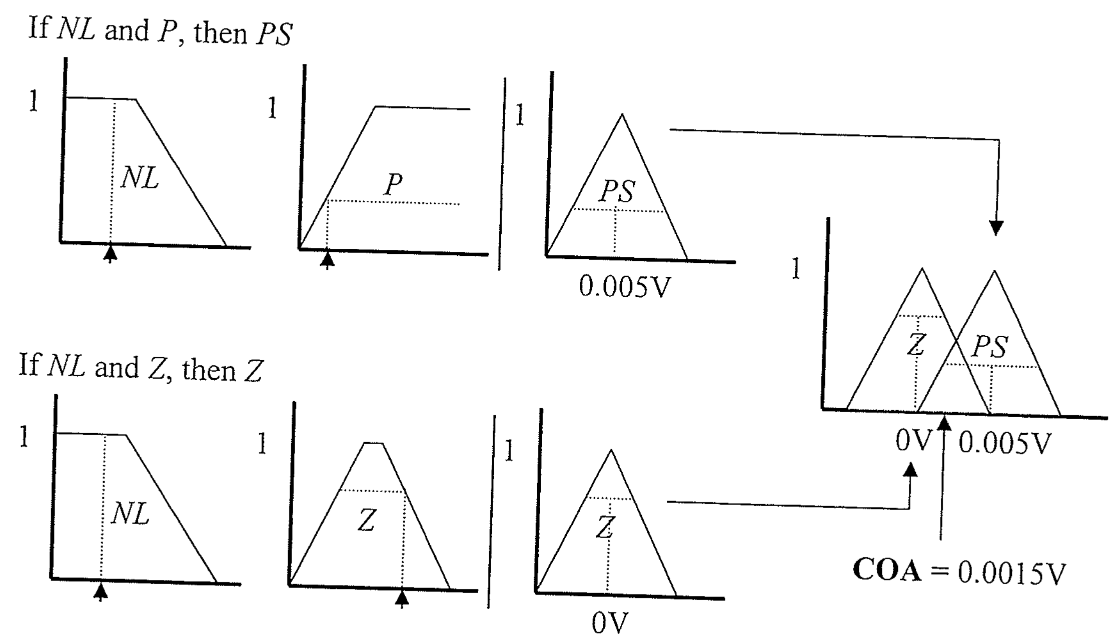


Figure 2.3 – Center of area (COA) defuzzification.

7 - Test and optimize the controller – The system requires tuning to ensure that the control system performs optimally. This is accomplished by:

- setting the system gain coefficients to an estimated value and assess stability through testing,

- modifying or adding rules if the knowledge base does not completely describe the required input condition states,
- adjusting the system gains in the pre- and/or post-processing logic before attempting further optimization, and
- adjusting the membership functions through width and peak tuning.

The most common method of optimizing a system controlled by a fuzzy logic controller is through width and peak tuning [23]. Width tuning refers to changing the shape of the membership functions. In the case of a simple triangular membership function as shown in Figure 2.4, increasing or decreasing the width of the base of the triangle realizes width tuning. Decreasing the width has the effect of increasing the sensitivity of that specific membership function, while increasing the width of the triangle has the opposite effect.

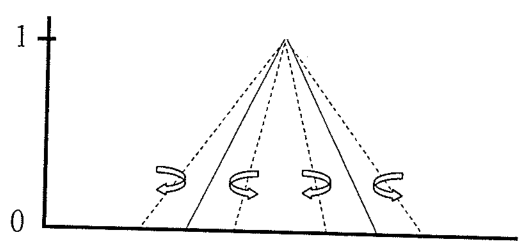


Figure 2.4 – Width Tuning.

Peak tuning refers to translation of the entire membership function along the abscissa, while the shape of the membership function is maintained. An example of peak tuning is shown in Figure 2.5. Peak tuning changes the ranges in which certain rules are applied, while having no effect on the sensitivity of the controller.

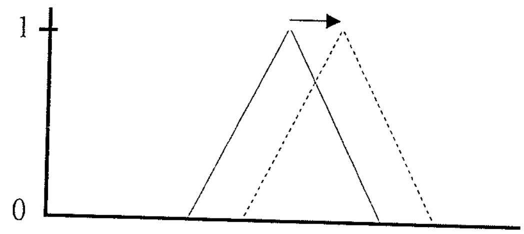


Figure 2.5 – Peak Tuning.

2.3 Conventional Control

The elements of conventiona control that are used in this thesis are standard proportional and integral control. A proportional controller takes the form of:

$$u = K_p * e$$

where u is the control signal, K_p is the proportional gain, and e is the error signal [26]. The error signal is multiplied by a scalar gain to obtain a control signal. A PI, or proportional plus integral controller, takes the form of:

$$u = K_p * e + K_I \int_0^t e\,dt$$

where u, K_p, and e are the same as above, and K_I is the integral gain. The integral component of the controller is responsible for removing any steady state error that may be present.

Chapter 3

Experimental Test Rig

The experimental test rig shown in Figure 3.1 is comprised of several components. The clamming device shown in Figure 3.1 is a scaled model of the actual clamming device shown in Figure 1.1. The winches and hydraulic motors are situated on a rigid base that is bolted to the floor. The cables from the winches loop around independent pulleys fixed to the ceiling of the lab before connecting to the clamming device.

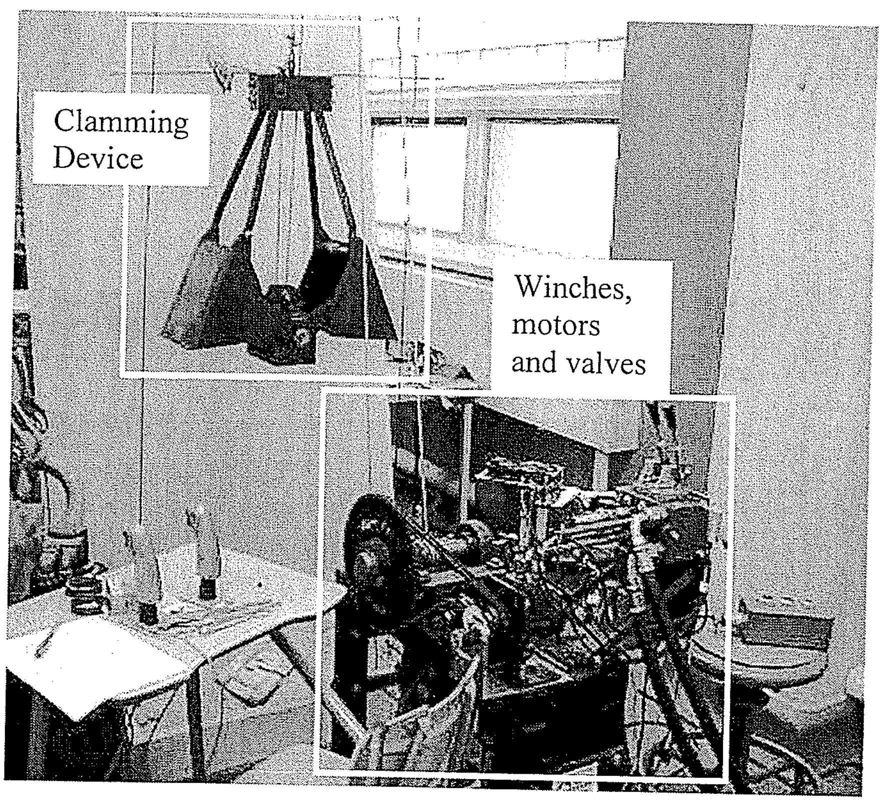


Figure 3.1 – Experimental test rig.

Two independently actuated cables drive the clamming device, which is shown in Figure 3.2. Cable 2 is attached to the upper block of the clamming device. Cable 1 passes through the upper block and loops around a pulley on the lower block of the clamming device before being connected to the bottom of the upper block. Opening or closing the clamming device is accomplished by relative motion between Cable 1 and Cable 2. For example, if the upward speed if Cable 1 is greater than the upward speed of Cable 2, the clamming device closes.

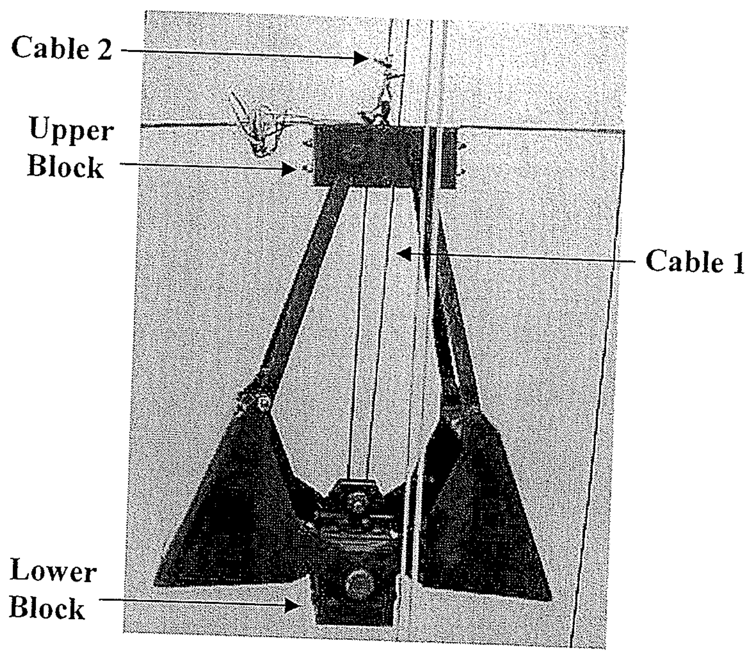


Figure 3.2 – Clamming device shown fully open.

A pair of Danfoss hydraulic motors, which are supplied by fluid pressurized to approximately 1100 psi, actuate the system. Figure 3.3 shows the hydraulic motor and winch for Cable 1, along with the control valves for the system.

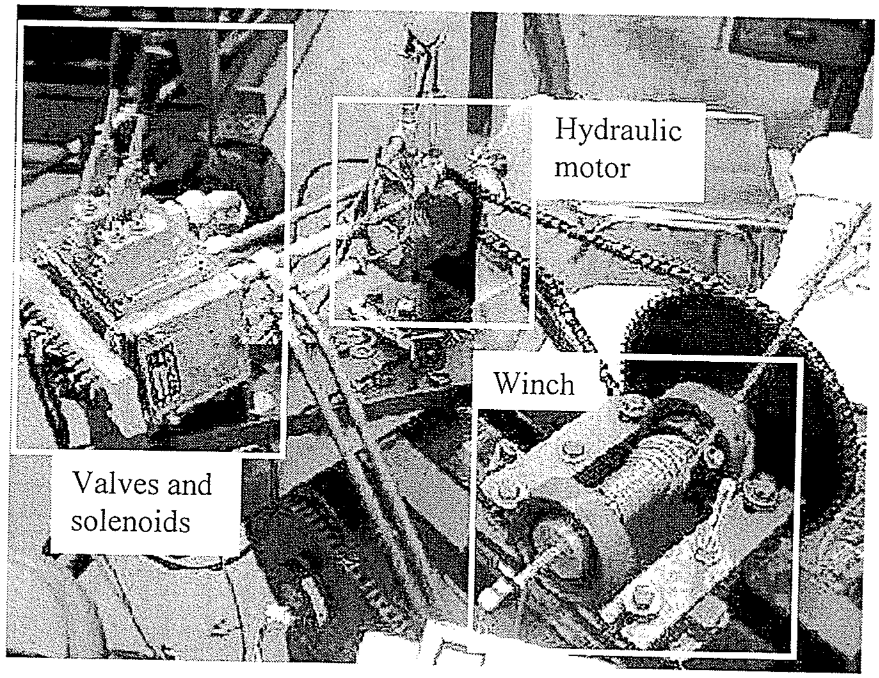


Figure 3.3 – Actuation system for Cable 1.

The proportional valves shown in Figure 3.3 are manufactured by Danfoss. Computer control is realized by sending control signals to solenoids located on the bottom of the valves, while levers on the top of the valve set allow for manual control of the actuators. The bi-polar control signals (±3.0V) are sent to the solenoids from the DDA-06 data acquisition card through a routing circuit with a hardwired override switch that zeros the valves in case of emergency. A chain drive supplies rotary motion to the winches from the hydraulic motors with a minimum amount of backlash. One of these motors is shown in Figure 3.3. The winches are supported by pillow blocks, and the shafts are machined with a helical groove to direct the cable and maintain a smooth wrapping motion.

A condition of the design of the experimental test rig is that any sensors used to collect data must not be placed on the clamming device itself, to protect the sensors from foreign object damage. This leads to the necessity of indirectly measuring the variables of absolute vertical speed and cable tension. The vertical speed is estimated by recording the rotary speed of the two winch shafts. The two shafts are machined to the same diameter, therefore the relationship between vertical speed and rotary winch speed are identical for each cable, allowing for the use of the rotary winch speed to indirectly assess vertical speed of both cables. Optical encoders measuring 1024 counts per revolution are utilized to directly measure the rotary position of each winch. The rotary speed is determined by numerically differentiating the rotary position through the use of a 50-point numerical differentiation algorithm. The computer collects the signals from the rotary encoders through a TE5312 data acquisition card at 200 Hz operating on a 500 MHz desktop computer.

To indirectly assess the cable loading, pressure transducers are placed across the ports of the hydraulic motor for Cable 2. The pressure transducers are manufactured by Ashcroft and have a limit of 2000 psi. A DAS-16 data acquisition card collects the signals from these pressure transducers at 200 Hz. A low-pass filtering algorithm, an example of which is shown in Figure 3.4, smoothes the signals from the pressure transducers by calculating the rolling average for the previous 65 points, approximately one-third of a second. Figures 3.4a and 3.4b show the unfiltered data from the pressure transducers for a typical experimental evaluation, while Figures 3.4c and 3.4d show the pressure data after passing through the low-pass filtering algorithm to remove the high frequency noise and initial inertial effects. The difference between the filtered pressure data is shown in Figure 3.5a. These data for the pressure difference is filtered using a low-pass filter that calculates the rolling average of the previous 10 points to desensitize the controller to the small remaining noise left in the system. The filtered pressure differential data, shown in Figure 3.5b, constitutes the load state of the clamming device.

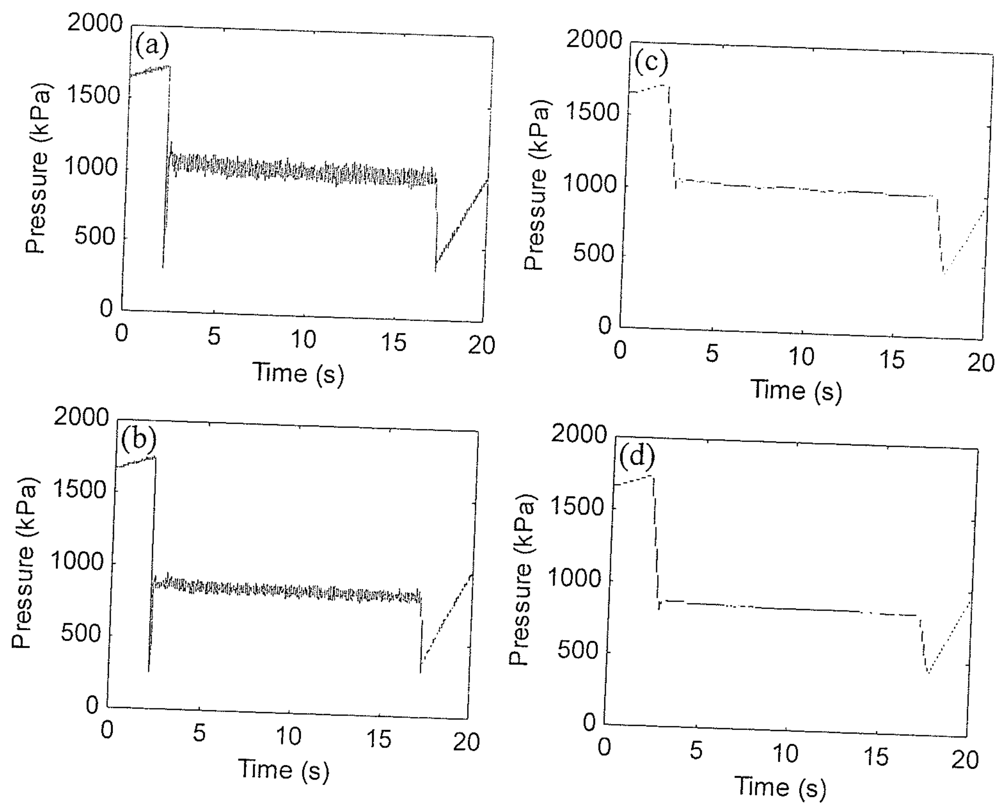


Figure 3.4 – Unfiltered and filtered pressure data.

The difference between the desired speed and the actual speed calculated by numerically differentiating the rotary position of the encoders constitutes the speed error. Figure 3.6 shows the encoder and pressure transducers used on the experimental test rig for Cable 2.

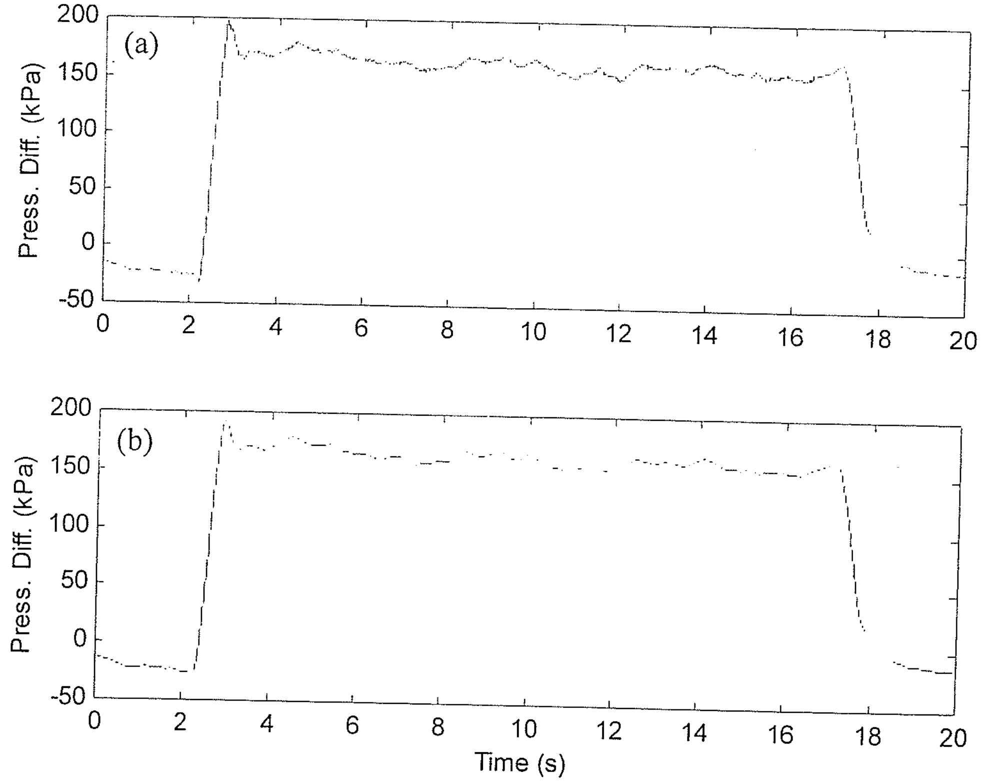


Figure 3.5 – Unfiltered and filtered pressure differential data.

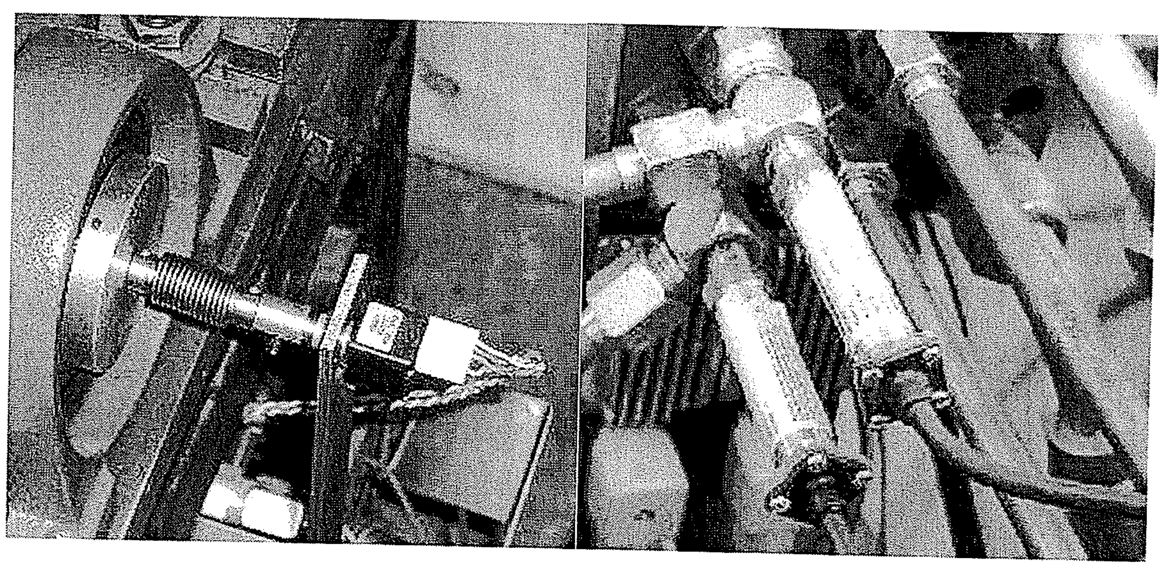


Figure 3.6 – Encoder and pressure transducers.

Chapter 4

Controller Design

While an exact mathematical model for the clamming device under investigation is difficult to obtain, the qualitative relationships between the independent variables are well understood. Each of the input and output variables are known, along with how they relate to each other qualitatively. These conditions indicate that this is an ideal application for fuzzy logic control.

4.1 Outline of the Control Scheme

The fuzzy logic controller presented in this thesis is intended to ease the burden on the operator of the clamming device by completing all of the necessary corrections to the rotary speed of the winches in order to keep the clamming device in a coordinated state. The fuzzy logic controller makes qualitative, or fuzzy, judgments and creates a crisp quantitative response. Instead of relying on visual assessment to judge the tensions in each cable as the operator does, the fuzzy logic controller relies on numerical inputs from electronic sensors.

The two types of sensors used on the test apparatus are pressure transducers and optical encoders. The pressure transducers were placed across the ports on only the hydraulic motor for Cable 2 to minimize cost and keep the system as simple as possible. Since the pressure transducers are used to measure the cable loadings indirectly, a high degree of accuracy is not required, although repeatability is critical. The optical encoders measure the rotary position of the winch shafts. Numerical differentiation of these positions leads to the rotary speed of the winch shafts, which is a variable of interest. The encoders are highly accurate and provide repeatable data with a minimum amount of electronic noise. A pair of hydraulic motors controlled by proportional valves drives the system, indicating that corrections to the control signal sent to each of the proportional valves is the appropriate output from the fuzzy logic controller.

Figure 4.1 shows the block diagram for the proposed control system. This block diagram is valid for both cables; it is modified using Table 1 to adapt the block diagram for Cable 1 and Cable 2. For each of the four operating modes (up closed, up open, down closed, and down open) one cable is controlled by a conventional proportional plus integral (PI) controller, and a conventional proportional plus integral-type fuzzy logic (PF) controller controls the other cable. The control system receives an input signal, in this case the desired speed of the system. The feedbacks to the control system are the load state and speed state of the experimental test rig. The difference between the desired speed and the speed state of each cable constitutes the speed error for that specific cable, and is used by the proportional, integral and fuzzy logic controllers. The fuzzy logic controller also receives load state data, which is defined to be the pressure differential across the hydraulic motor for Cable 2, and a set of rules specific to each operating mode. The corrections made by the fuzzy logic controller are incrementally added together to create a control signal that behaves like an integral controller.

Table 4.1 shows how to determine which cable is PI controlled and which is PF controlled for each operating mode. The constants s_1 and s_2 are used to distinguish the control scheme for each cable. For example, in the up open operating mode, a PF controller controls Cable 1 with the R_{UO} rule set and a PI controller controls the speed of Cable 2.

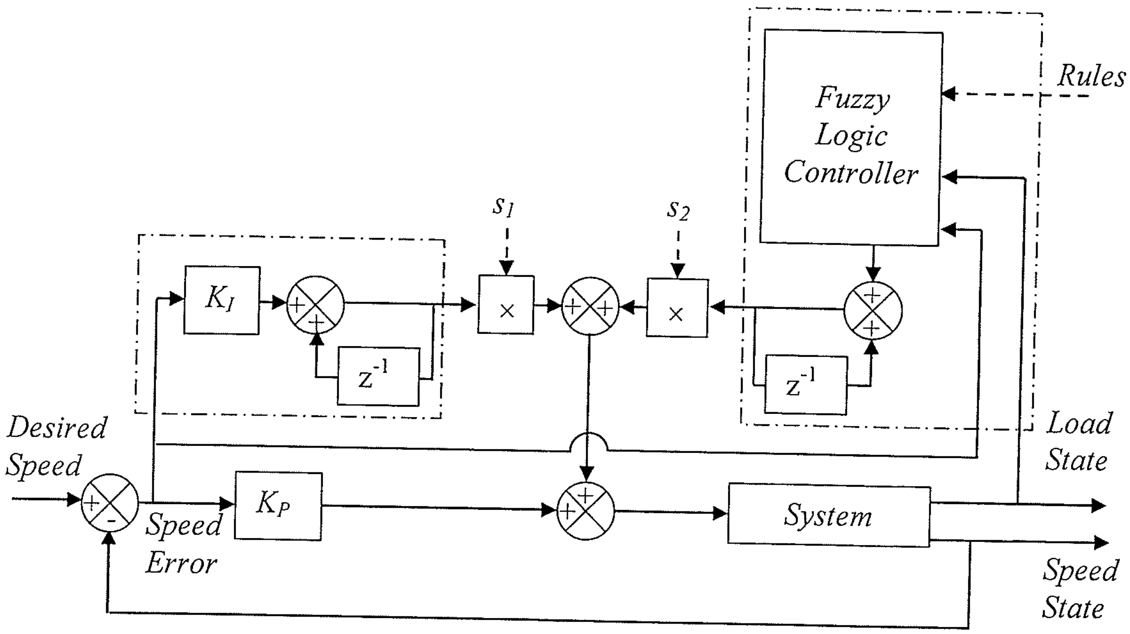


Figure 4.1 – Block diagram of the control system.

Table 4.1 – Controller switching rules.

Case	*Cable 1*	*Cable 2*	*Rule*
Up Open	$s_1 = 0$ $s_2 = 1$	$s_1 = 1$ $s_2 = 0$	R_{UO}
Up Closed	$s_1 = 1$ $s_2 = 0$	$s_1 = 0$ $s_2 = 1$	R_{UC}
Down Open	$s_1 = 1$ $s_2 = 0$	$s_1 = 0$ $s_2 = 1$	R_{DO}
Down Closed	$s_1 = 0$ $s_2 = 1$	$s_1 = 1$ $s_2 = 0$	R_{DC}

The controller for the each cable for each operating mode was chosen so that if the fuzzy logic controller slowed or halted the progress of one cable, the net effect was the desired corrective response. For example, in the up closed operating mode, if the fuzzy logic controller for Cable 2 responds to an error in load state, i.e. a partially open clamming device, by slowing the progress of Cable 2, the difference between the speeds of Cable 1 and Cable 2 causes the clamming device to close, as expected for the up closed operating mode. This inherent self-correcting nature creates the fastest possible corrective response to an error in the load state.

There are two remaining operations not shown in Figure 4.1, namely opening and closing the clamming device. Figure 4.2 shows the complete block diagram for the control system, and Table 4.2 shows the parameters required to facilitate opening and closing.

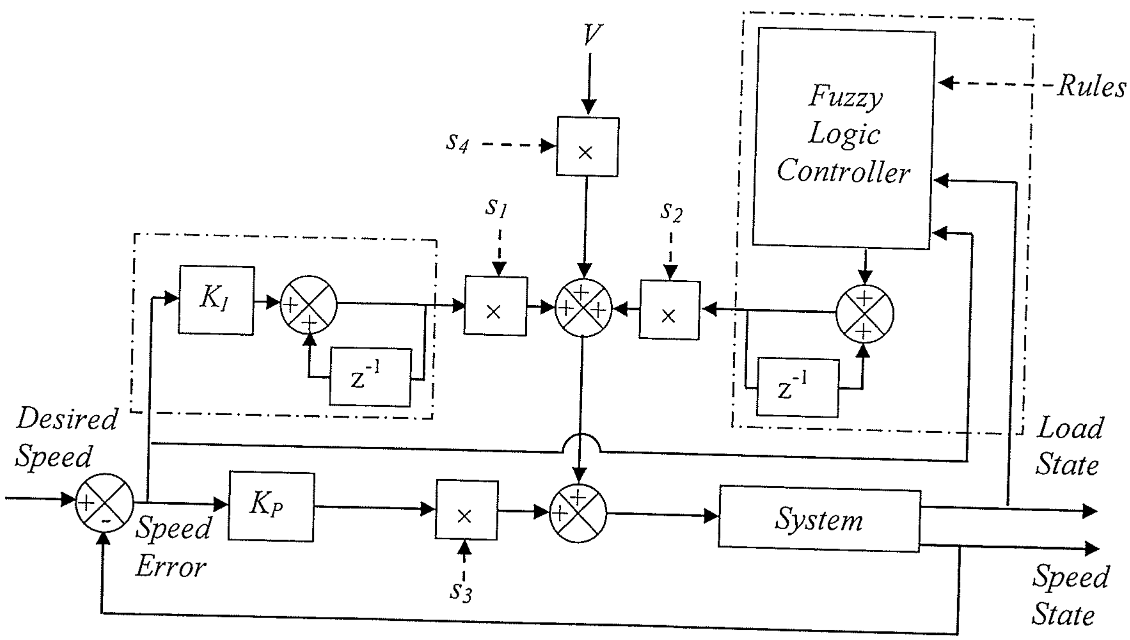


Figure 4.2 – Complete block diagram of the control system.

Table 4.2 – Opening and closing parameters.

Case	*Cable 1*	*Cable 2*
Open	$s_1, s_2, s_3, s_4 = 0$	$s_1, s_2, s_3 = 0$ $s_4 = 1$
Close	$s_1, s_2, s_3 = 0$ $s_4 = 1$	$s_1, s_2, s_3, s_4 = 0$

Referring to Figure 4.2 and to Table 4.2, the parameters s_1 and s_2 are identical to the parameters shown in Figure 4.1 and Table 4.1. The additional parameters of s_3 and s_4 are used to open and close the clamming device. For example, to open the clamming device, s_1, s_2 and s_3 are all set to 0. The parameter s_4 for Cable 1 is set to 0 while s_4 for Cable 2 remains 1. This allows a constant voltage to be passed to the solenoids controlling the hydraulic motor for Cable 2. Cable 1 remains stationary as Cable 2 ascends to open the clamming device. To close the clamming device, Cable 1 is supplied the constant voltage to lift that cable while Cable 2 remains stationary.

4.2 *Fuzzy Logic Membership Functions*

The two inputs required for this contoller are the load state and the speed error. The outputs are the control signals sent to the valves that operate each winch. The membership functions for the load state input variables are shown Figure 4.3.

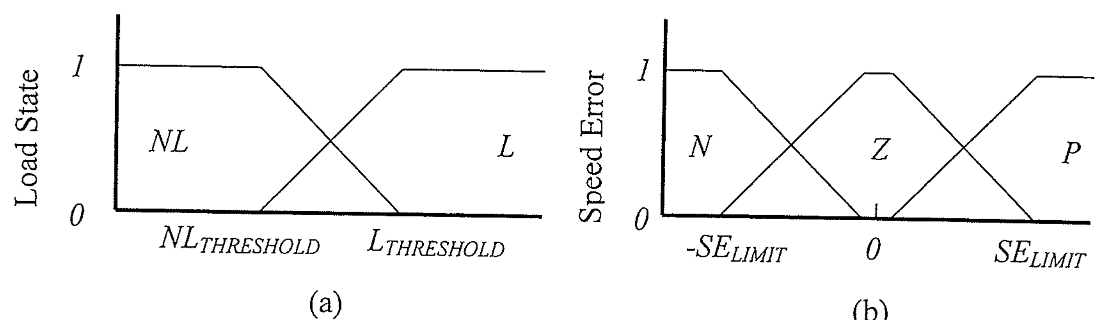


Figure 4.3 – Input membership functions.

Referring to Figure 4.3a, the load state (LS) is defined as the pressure differential across the hydraulic motor where a positive differntial indicates that the clamming device is ascending and a negative differential indicates that the clamming device is descending. At any point in time the load state exists in one of three regions, no load (NL), load (L), or the fuzzy region between these two regions. Any load state less than the no load threshold, $NL_{THRESHOLD}$, is fully in the no load region where only NL exists. Any load state greater than the load threshold, $L_{THRESHOLD}$, is fully in the load region where only L exists. If the load state is between $NL_{THRESHOLD}$ and $L_{THRESHOLD}$ then it exists in the fuzzy region, where both NL and L co-exist with their degrees of membership in each memebership function valued between 0.0 and 1.0.

The values for $NL_{THRESHOLD}$ and $L_{THRESHOLD}$ are shown in Table 4.3. To simplify the control system, and to impose a minimum amount of modification to the experimental test rig, only one set of pressure tranducers are used, for Cable 2. The values shown in Table 4.3 were determined experimentally in two steps. First, the clamming device is fully opened, therefore Cable 2 is in tension and Cable 1 is slack. The clamming device is raised and lowered, and the pressure differential is recorded and plotted. Second, the clamming device is fully closed, putting all of the load on Cable 1 while Cable 2 is slack. The clamming device is raised and lowered, and the recorded pressure differential data are plotted and superimposed onto the first test, yielding a plot shown in Figure 4.4. The values for $NL_{THRESHOLD}$ and $L_{THRESHOLD}$ were estimated from plots similar to the one shown in Figure 4.4, as the values for the pressure differential varied day to day. The values in Table 4.3 are those used during the experimental evaluation of the controller.

Table 4.3 – Control Variables.

	Up	Down
$NL_{THRESHOLD}$	241.3 kPa (35 psi)	-137.9 kPa (-20 psi)
$L_{THRESHOLD}$	413.7 kPa (60 psi)	-103.4 kPa (-15 psi)
SE_{LIMIT}	10 rpm	10 rpm

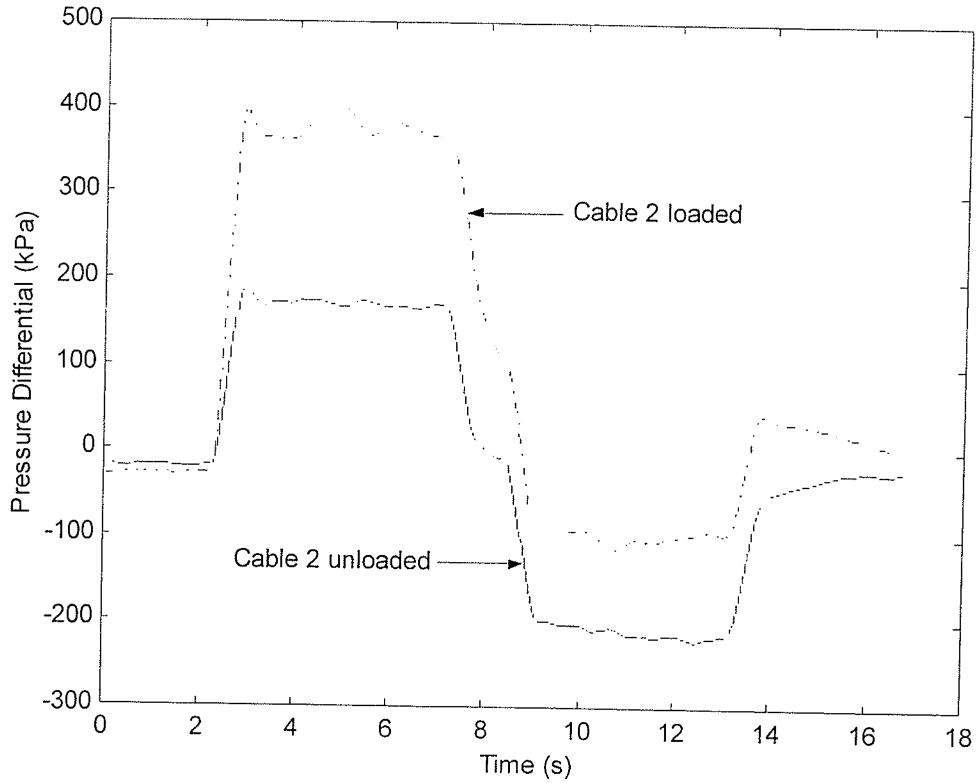


Figure 4.4 – Typical calibration test plot.

Figure 4.3b shows the membership functions used for speed error. Speed error (*SE*) is defined as the difference between the desired speed and the actual speed for each cable. The three speed error membership functions are broken up into five regions: negative (*N*), zero (*Z*), and positive (*P*), along with fuzzy regions between negative and zero, and zero and positive. Any speed error less than $-SE_{LIMIT}$ is fully in the negative region. Any speed error greater than SE_{LIMIT} is fully in the positive region. The zero membership function has a small band of acceptability around 0 rpm of ±0.15 rpm. This band of acceptability is included to increase the system's stability by making it less sensitive to fluctuations in the speed error during steady state conditions. Values of speed error that fall between $-SE_{LIMIT}$ and the lower limit of the band of acceptability fall into a fuzzy region where both N and Z co-exist and are valued between 0.0 and 1.0. The same is true for speed errors that lay between the upper limit of the band of acceptability and SE_{LIMIT} in the other fuzzy region, except that it is Z and P that co-exist and are valued between 0.0 and 1.0.

There are five output membership functions: negative large (*NL*), negative small (*NS*), zero (*Z*), positive small (*PS*) and positive large (*PL*). These output membership functions are shown in Figure 4.5. The values for the output membership functions were determined experimentally, given consideration to stability and the speed of the response.

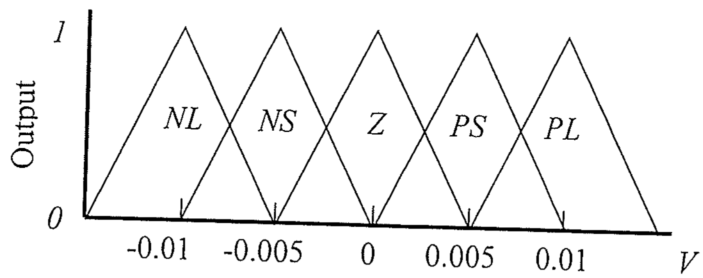


Figure 4.5 – Output membership functions.

4.3 Fuzzy Logic Rules

Since there are four unique operating modes investigated in this thesis, four unique sets of fuzzy logic rules are required. In the case of the up closed operating mode, Cable 1 ideally carries the full load while Cable 2 follows while bearing no load. Therefore, when the load is fully on Cable 1, the fuzzy logic controller brings Cable 2 to its desired speed while the PI controller for Cable 1 does the same. The rule matrix for the up closed operating mode for controlling Cable 2 is shown in Table 4.4a where the load state is imported from Cable 2 and the speed error is that of Cable 2. If Cable 2 begins to carry any portion of the load, a corrective measure is taken by the fuzzy logic controller to remove that load from Cable 2. This is accomplished by slowing the upward progress of Cable 2 until the load state has corrected itself. The use of the *NL* output membership function facilitates this response, since a negative incremental correction decreases the positive control signal sent to the solenoid controlling Cable 2, therefore slowing the cable's upward progress. These corrective responses necessarily create a speed error, but the fuzzy logic controller is capable of dealing with both the errors in the load state and speed error simultaneously. Once the load state is corrected, the fuzzy logic controller brings Cable 2 to its desired speed.

Table 4.4 – Fuzzy logic rules.

(a) **Up Closed**		**Load State**	
		NL	***L***
Speed Error	*N*	*NS*	*NL*
	Z	*Z*	*NL*
	P	*PS*	*NL*

(b) **Up Open**		**Load State**	
		NL	***L***
Speed Error	*N*	*NL*	*NS*
	Z	*NL*	*Z*
	P	*NL*	*PS*

(c) **Down Closed**		**Load State**	
		NL	***L***
Speed Error	*N*	*NS*	*PS*
	Z	*Z*	*PS*
	P	*PS*	*PS*

(d) **Down Open**		**Load State**	
		NL	***L***
Speed Error	*N*	*PS*	*NS*
	Z	*PS*	*Z*
	P	*PS*	*PS*

For the up open operating mode, Cable 2 ideally carries the full load of the clamming device under PI control while Cable 1 is driven by a PF controller to follow without any load. Table 4.4b shows the rule matrix for this operating mode, where the load state is measured for Cable 2 and the speed error is that of Cable 1. When the Cable 2 carries the full load, the fuzzy logic controller brings Cable 1 to its desired speed while the PI controller for Cable 2 does the same. In the presence of an error in the load state, the upward progress of Cable 1 is slowed through the use of the *NL* correction until the load state is corrected.

The cable loading situation for the down closed operating mode is identical to that of the up closed operating mode. Cable 1 ideally carries the full load while Cable 2 follows without any load. Cable 1 is controlled by a PF controller through the load state of Cable 2 and the speed error of Cable 1, while Cable 2 is PI controlled. Table 4.4c shows the rule matrix for this operating mode. When Cable 2 is carrying no load, the fuzzy logic controller acts to bring the speed of Cable 1 to its desired level. When any portion of the load is detected on Cable 2, the fuzzy logic controller responds to remove that load. This is accomplished by decreasing the downward speed of Cable 1 by using the *PS* output membership function until the load state has corrected itself. In order to increase the controller's stability, the fuzzy rules for the two descending cases utilize *PS* corrections instead of *PL* corrections at the cost of a somewhat slower response. The utilization of *PL* correction caused large overshoots and oscillatory speed responses.

The cable loading for the down open operating mode is opposite that of the down closed operating mode; Cable 2 ideally carries the full load while Cable 1 follows without load. A PF controller controls Cable 2 and Cable 1 is PI controlled in this study. The load state is taken from Cable 2, and the speed error used is measured from Cable 2. Table 4.4d shows the rule matrix for the down open operating mode. The fuzzy logic controller brings the speed of Cable 2 to its desired value when Cable 2 is fully loaded. When a portion of the load is taken by Cable 1, the fuzzy logic controller responds as described for the up closed operating mode, except that it is Cable 2's downward progress that is slowed to allow the load state to correct itself.

In order to facilitate the fastest possible response to an error in the load state of the clamming device, a special condition is coded into the controller. When the incorrect cable begins to take a significant portion of the load, the controller sets the speed error to zero, to make the correction of the load state the highest priority. Referring to Table 4.4, this condition occurs when the degree of membership in L becomes greater than 0.15 for the up closed and down closed operating modes, or when the degree of membership in NL becomes greater than 0.15 for the up open and down open operating modes. This allows the fuzzy logic portion of the controller to operate within a simplified set of rules, and prevents conflicts between positive and negative outputs that would delay the corrective response of the controller. Also, the fuzzy control signal is uni-polar for all operating modes, i.e. it cannot switch from positive to negative or vice versa.

4.4 Fuzzy Control Surfaces

Fuzzy control surfaces are used to evaluate the linearity of a fuzzy logic portion of the controller. Since each of the operating modes has its own set of rules, each will have its own unique fuzzy control surface. Figures 4.6 through 4.9 show the fuzzy control surfaces for each of the four operating modes. While the overall fuzzy control surfaces are nonlinear, certain regions are linear. These regions correspond with columns or rows in the rule matrix. For example, in the case of the up closed operating mode, the L

column of the load state generates an *NL* response that leads to the large flat region for all speed errors and load states above 413.7 kPa, as the rule matrix implies (see Figure 4.6).

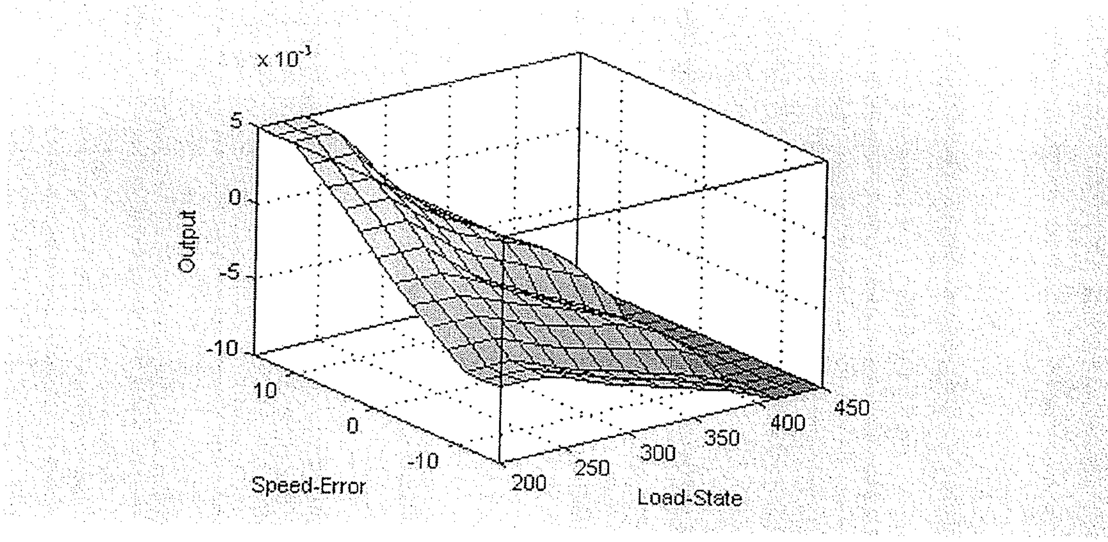


Figure 4.6 – Fuzzy control surface for up closed operating mode. (load state (kPa), speed error (rpm), output (V))

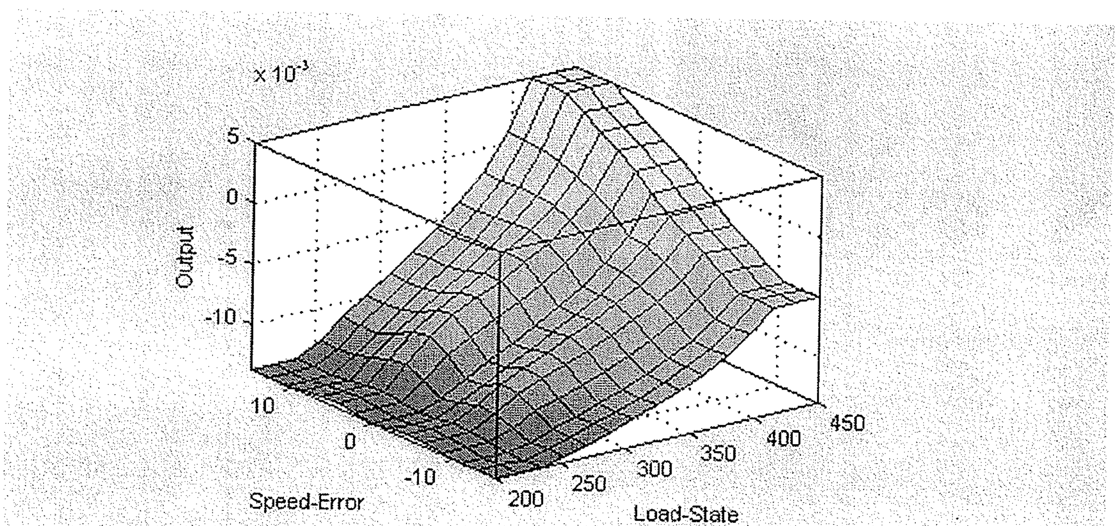


Figure 4.7 – Fuzzy control surface for up open operating mode. (load state (kPa), speed error (rpm), output (V))

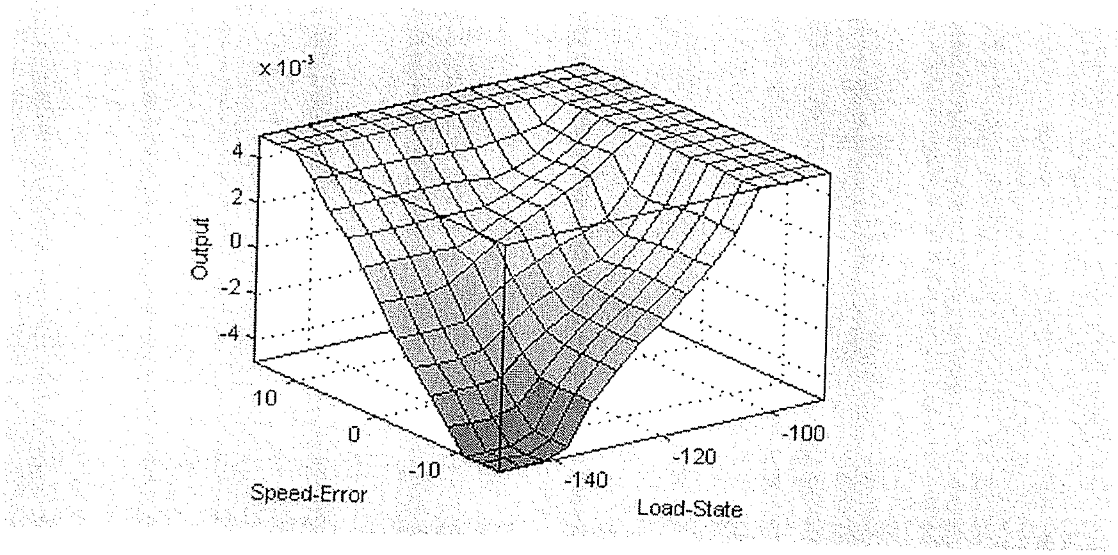


Figure 4.8 – Fuzzy control surface for down closed operating mode. (load state (kPa), speed error (rpm), output (V))

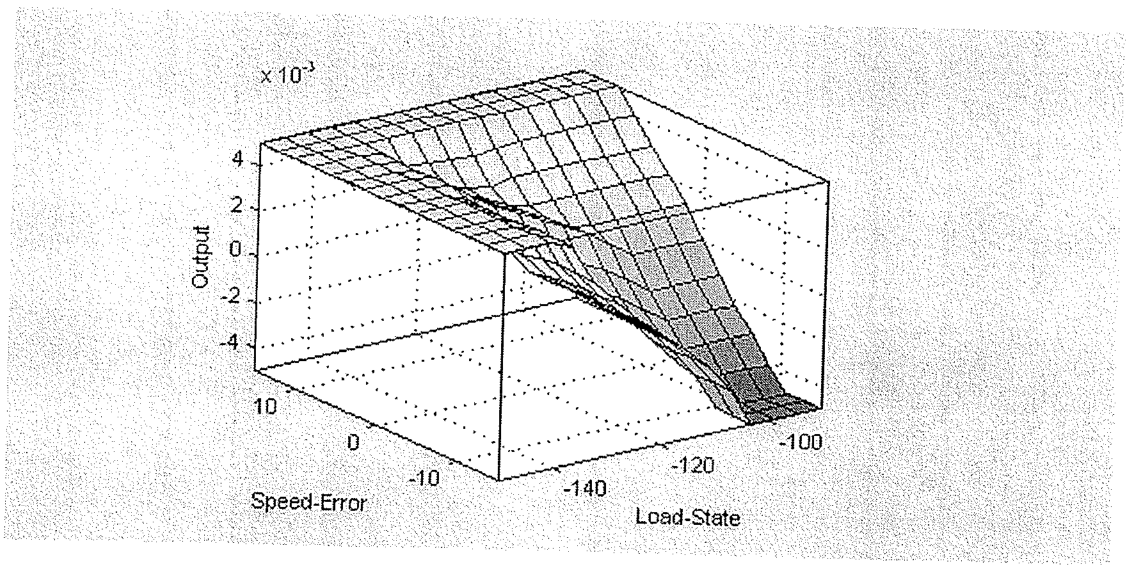


Figure 4.9 – Fuzzy control surface for down open operating mode. (load state (kPa), speed error (rpm), output (V))

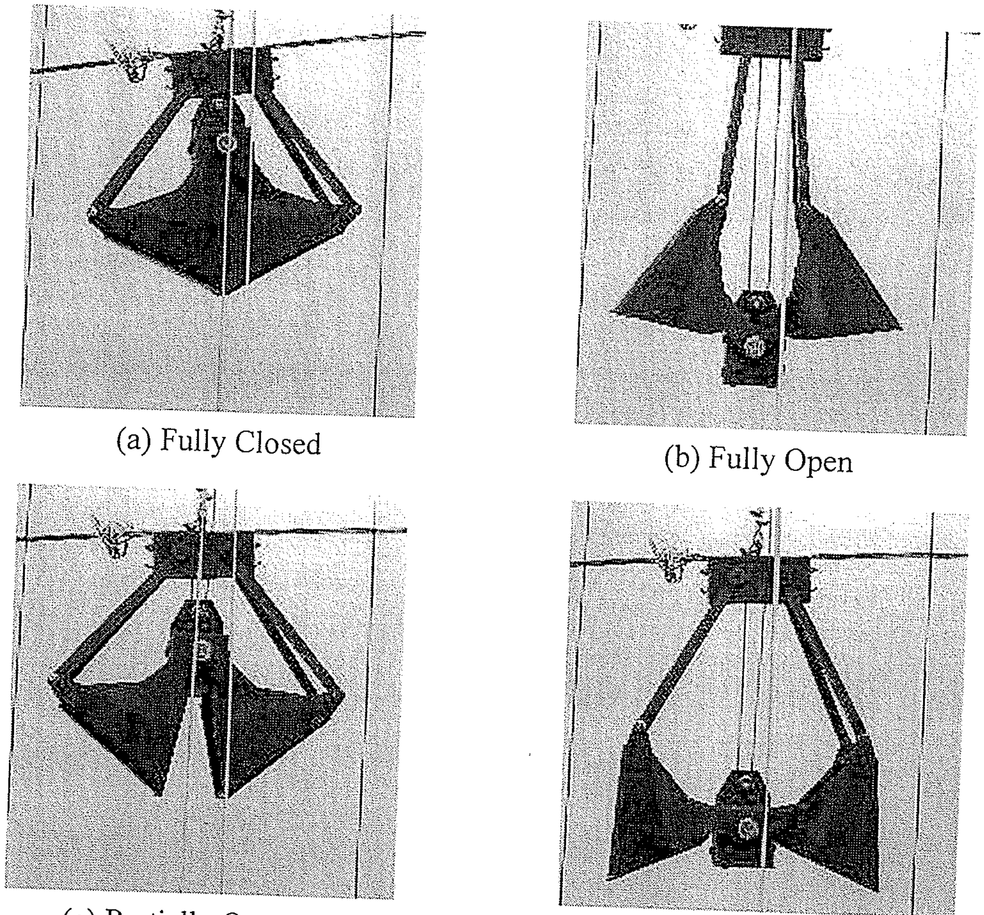
Chapter 5

Experimental Results

This chapter outlines the results obtained on the experimental test rig described in Chapter 3. Section 5.1 describes the results of the simple case studies for each of the four operating modes. A complete explanation of the fuzzy logic control performance for the up closed test study is documented. Section 5.2 details a study of two operating modes tested sequentially with an external load present. Section 5.3 presents three advanced case studies that are sequential combinations of the operating modes to simulate typical trash removal operations.

5.1 Simple Case Studies

In this section, the results pertaining to the simple case studies are presented. There are four operating modes for the clamming device: up closed, up open, down closed and down open. Each of the simple case studies was conducted for two scenarios, one with the clamming device fully open or fully closed as prescribed by the particular operating mode to be used, and one with an initial error in the load state of the clamming device introduced by partially opening or closing the clamming device. Figure 5.1 shows the four different initial positions of the clamming device used in these studies.



(a) Fully Closed

(b) Fully Open

(c) Partially Open

(d) Partially Closed

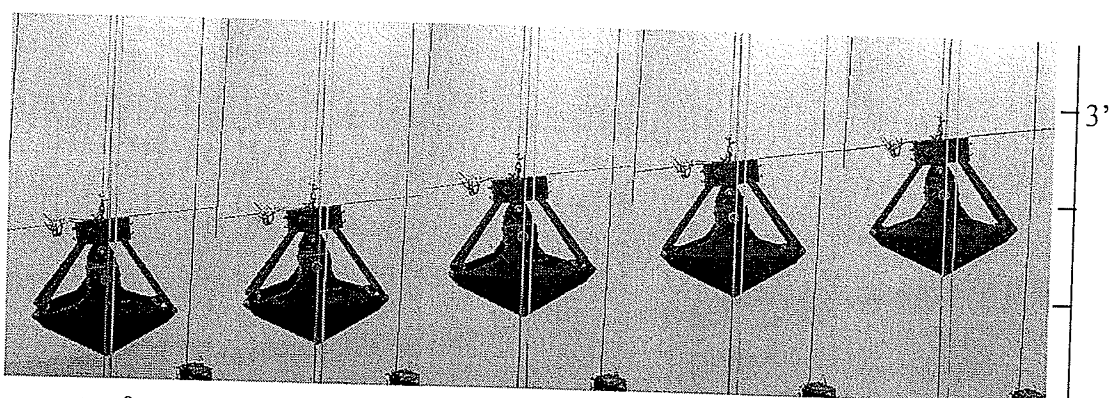
Figure 5.1 – Initial positions of the clamming device.

The studies performed with the clamming device fully open or closed are conducted with the proper cable carrying the full load and the other cable tensionless as shown in Figures 5.1a and 5.1b. In the studies with the clamming device initially partially open or closed, the tension on each cable was preset incorrectly by partially opening (see Figure 5.1c) or closing (see Figure 5.1d) the clamming device, causing an initial load state error for the controller to correct. This causes the cables to share the load between them. Optimally, only one cable at a time is expected to carry the full load of the clamming device plus any external loading. Cable 1 should carry the full load when the clamming device is fully closed, and Cable 2 should carry the full load when the clamming device is fully open.

5.1.1 – Up closed study with clamming device initially fully closed

In this study the clamming device is intended to move upward at a constant winch speed of 15 rpm while remaining fully closed during ascension. In the case of this study, the cable loading is preset to ensure that Cable 1 carries the full load and is therefore fully closed to start the study. An experienced operator would complete this task by lifting Cable 1 at a constant speed while observing Cable 2. Cable 2 must follow the upward progress of Cable 1 without carrying any portion of the load.

Figure 5.2 shows a sequence of digital photographs of the clamming device. The sequence begins and ends with the clamming device fully closed as it ascends approximately 1 foot every 10 seconds. Only the first 12 seconds are shown in the photograph sequence for brevity, as a steady state of ascension has been reached.



t ≈ 0s t ≈ 3s t ≈ 6s t ≈ 9s t ≈ 12s

Figure 5.2 – Photo sequence for the up closed study with the clamming device initially fully closed.

In the controller designed here, a PI controller drives Cable 1 to 15 rpm while a PF controller controls the speed of Cable 2 to do the same while receiving inputs from the load state of Cable 2 and the speed error of Cable 2. Without the presence of an error in the load state, the speed response of Cable 2 is expected to closely follow the speed response of Cable 1, as shown in Figure 5.3.

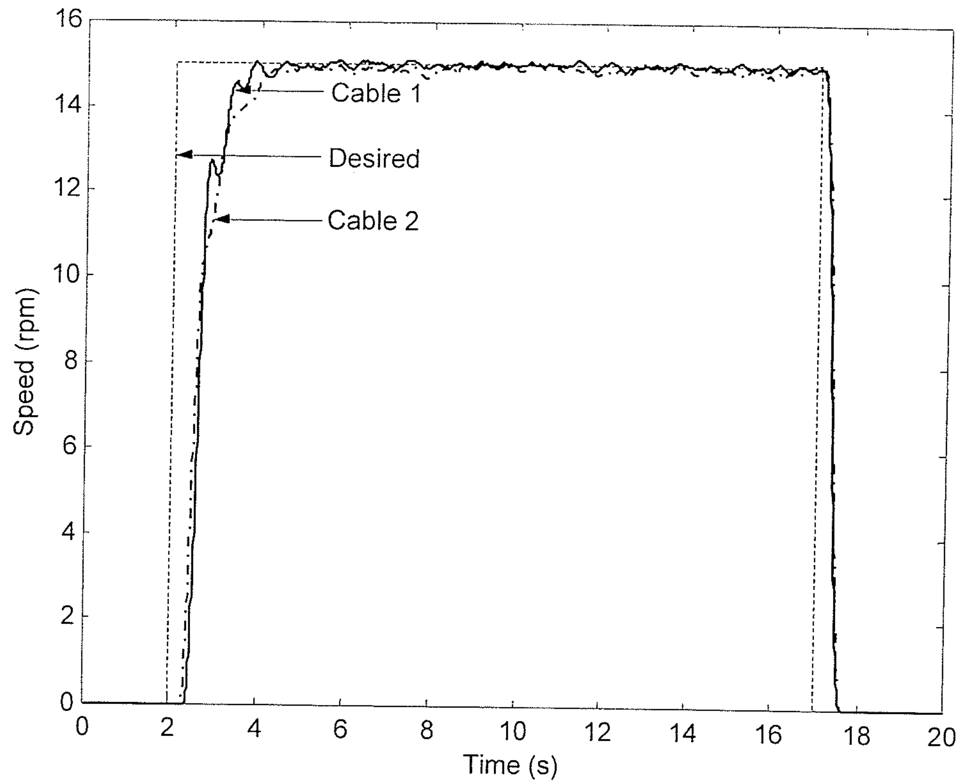


Figure 5.3 – Speed responses pertaining to Figure 5.2.

Figure 5.4 shows the input values, i.e. load state and speed error, for the fuzzy logic controller that controls Cable 2. To explain how the fuzzy controller drives the system, a single operating point is considered. Referring to Figure 5.4, consider operating point *A* at t ≈ 3s. For this operating point, which corresponds to a transient phase of the controller, the speed error is 3.12 rpm and the load state is 218.8 kPa. Figure 5.5 depicts how the values of the degree of membership for the load state and speed error for this operating point are determined.

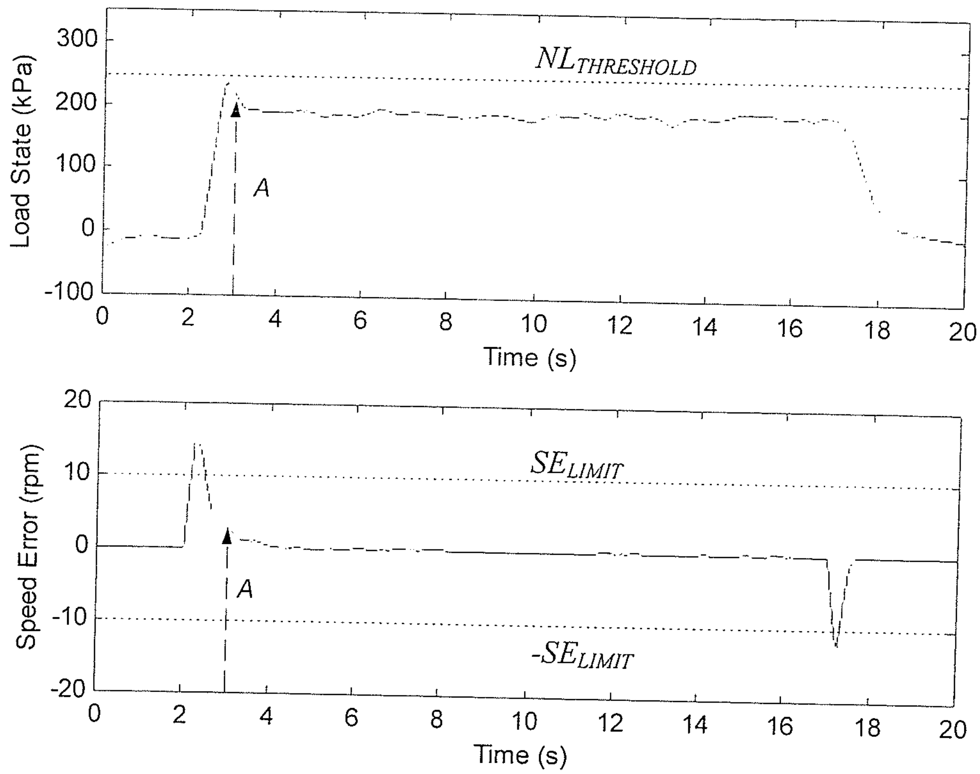


Figure 5.4 – Inputs pertaining to Figure 5.2.

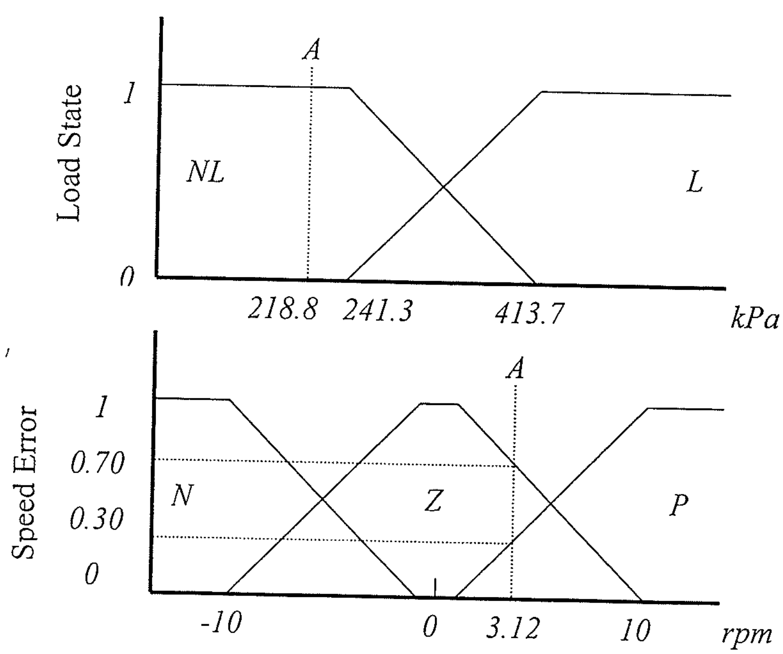


Figure 5.5 – Degree of membership for a selected point pertaining to Figure 5.2.

Operating point A exists only in the load state membership function of no load (NL), indicating a degree of membership of 1.0 for NL and a degree of membership of 0.0 for load (L). Operating point A co-exists in two membership functions simultaneously for speed error: Z and P. This correlates to a degree of membership of 0.70 in Z, and a degree of membership of 0.30 in P. These values for operating point A are shown in Figure 5.6 along with the degree of membership data for the study.

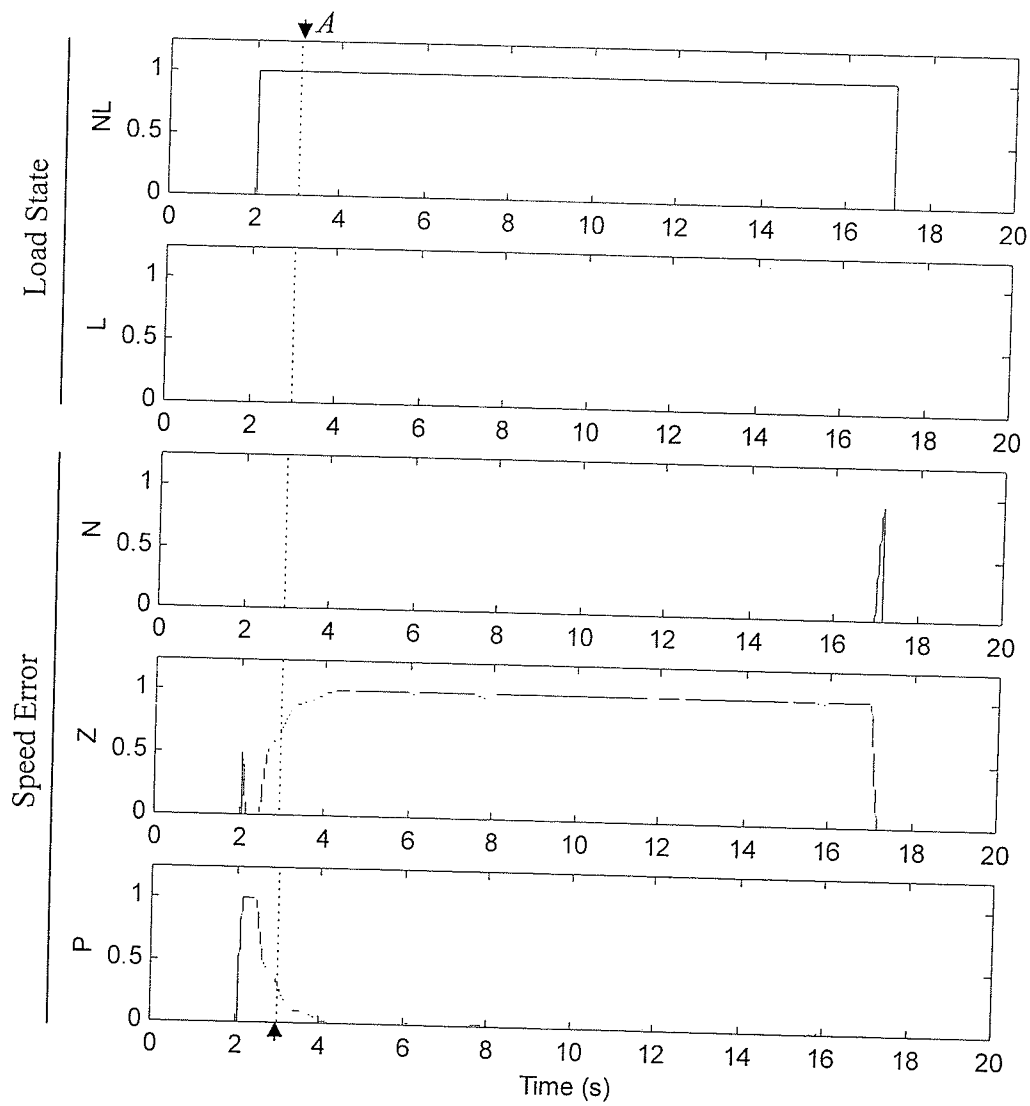


Figure 5.6 – Degrees of membership pertaining to Figure 5.2. (NL = No Load, L = Load, N = Negative speed error, Z = Zero speed error, P = Positive speed error)

Referring to Figure 5.6, the fuzzy logic rules are evaluated with these degrees of membership as inputs to the controller to determine a crisp output response. The fuzzy logic rules for operating point A are evaluated as shown in Figure 5.7.

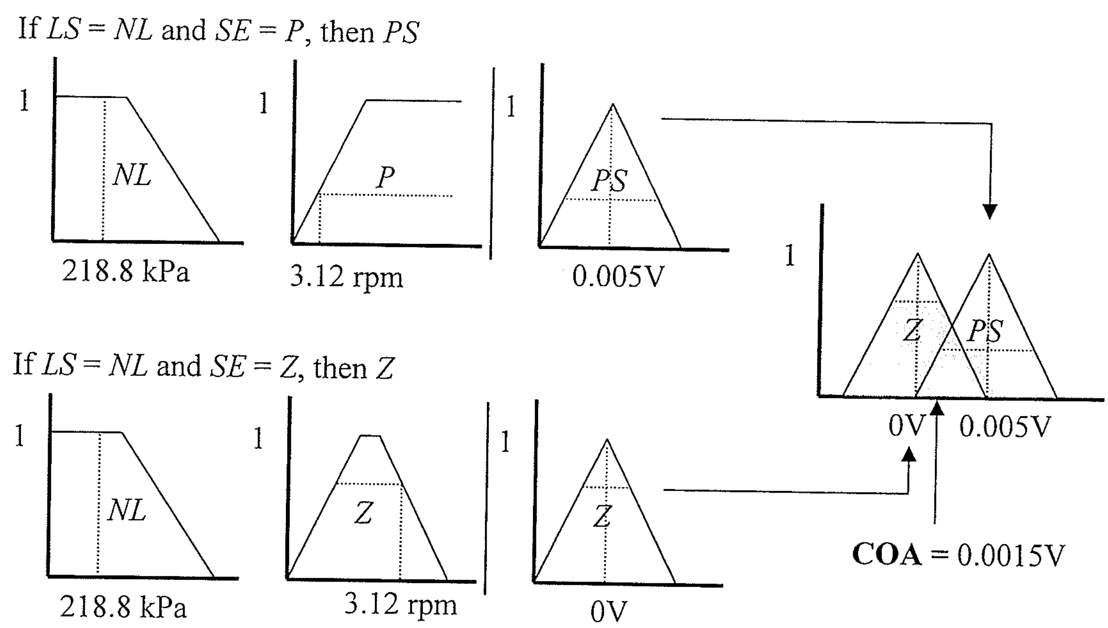


Figure 5.7 – Fuzzy reasoning and defuzzification for operating point *A*.

Referring to Figure 5.7, the center of area (COA) for point A is a positive value indicating a change in the incremented output of the fuzzy logic controller for Cable 2 to increase the rate of the upward progress of Cable 2 to its desired speed. Figure 5.8 shows the output values for the entire study along with the incremented fuzzy output. For each time step, the COA of the outputs is calculated as shown in Figure 5.7 and incremented onto the previous value, like an integral type controller. The incremented fuzzy output, shown in the bottom plot of Figure 5.8, is added to the instantaneous proportional signal to yield the total output signal applied to Cable 2 of the system. This PF control signal is shown in Figure 5.9. Figure 5.10 shows the PI control signals for Cable 1.

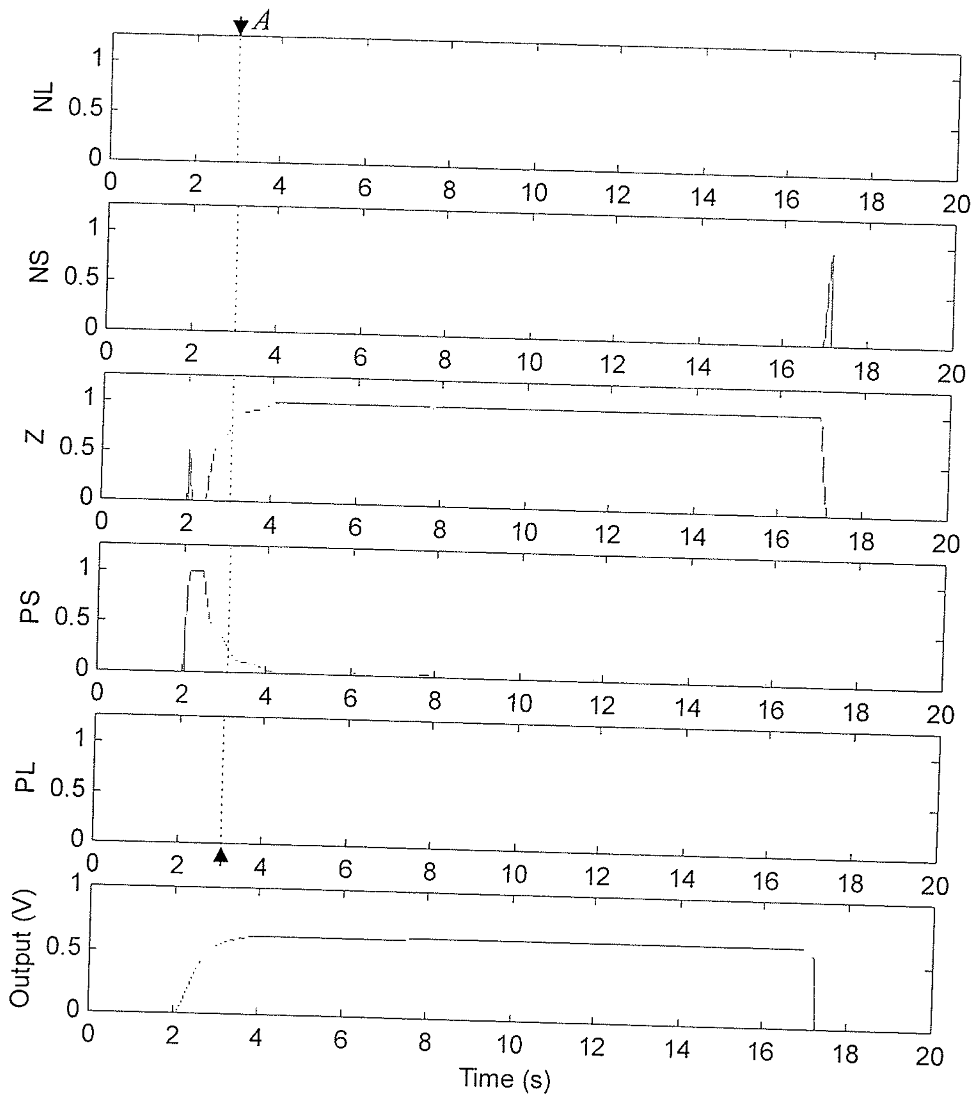


Figure 5.8 – Fuzzy and total outputs pertaining to Figure 5.2. (NL = negative large, NS = negative small, Z = zero, PS = positive small, PL = positive large)

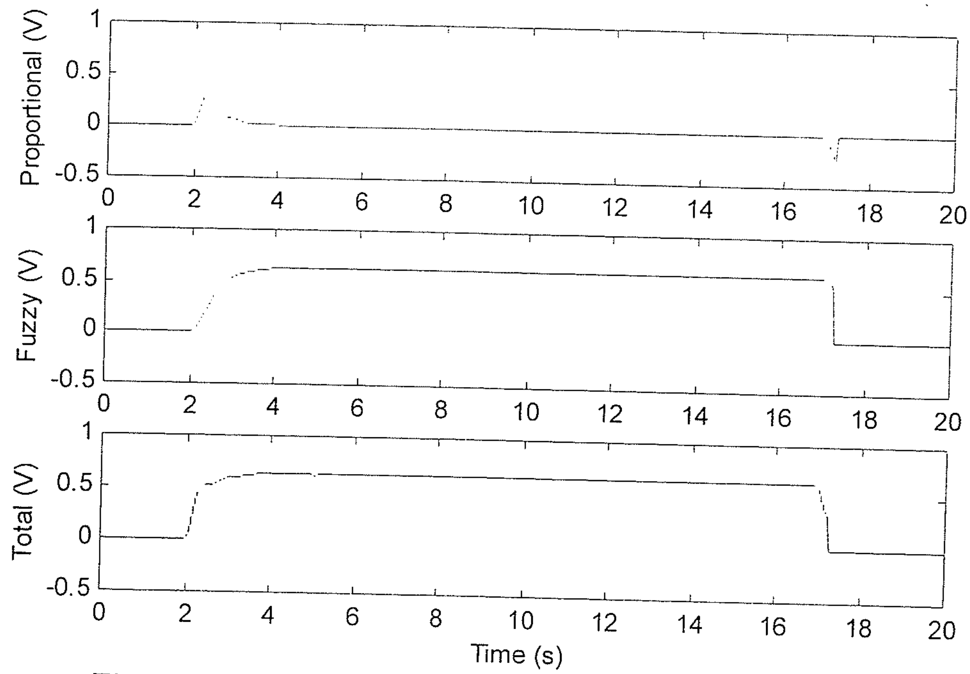


Figure 5.9 – Cable 2 control signals pertaining to Figure 5.2.

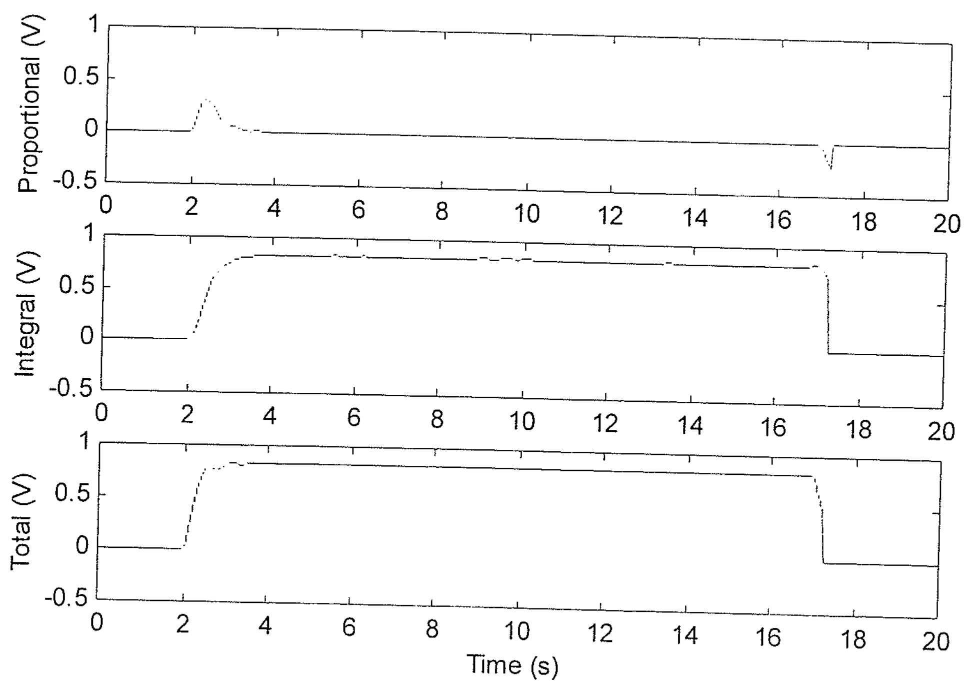


Figure 5.10 – Cable 1 control signals pertaining to Figure 5.2.

To validate the speed response to the system, the speed differential (SD), defined as the difference between the speed of Cable 1 and the speed of Cable 2, is measured. A positive SD indicates that the clamming device is closing, due to the fact that the speed of Cable 1 is greater than the speed of Cable 2. A negative SD indicates that the clamming device is opening because the speed of Cable 2 is greater than the speed of Cable 1. Referring to Figure 5.11, the slight negative discrepancy in the speed differential at t ≈ 2.5s is due to the difference in the deadbands in the hydraulic valves used on the experimental test apparatus. The deadband is approximately ±0.45 V for Cable 1 and approximately ±0.30 V for Cable 2. It takes the control signal for Cable 1 longer to emerge from the deadband than for the control signal for Cable 2. During steady state operation after t ≈ 4s, the speed differential becomes small, indicating that the clamming device has remained in its initial position throughout the study, as shown in Figure 5.2.

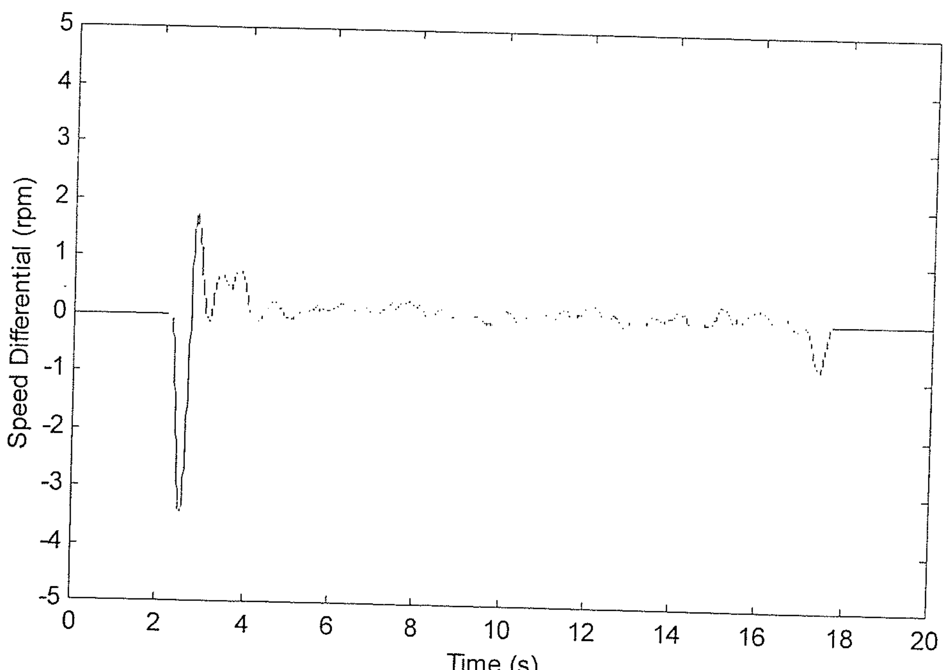


Figure 5.11 – Speed differential pertaining to Figure 5.2.

The speed responses of the two cables are highly similar, showing that the controller is operating properly but not at its full multivariable capacity. The next study introduces an error in the load state, allowing the full potential of the fuzzy logic portion of the controller to be realized.

5.1.2 – Up closed study with clamming device initially partially open

This study is similar to the previous study in all respects but one; a load error has been introduced to the system by partially opening the clamming device at the beginning of the study (see Figure 5.1c). The operator would correct this error by slowing the upward progress of Cable 2 until he/she visually determines that Cable 2 loses tension while moving both cables upward.

Figure 5.12 shows a sequence of digital photographs of the clamming device for this study. The sequence begins with the clamming device partially open as seen in the leftmost digital photograph. At t ≈ 4.5s the clamming device closes fully and begins to ascend at a constant speed of 15 rpm while remaining fully closed.

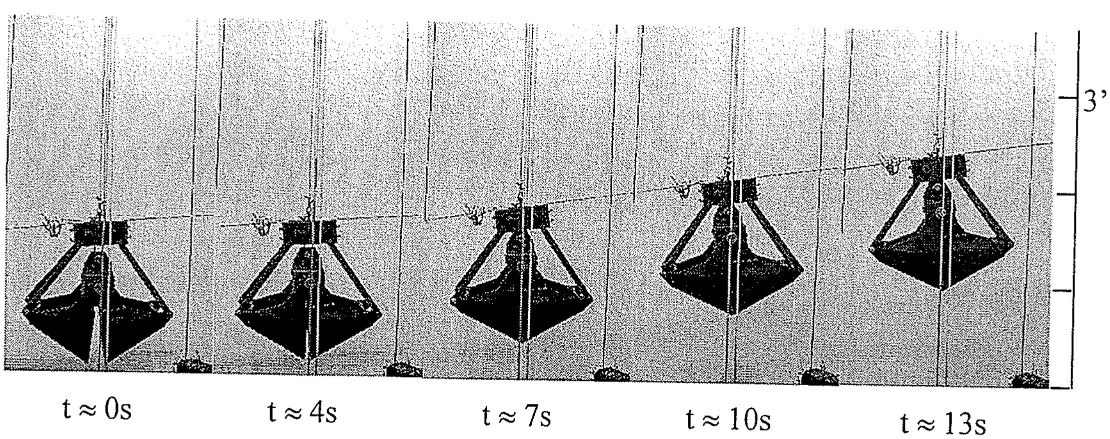


Figure 5.12 – Photo sequence for up closed study with the clamming device initially partially open.

In the case of the proposed controller, Cable 1 is PI controlled and ascends at a constant rate of 15 rpm while the PF controller driving Cable 2 reduces the speed of that cable in response the presence of a load on Cable 2. The controller is not aware in advance that the clamming device is partially open; it determines that the clamming device is partially open by assessing the pressure differential once the cables have started to move. Once the load is fully restored to Cable 1, i.e. the clamming device is fully closed, the PF controller brings the speed of Cable 2 to 15 rpm, matching the speed of Cable 1. The speed responses of the cables subject to the initial error in the load state are shown in Figure 5.13. The speed responses in Figure 5.13 are quite different than those observed in Figure 5.3 as a result of the control system having to mitigate the effects of the incorrect load state present in this study.

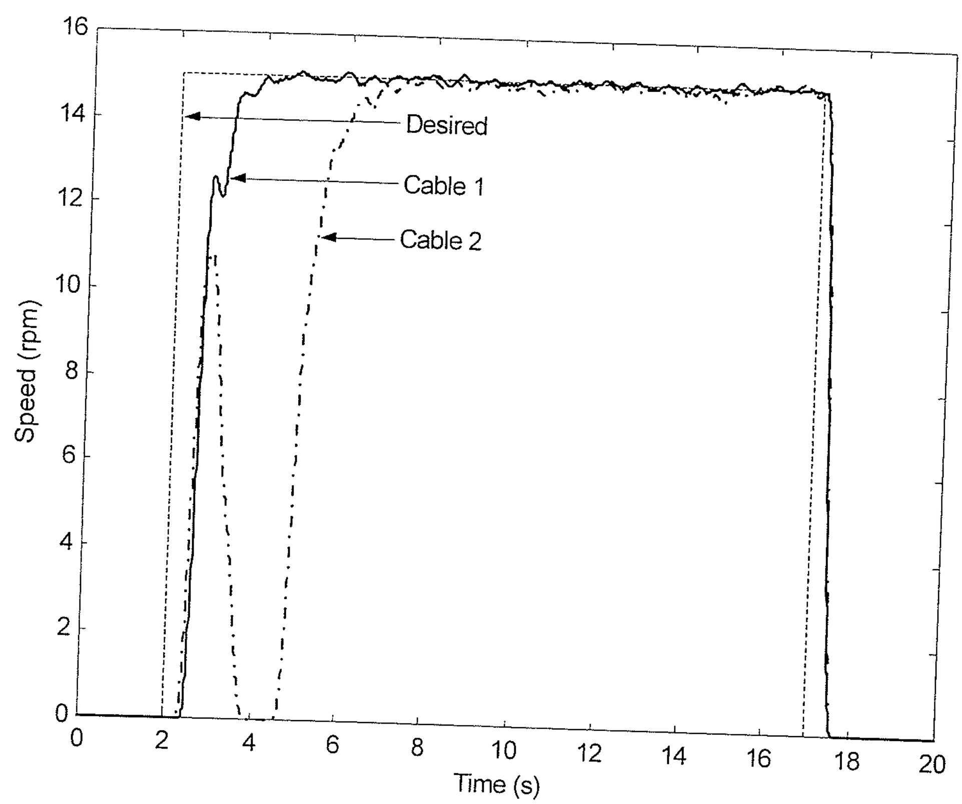


Figure 5.13 – Speed responses pertaining to Figure 5.12.

Referring to Figure 5.13, the reason for the initial increase in the speed of Cable 2 is observed in Figure 5.14, which shows the input values for load state and speed error used by the fuzzy logic controller that controls Cable 2. Initially, the PF controller for Cable 2 attempts to lift that cable at 15 rpm because the inputs indicate that the load state is correct, for this operating mode, despite the error in the load state produced by partially opening the clamming device at the beginning of the study. Once the load state surpasses the no load threshold of 241.3 kPa (at t ≈ 2.75s) as a result of the error in the load state and the controller determines that a corrective action is needed, the fuzzy logic portion of the controller decreases the speed of Cable 2 until the load state drops below the no load threshold at t ≈ 4s. The temporary difference in the relative speeds of the cables, as seen in Figure 5.13, causes the clamming device to close. Once the clamming device is fully closed at t ≈ 4.5s, the system returns Cable 2 to its desired speed of 15 rpm.

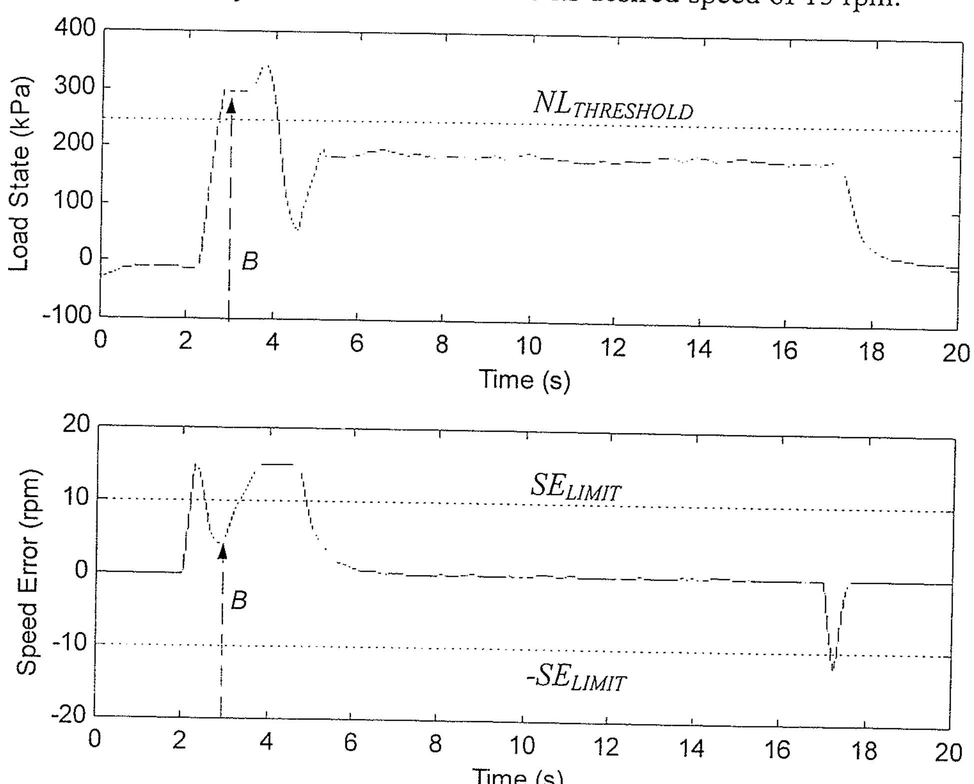


Figure 5.14 – Inputs pertaining to Figure 5.12.

Referring to Figure 5.14, at operating point B (t ≈ 3s) the speed error is 5.21 rpm and the load state is 296.2 kPa. These values for point B are shown in Figure 5.15, where their respective degrees of membership are displayed. Operating point B co-exists in a pair of membership functions for both the load state and speed error inputs. In the case of load state, the degree of membership values for NL and L are 0.68 and 0.32, respectively. The speed error of operating point B yields a degree of membership in Z of 0.49 and a degree of membership in P of 0.51.

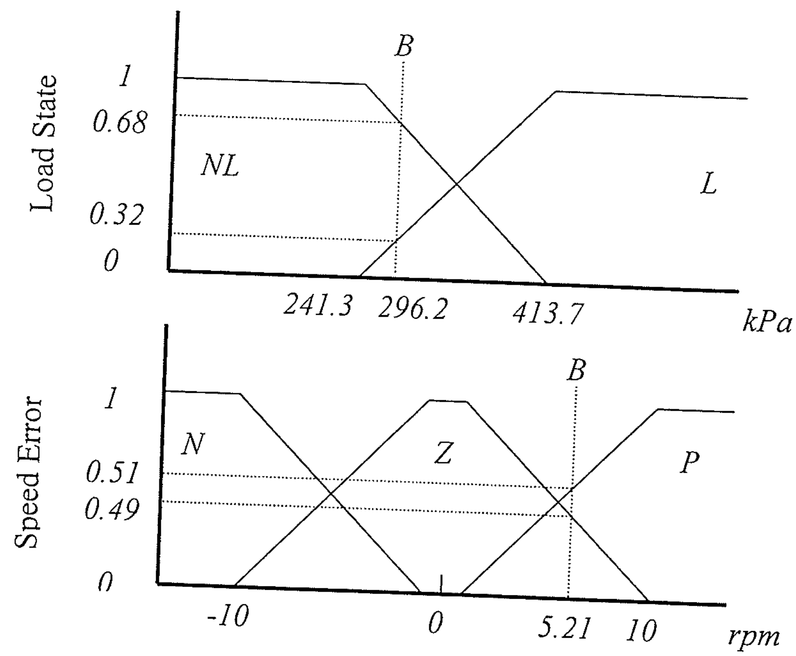


Figure 5.15 – Degree of membership for a selected point pertaining to Figure 5.12.

The above-mentioned data for the degree of membership of the load state is shown in Figure 5.16 with the full degree of membership data for the study. The speed error at t ≈ 3s in Figure 5.16 shows a value of 1.0 for Z and values of 0.0 for each of P and N. This is a result of the special condition, described in Section 4.3, to make the removal of the error in the load state the highest priority by simplifying the fuzzy rules used in determining the output signal sent to the solenoids.

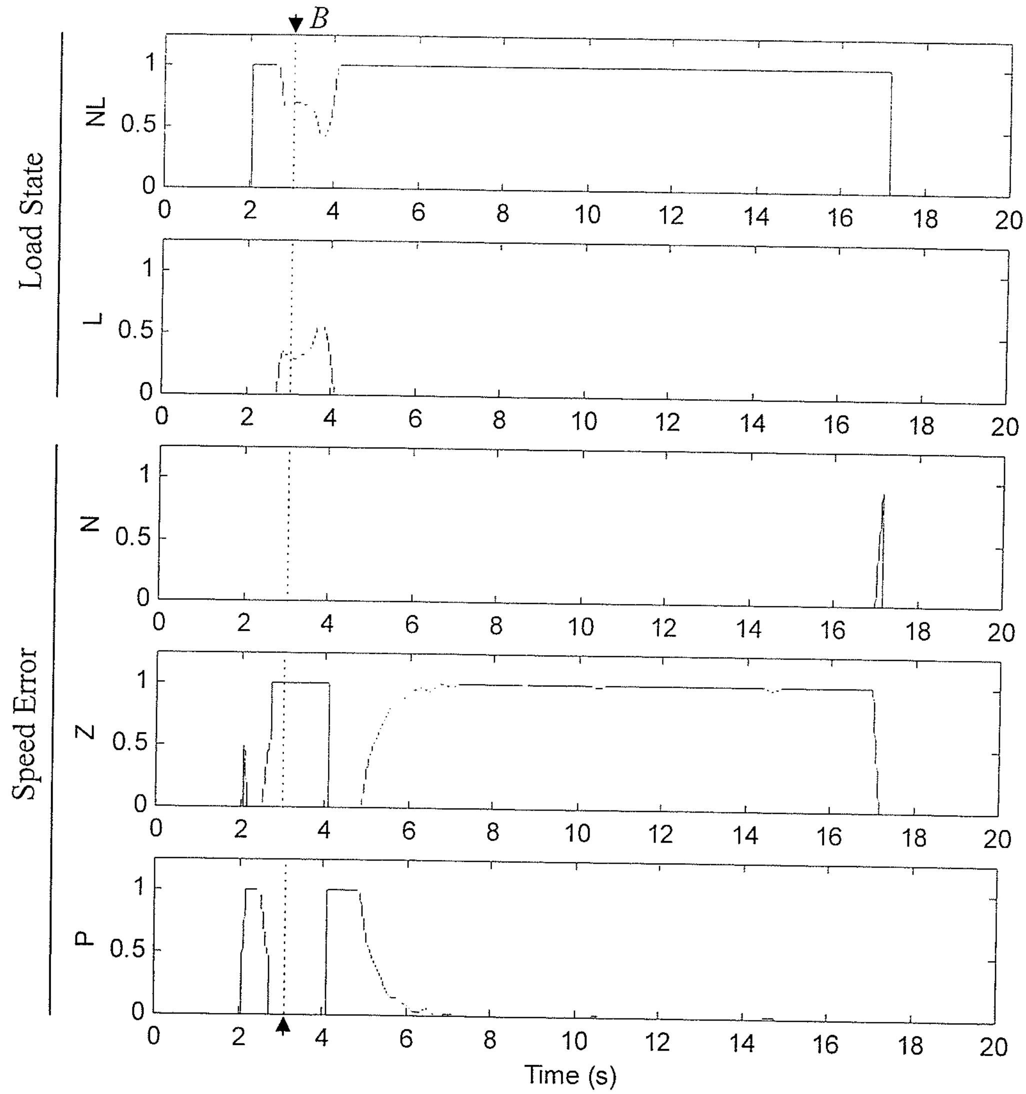


Figure 5.16 – Degrees of membership pertaining to Figure 5.12. (NL = No Load, L = Load, N = Negative speed error, Z = Zero speed error, P = Positive speed error)

The fuzzy rules for operating point *B* given the previously mentioned condition are evaluated as shown in Figure 5.17, which shows the COA for point *B* as a negative value. This value would decrease the output signal of Cable 2 therefore decreasing its speed, as expected in the presence of an error in the load state. Figure 5.18 shows these fuzzy output values for point B along with the data for the fuzzy outputs and the total incremented fuzzy response for this study. The incremented fuzzy output, shown in the last plot of Figure 5.18, is added to the instantaneous proportional signal to yield the total control signal for Cable 2 as shown in Figure 5.19.

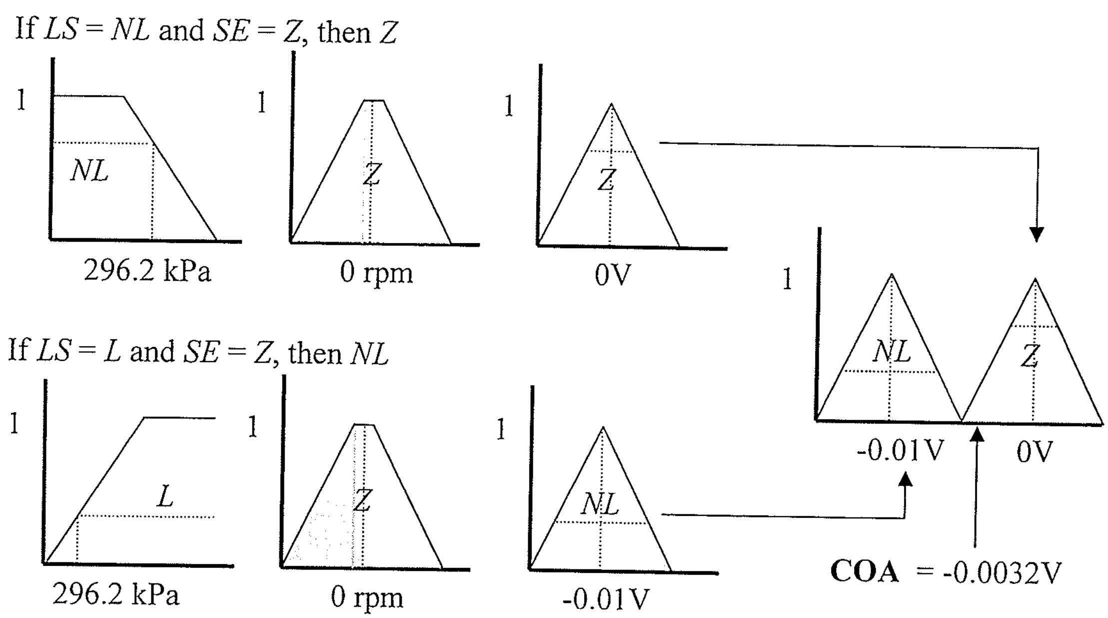


Figure 5.17 – Fuzzy reasoning and defuzzification for operating point *B*.

Referring to Figure 5.19, the proportional signal alone, from $t \approx 3.5$s to $t \approx 4.5$s, for Cable 2 is insufficient to cause the total output voltage to exceed the deadband threshold, which is confirmed by a speed of zero at the same period of time as shown in Figure 5.13. This has been found to be advantageous to create a swift and stable corrective response to a load state error. The total PF control signal for Cable 2, shown in Figure 5.19, is quite different from that of the PI control signals for Cable 1, as shown in Figure 5.20, due to the fuzzy logic controller correcting the load error introduced by partially opening the clamming device at the beginning of the study. The fuzzy control signal is uni-polar for all operating modes, i.e. it cannot switch from positive to negative. This is seen in Figure 5.19 from t ≈ 3.5s to t ≈ 4.5s, where the fuzzy control signal remains positive at all times.

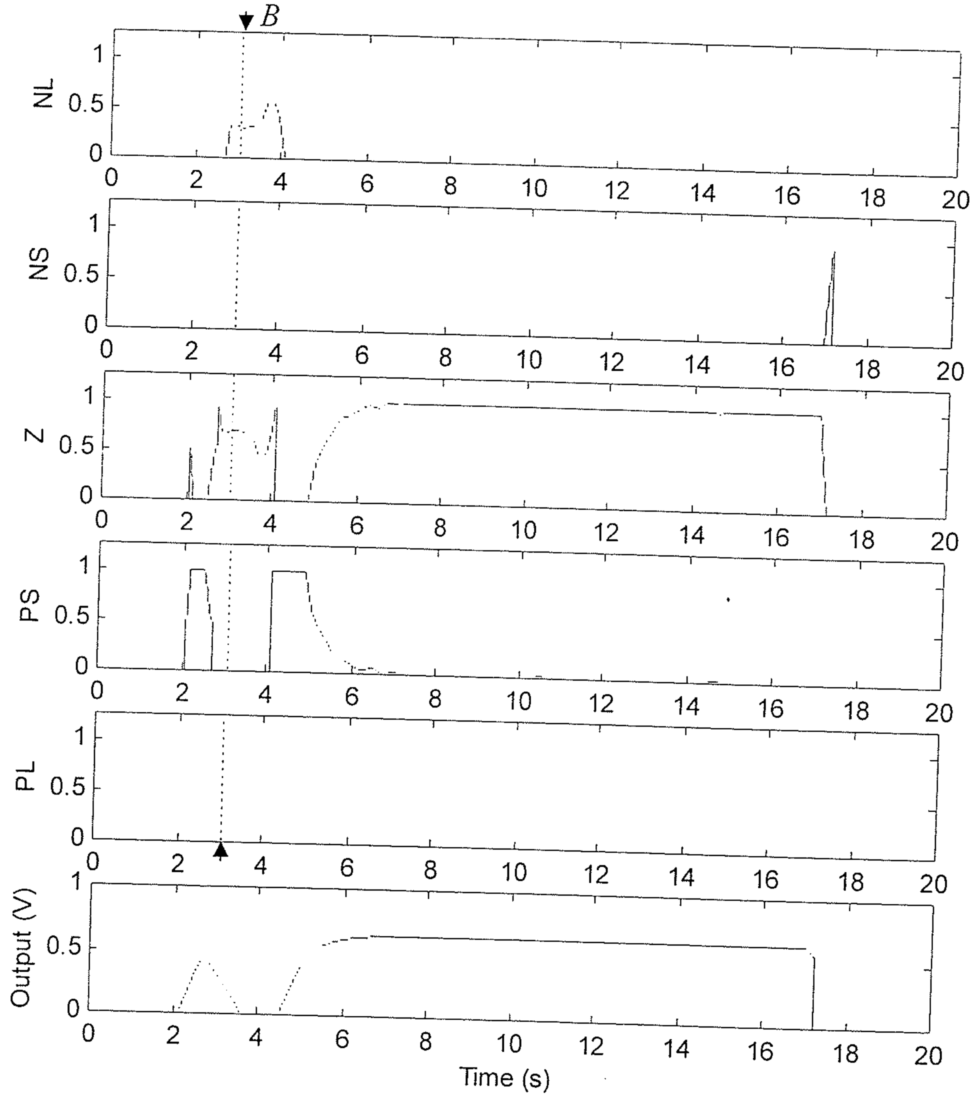


Figure 5.18 – Fuzzy and total outputs pertaining to Figure 5.12. (NL = negative large, NS = negative small, Z = zero, PS = positive small, PL = positive large)

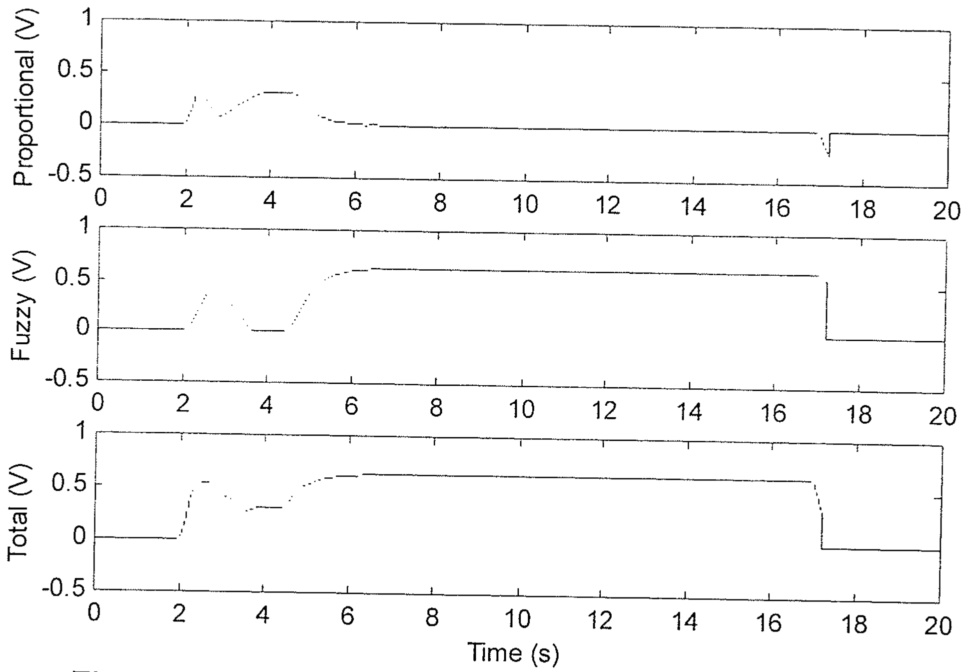


Figure 5.19 – Cable 2 control signals pertaining to Figure 5.12.

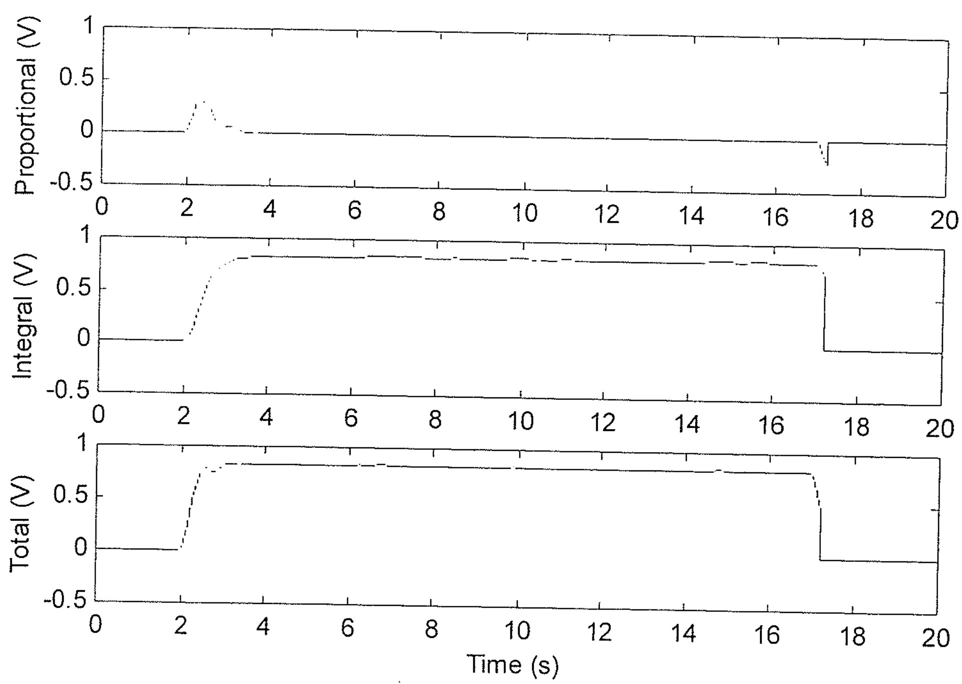


Figure 5.20 – Cable 1 control signals pertaining to Figure 5.12.

Figure 5.21 shows the speed differential for this study. A small negative discrepancy due to the differing deadband thresholds is visible, along with a large positive speed differential between t ≈ 3s and t ≈ 5s, indicating that the clamming device closes. The speed differential rapidly decreases after the clamming device fully closes at t ≈ 4.5s, due to Cable 2 accelerating to 15 rpm after the load fully returns to Cable 1. The corrective action taken by the fuzzy logic controller here shows the full potential of the controller.

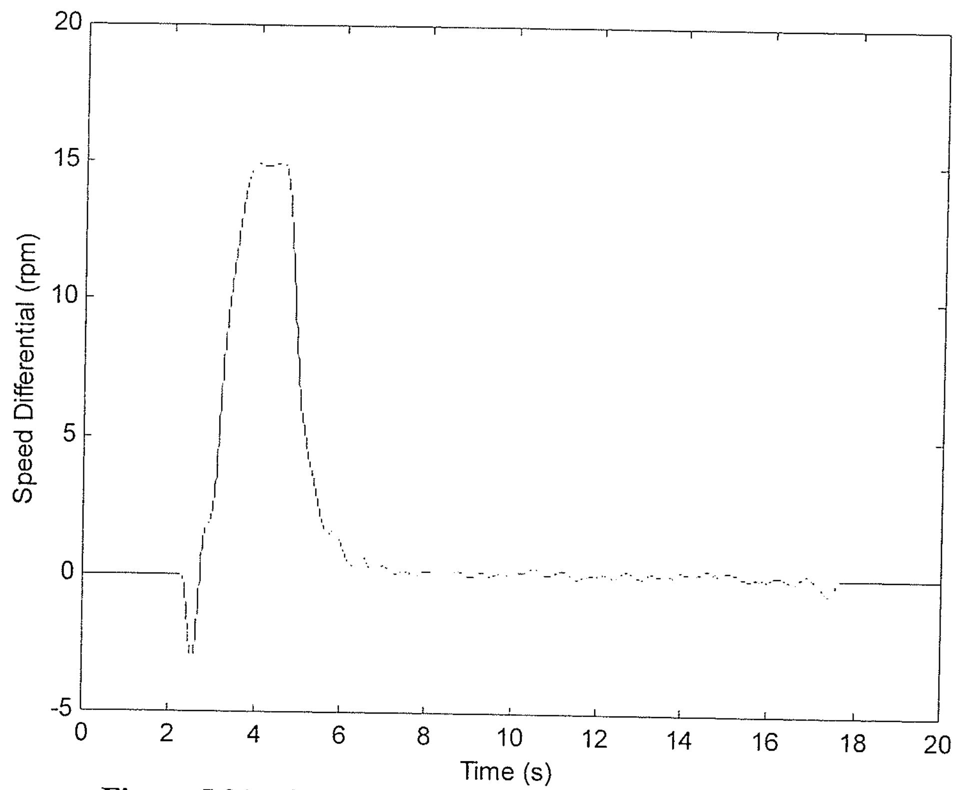


Figure 5.21 – Speed differential pertaining to Figure 5.12.

5.1.3 – Up open study with clamming device initially fully open

In this study, the clamming device is initially fully open and should remain so during ascension. An experienced operator would complete this task in a similar manner to the up closed study, but in this study allowing Cable 2 to carry the full load of the clamming device. Cable 1 would only follow the constant upward progress of Cable 2 without carrying any portion of the load.

Figure 5.22 shows the performance of the clamming device for this study through a digital photograph sequence. The clamming device is initially fully open and remains so as it ascends throughout the study.

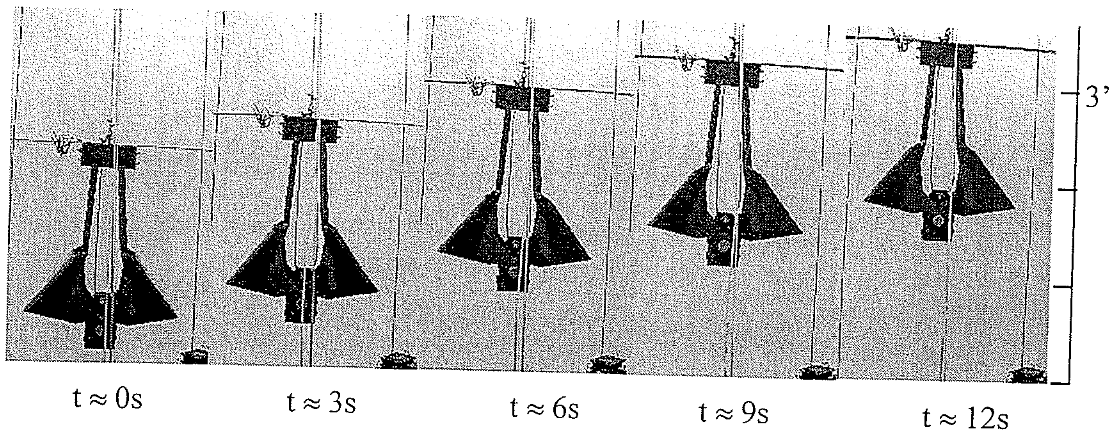


Figure 5.22 – Photo sequence for the up open study with the clamming device initially fully open.

Here, Cable 2 is PI controlled to a rate of ascension of 15 rpm while Cable 1 operates under PF control, receiving inputs from the load state of Cable 2 and the speed error of Cable 1. The speed responses for both cables are shown in Figure 5.23. The proportional, fuzzy and total control signals for Cable 1 are shown in Figure 5.24 while the control signals applied to Cable 2 are shown in Figure 5.25.

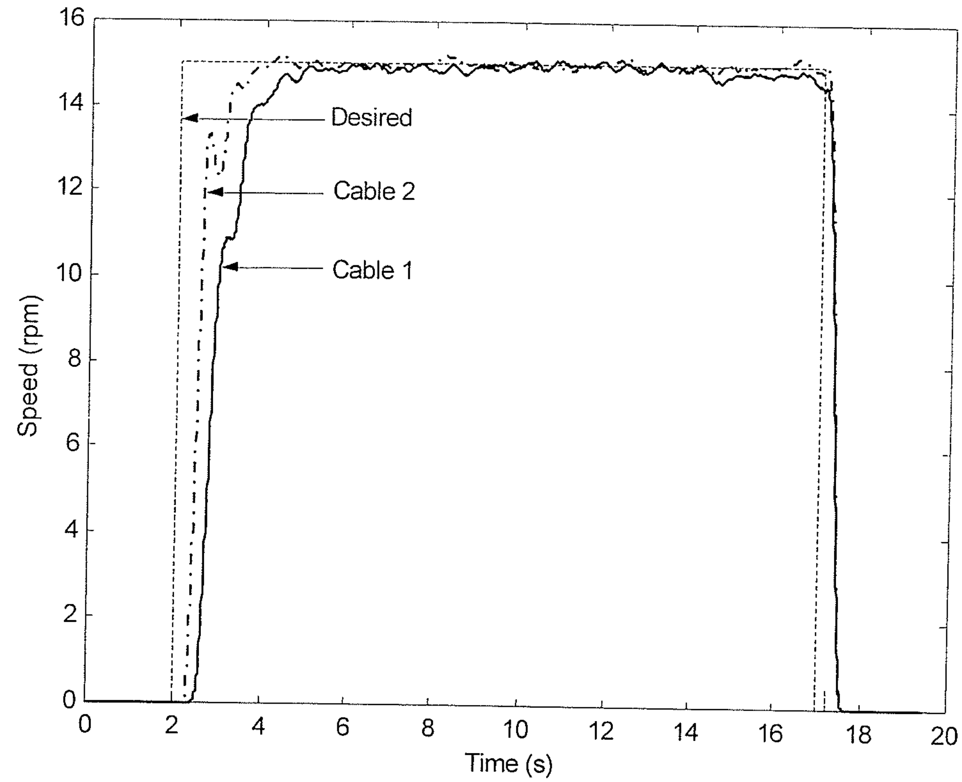


Figure 5.23 – Speed responses pertaining to Figure 5.22.

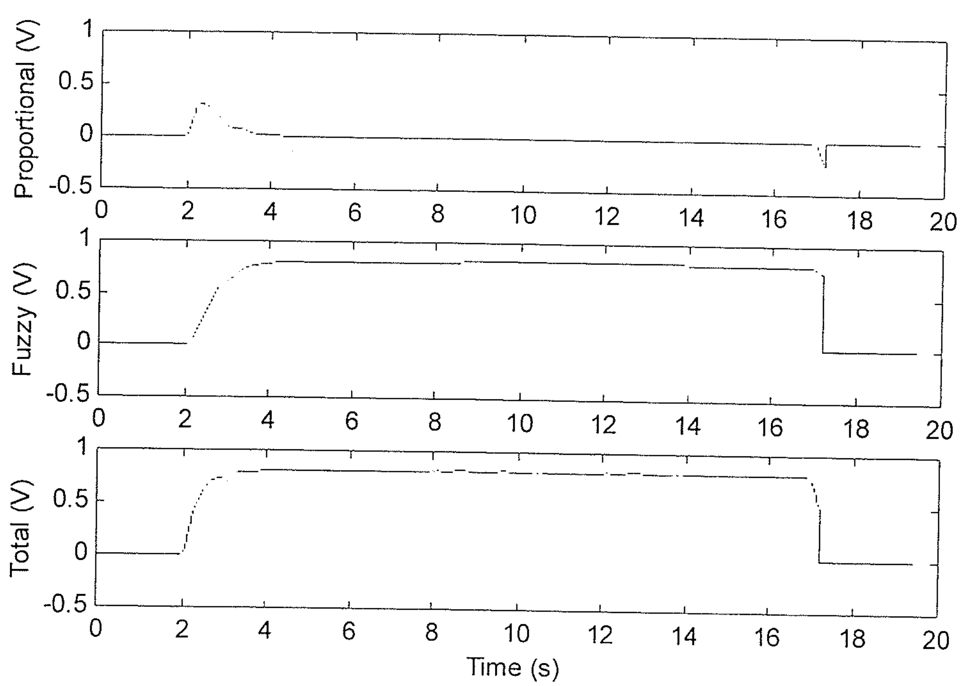


Figure 5.24 – Cable 1 control signals pertaining to Figure 5.22.

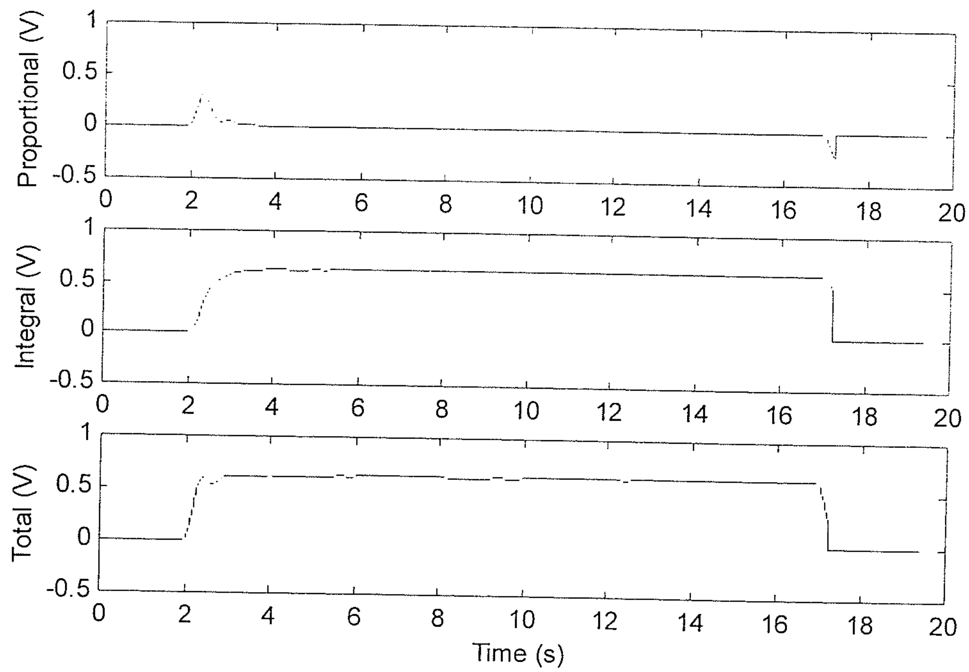


Figure 5.25 – Cable 2 control signals pertaining to Figure 5.22.

5.1.4 – Up open study with clamming device initially partly closed

This study is similar in nature to the study in Section 5.1.3, except that an incorrect initial loading condition is imparted onto the system by partially closing the clamming device at the beginning of the study (see Figure 5.1d). An operator would recognize this error by observing Cable 1 tightening, indicating that it is taking part of the load. He/she would correct this error by slowing the upward progress of Cable 1 until that cable is slack and the full load is transferred to Cable 2.

The digital photograph sequence for this study is shown in Figure 5.26. The clamming device begins partly closed but the fuzzy logic controller returns the load state to its correct condition by fully opening the clamming device. The clamming device fully opens at $t \approx 4$s, then continues to ascend at a steady 15 rpm while remaining fully open.

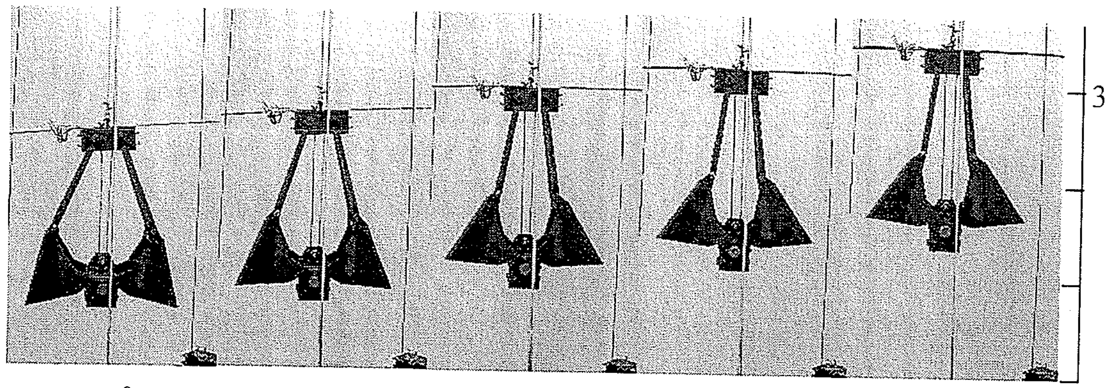


Figure 5.26 – Photo sequence for the up open study with the clamming device initially partly closed.

Cable 2 is under PI control while a PF controller drives Cable 1. The speed responses shown in Figure 5.27 demonstrate the PF controller correcting for the erroneous initial load state before arriving at a steady state of ascension.

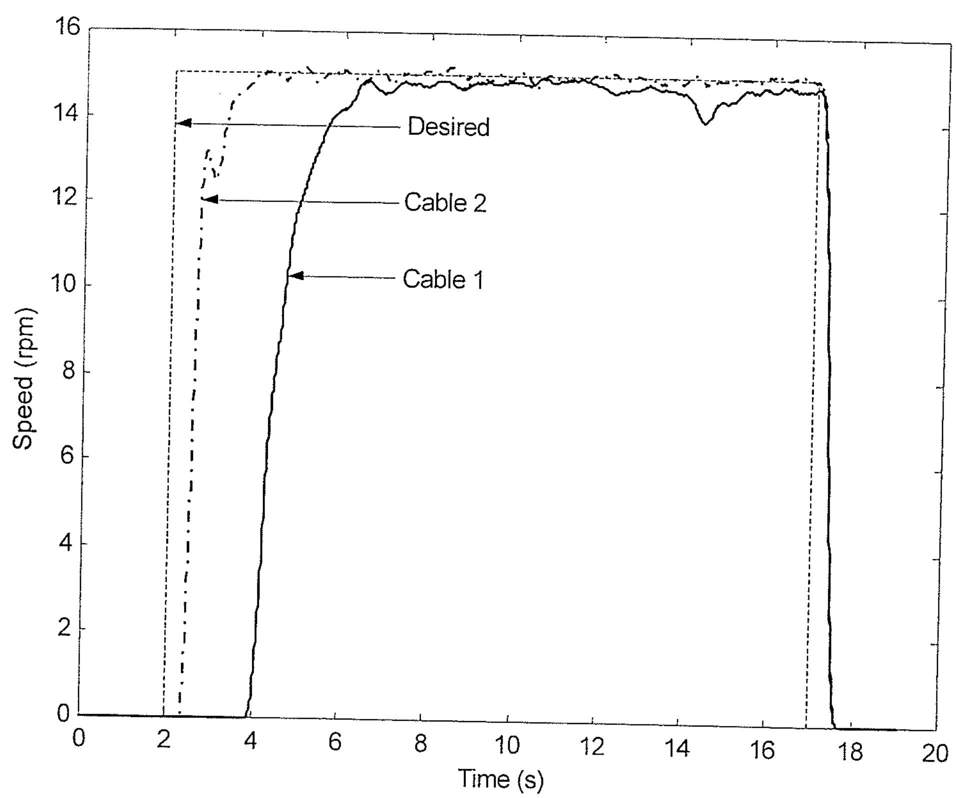


Figure 5.27 – Speed responses pertaining to Figure 5.26.

The fuzzy logic controller determines that Cable 2 is not carrying the full load by assessing the pressure differential across the hydraulic motors in a manner similar to the detailed example in Section 5.1.2. The fuzzy logic controller halts the upward progress of Cable 1 until the full load is restored to Cable 2 at t ≈ 4s. Cable 1 then begins to ascend at its desired speed of 15 rpm. The proportional, fuzzy and total output signals for Cable 1 are shown in Figure 5.28. Figure 5.29 shows the PI control signals for Cable 2.

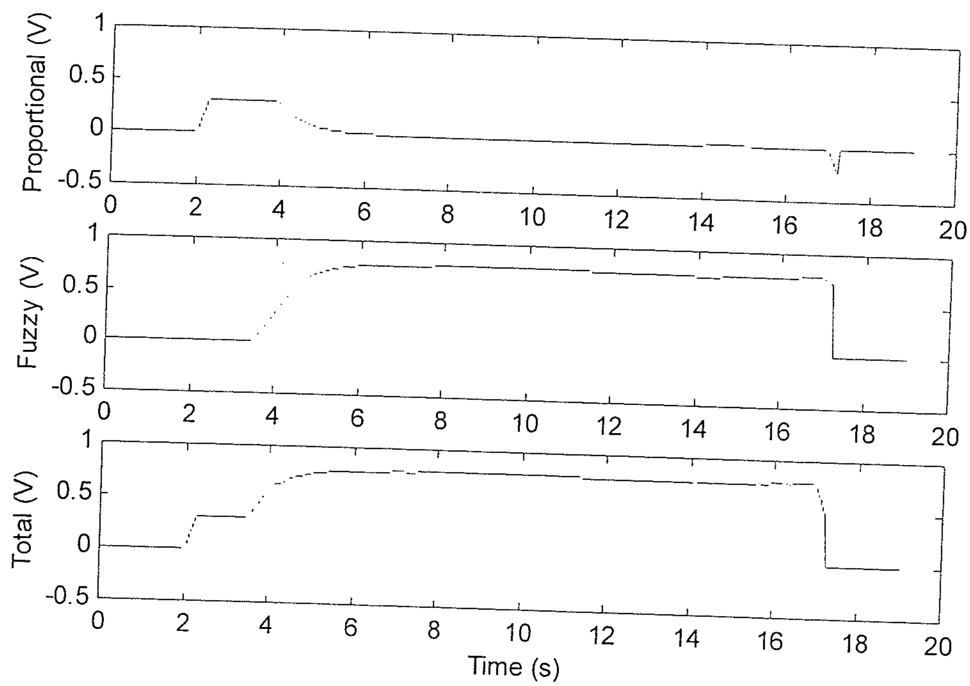


Figure 5.28 – Cable 1 control signals pertaining to Figure 5.26.

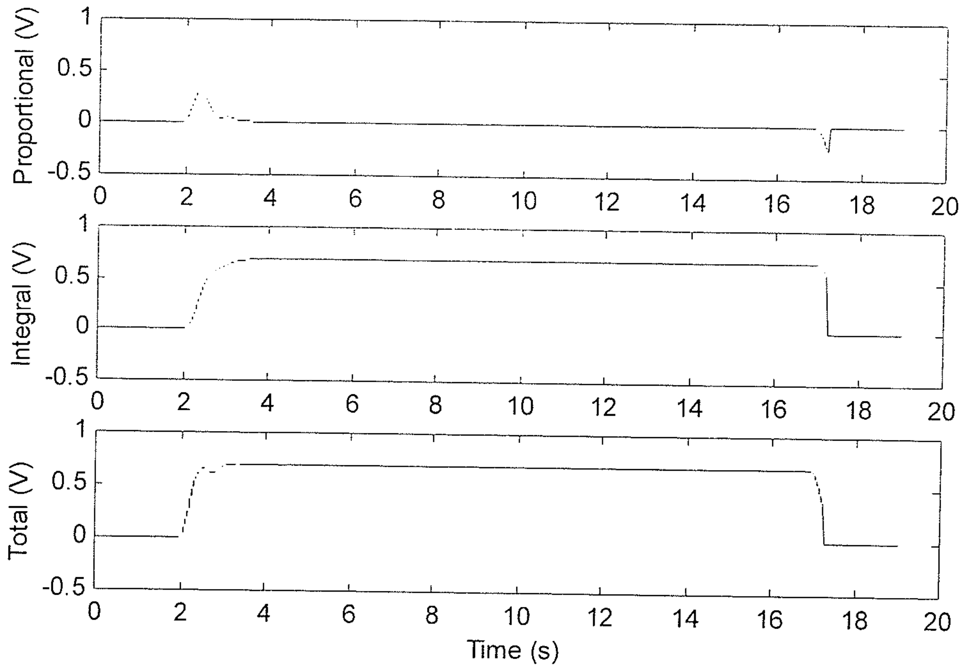


Figure 5.29 – Cable 2 control signals pertaining to Figure 5.26.

5.1.5 – Down closed study with clamming device initially fully closed

In this study the clamming device is intended to descend at a steady rate of 15 rpm while remaining fully closed for the duration of the study. The operator would complete this task by lowering Cable 1 at a constant speed while controlling Cable 2 to follow the motion of Cable 1 without taking any of the load.

The digital photograph sequence for this study is shown in Figure 5.30. The clamming device begins the study fully closed and remains so for the duration of the study.

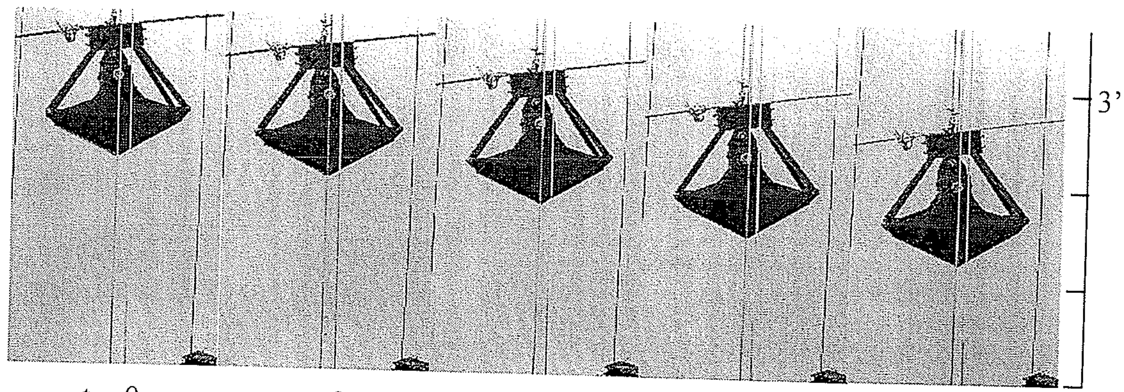


Figure 5.30 – Photo sequence for the down closed study with the clamming device initially fully closed.

Cable 1 carries the full load and is controlled by a PF controller while a PI controller controls Cable 2. The PF controller receives inputs from the load state of Cable 2 and the speed error of Cable 1. The speed responses for this study are shown in Figure 5.31.

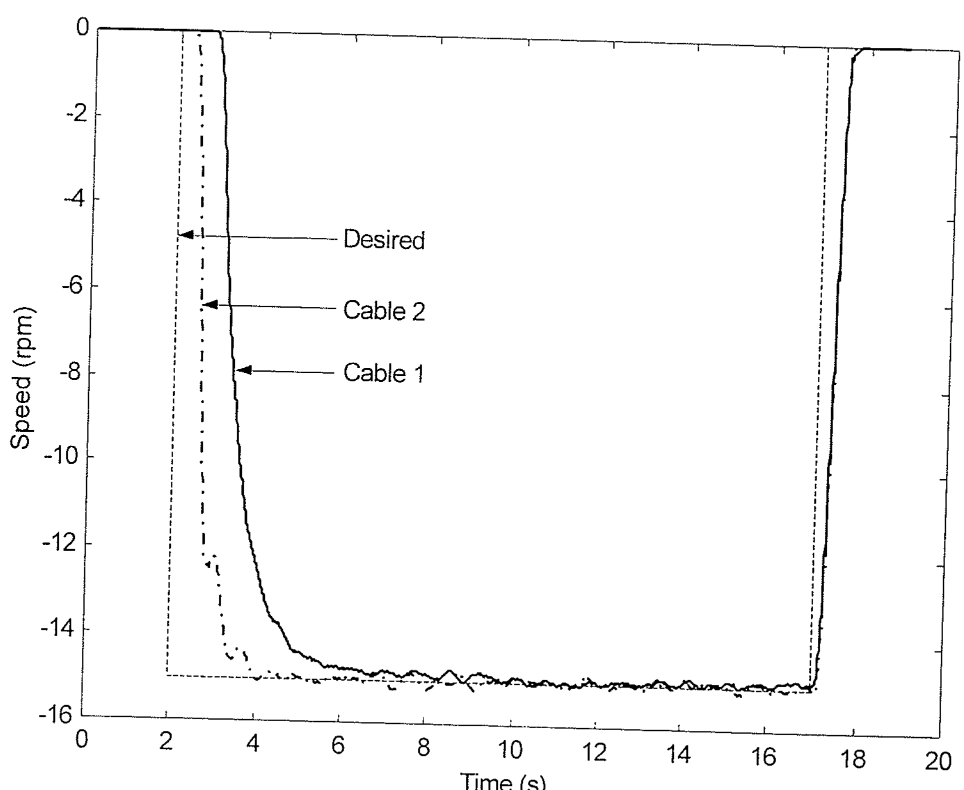


Figure 5.31 – Speed responses pertaining to Figure 5.30.

Referring to Figure 5.32, the controller observes that at t ≈ 2 s the load state is above the load threshold at −103.4 kPa and begins to take corrective action as directed by the rules for this operating mode (see Figure 4.6c). The fuzzy logic portion of the controller, unnecessarily correcting for the apparent error in the load state, causes the delay in the initial speed response of Cable 1. This delay must be minimized in order for Cable 1 to respond as fast as possible to a command to descend. This is accomplished by passing a large negative value for the load state to its low-pass filter at the instant that the command to descend is given. This causes the rapid decrease in the load state at t ≈ 3 seen in Figure 5.32. A slower response would transpire without this large negative value being passed to the filter. Figure 5.33 shows the proportional, fuzzy and total control signals for Cable 1 for this study while Figure 5.34 shows the PI control signals for Cable 2.

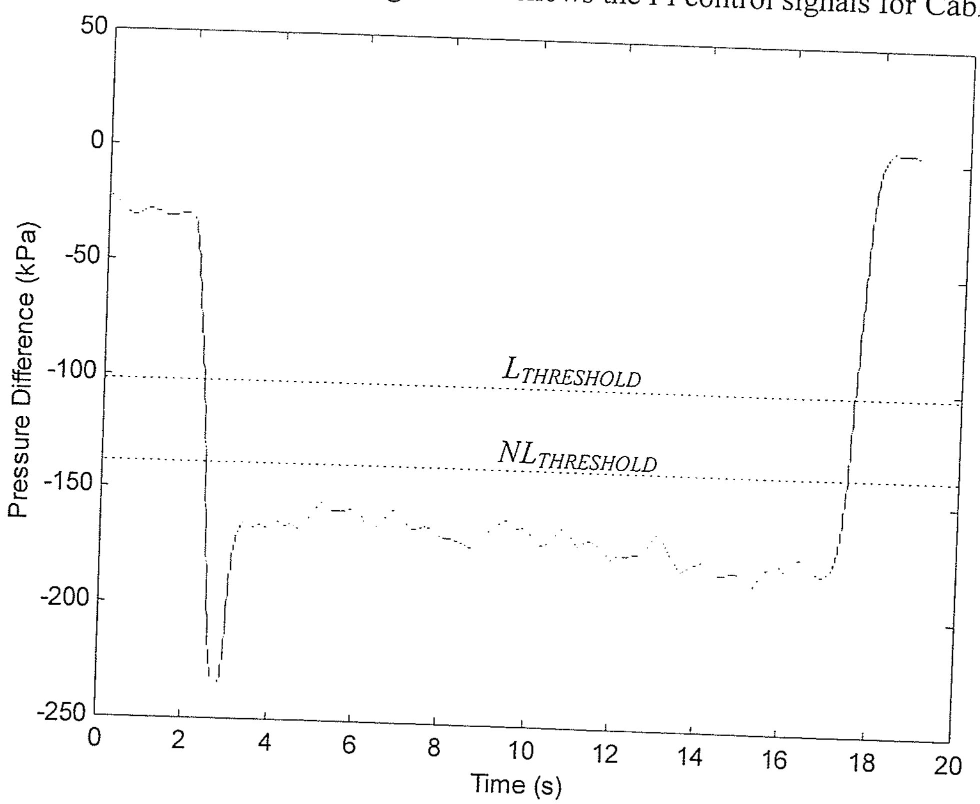


Figure 5.32 – Load state pertaining to Figure 5.30.

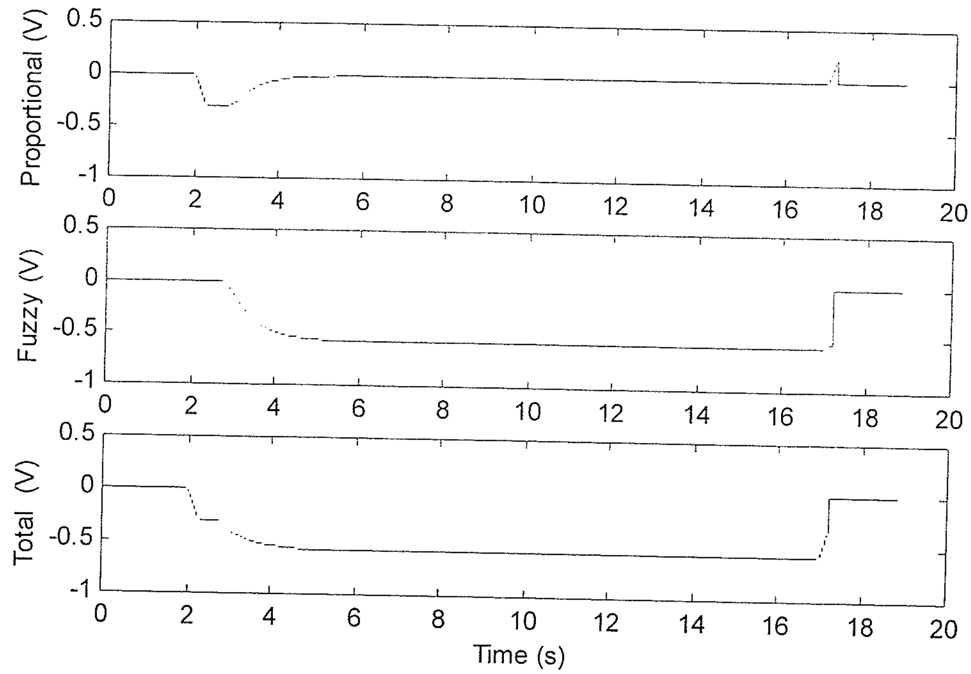


Figure 5.33 – Cable 1 control signals pertaining to Figure 5.30.

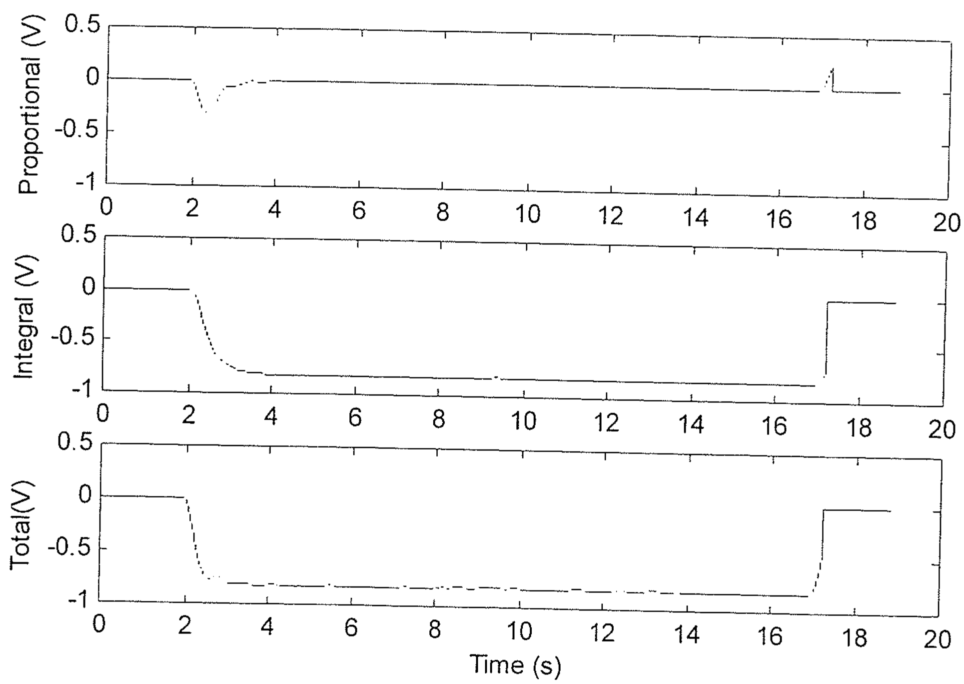


Figure 5.34 – Cable 2 control signals pertaining to Figure 5.30.

5.1.6 – Down closed study with clamming device initially partly open

Here, the down closed study was conducted with the clamming device initially partly open to simulate an incorrect initial load state for the PF controller to correct. An operator would recognize this error by observing Cable 2 tightening and taking a portion of the load. He/she would correct for this error by slowing the downward progress of Cable 1 until the load has fully removed from Cable 2.

Figure 5.35 shows the digital photograph sequence for this study. The clamming device begins the study partially open, as seen in the leftmost digital photograph. The clamming device fully closes at $t \approx 6.5s$ and continues to descend at its desired speed of 15 rpm.

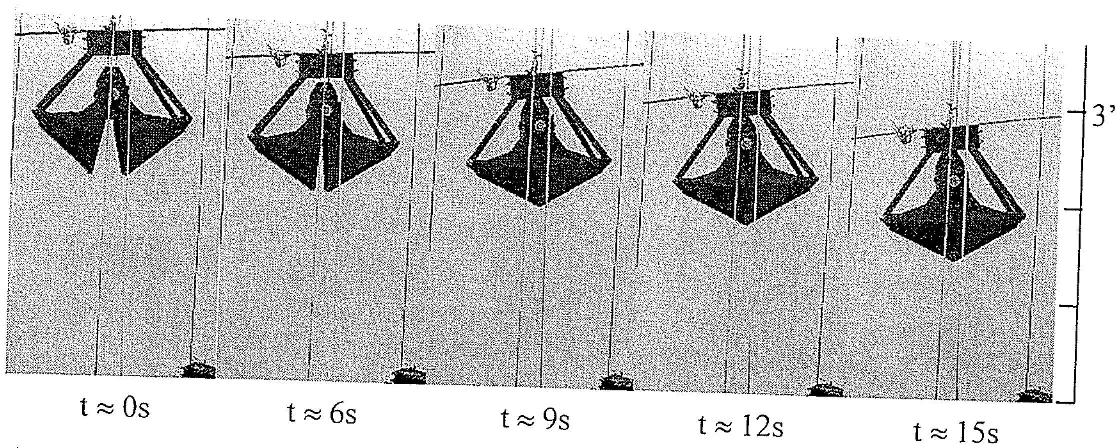


Figure 5.35 – Photo sequence for the down closed study with the clamming device initially partly open.

Cable 1, which is PF controlled, ideally carries the full load when the clamming device is fully closed. By partially opening the clamming device, part of the load was transferred to Cable 2, which is controlled by a PI controller. The fuzzy logic controller detects and removes the load from Cable 2 and returns the clamming device its closed position before continuing to descend. The speed responses are shown in Figure 5.36.

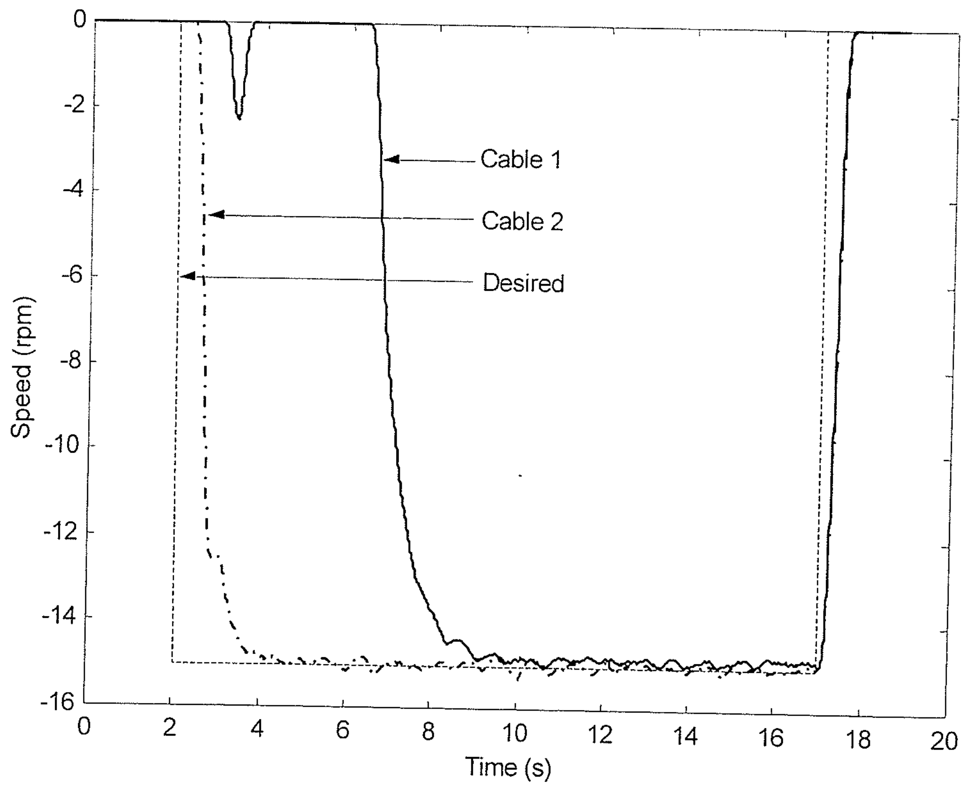


Figure 5.36 – Speed responses pertaining to Figure 5.35.

The fuzzy logic controller observes an error in the load state by assessing the pressure differential and determines that the clamming device is not fully closed at the beginning of the study. The controller subsequently removes the load from Cable 2 by temporarily halting the speed of Cable 1, as shown in Figure 5.36. Once the clamming device is fully closed, at t ≈ 6.5s, the PF controller brings Cable 1 to a steady descension of 15 rpm. The proportional, fuzzy and total control signal for Cable 1 is shown in Figure 5.37 and the PI control signals for Cable 2 are shown in Figure 5.38.

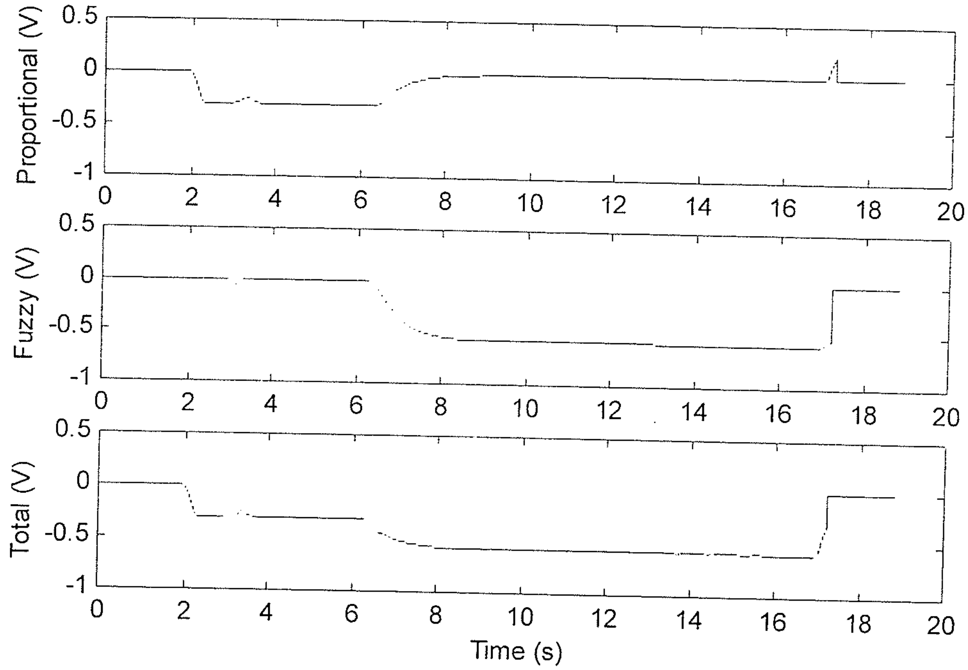


Figure 5.37 – Cable 1 control signals pertaining to Figure 5.35.

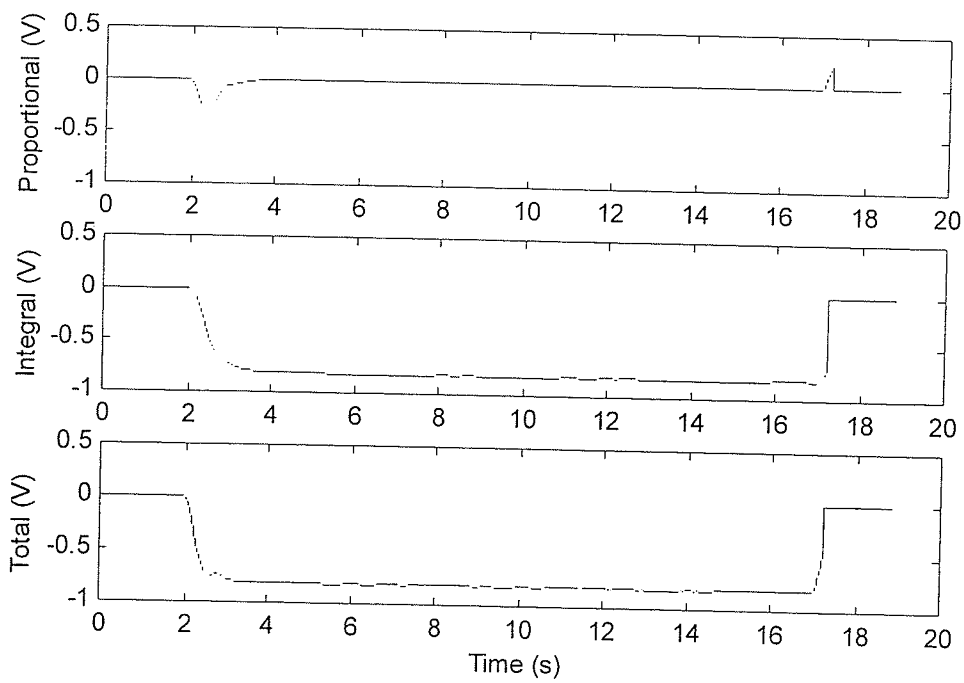


Figure 5.38 – Cable 2 control signals pertaining to Figure 5.35.

5.1.7 – Down open study with clamming device initially fully open

The final operating mode to be investigated is the down open operating mode, where the clamming device should descend at a steady rate of 15 rpm while remaining fully open. An experienced operator would achieve this task by lowering Cable 2 while Cable 1 follows, bearing no load.

The digital photograph sequence for this study is shown in Figure 5.39. The clamming device is initially fully open and remains fully open for the duration of the study.

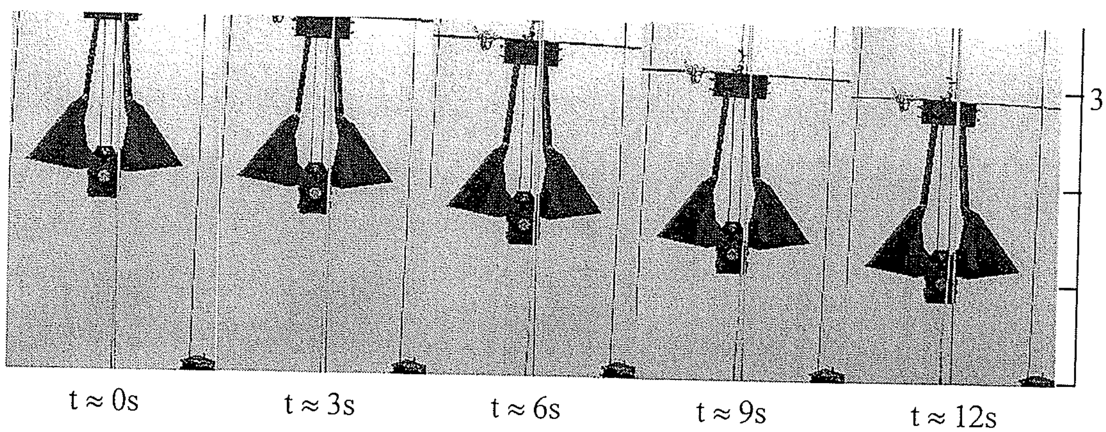


Figure 5.39 – Photo sequence for the down open study with the clamming device initially fully open.

Given the proposed control strategy, Cable 2 carries the full load while being driven by a PF controller that receives the load state of Cable 2 and the speed error of Cable 2 as inputs. A PI controller controls the speed of Cable 1. The speed responses of both cables are shown in Figure 5.40. The proportional, fuzzy and total control signals for Cable 2 are shown in Figure 5.41 while the PI control signals for Cable 1 are shown in Figure 5.42.

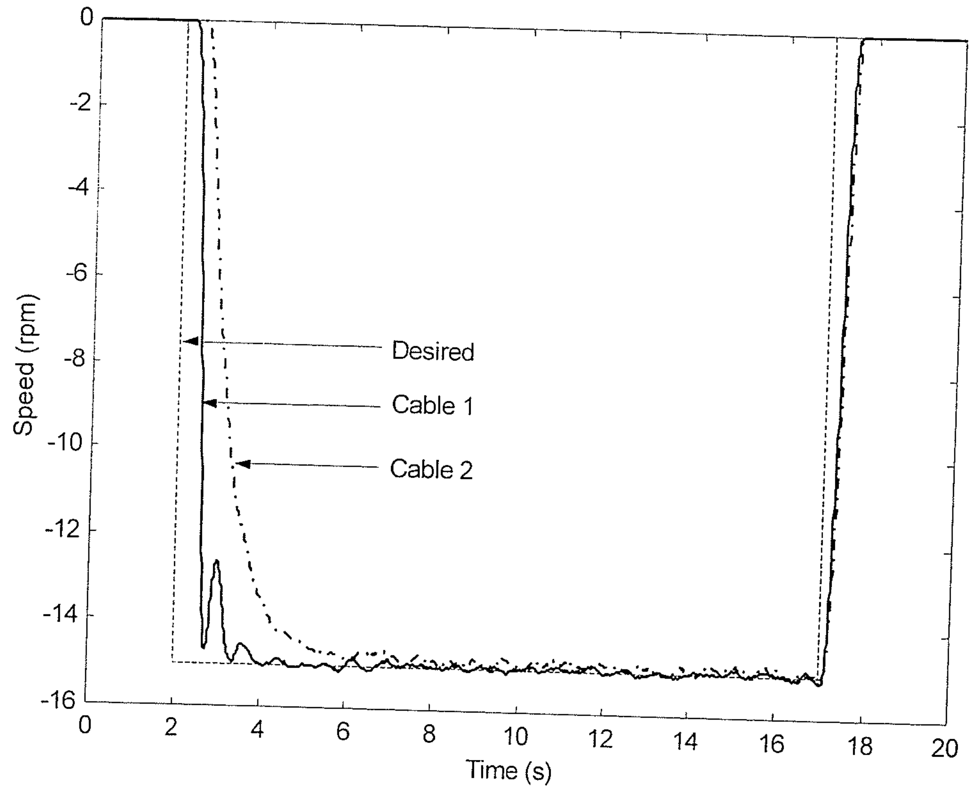


Figure 5.40 – Speed responses pertaining to Figure 5.39.

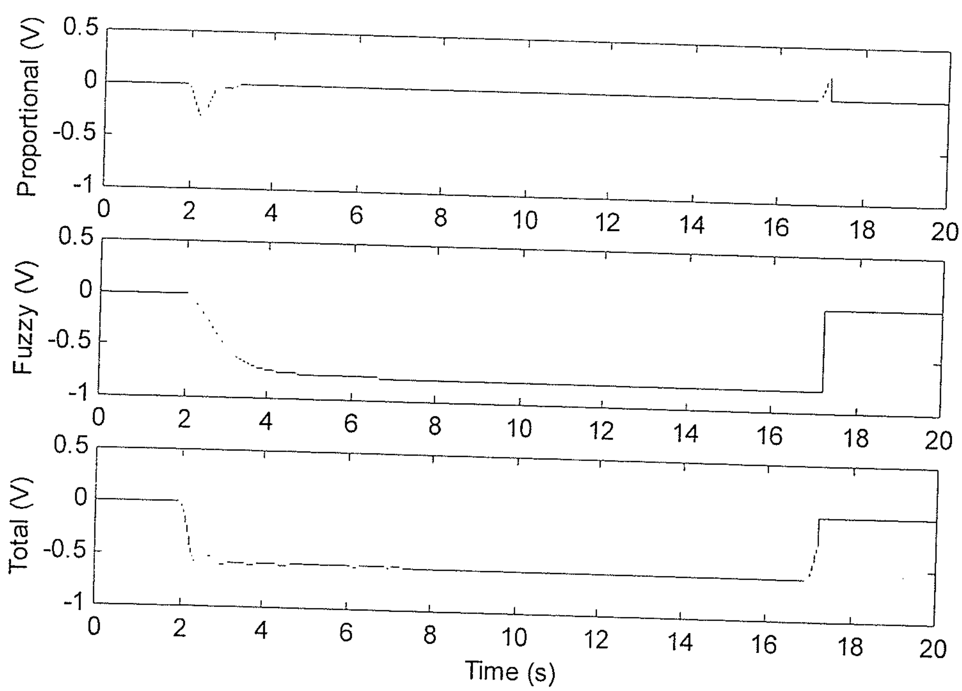


Figure 5.41 – Cable 2 control signals pertaining to Figure 5.39.

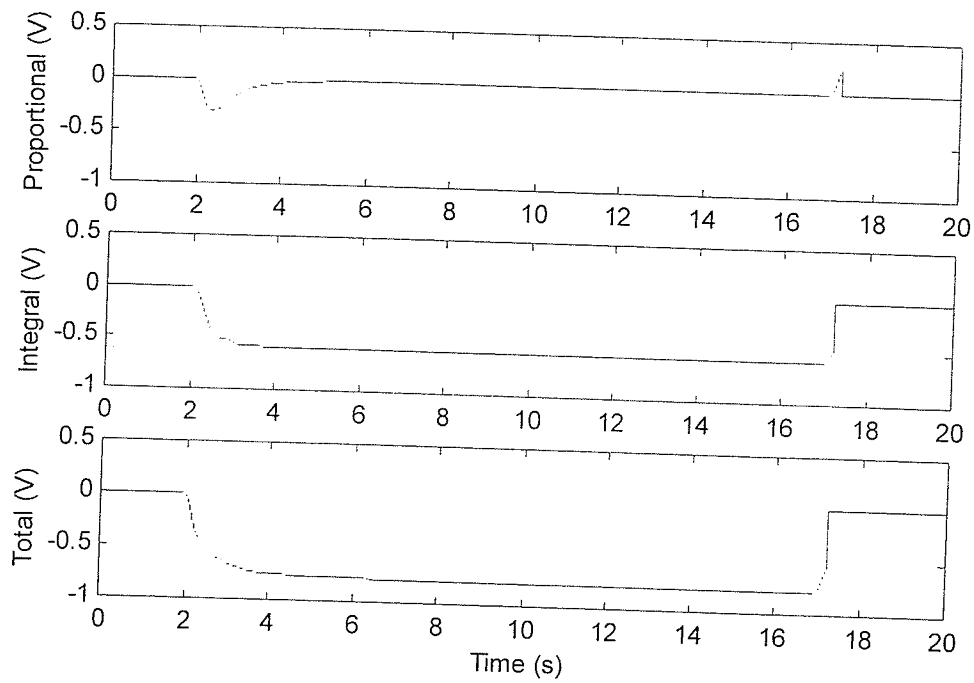


Figure 5.42 – Cable 1 control signals pertaining to Figure 5.39.

5.1.8 – Down open study with clamming device initially partly closed

This down open study was conducted with the clamming device initially partly closed to simulate an incorrect initial load state. The operator would detect this error by observing tension on Cable 1. He/she would correct for this load error by slowing the downward progress of Cable 2 until the full load is removed from Cable 1 to Cable 2.

Figure 5.43 shows the digital photograph sequence for this study. The clamming device is initially partly closed, as seen in the leftmost digital photograph. By t ≈ 3.5s the clamming device is fully open and continues to descend at a steady 15 rpm while remaining fully open.

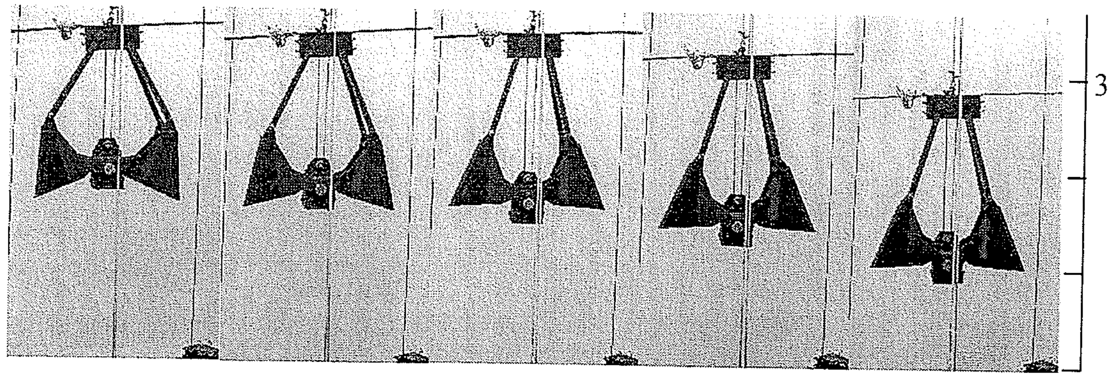


Figure 5.43 – Photo sequence for the down open study with the clamming device initially partly closed.

Cable 2 carries the full load while being controlled by the PF controller. The PI controller controls the speed of Cable 1. The fuzzy logic controller removes the load from Cable 1 and returns the full load to Cable 2 before descending at 15 rpm. The speed responses are shown in Figure 5.44.

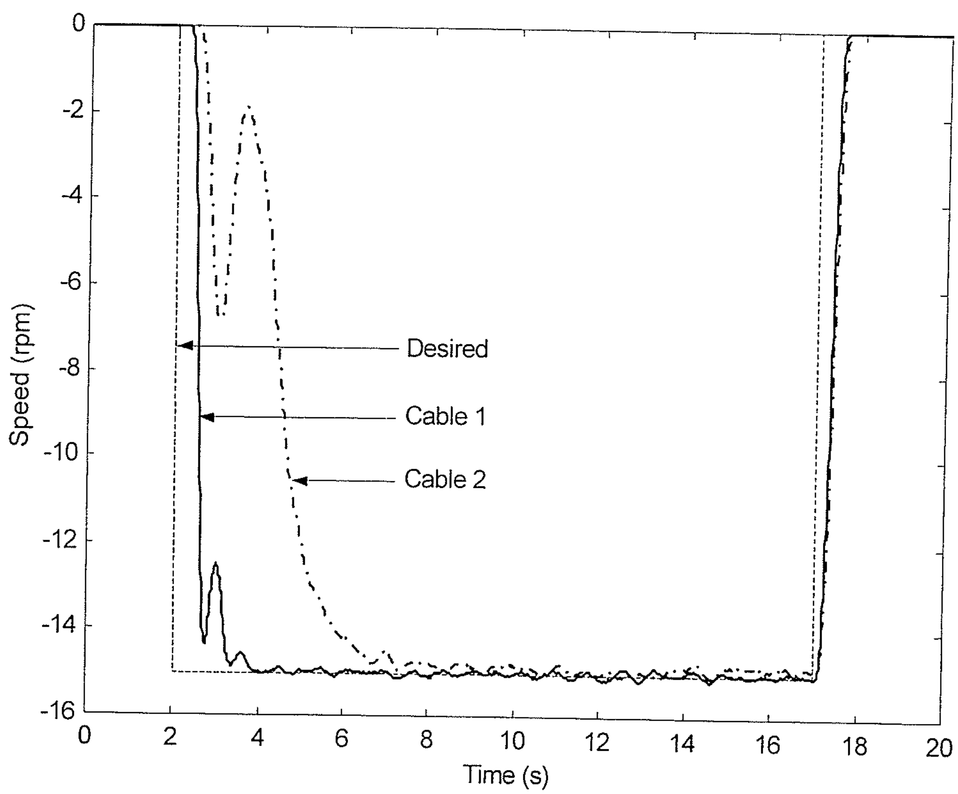


Figure 5.44 – Speed responses pertaining to Figure 5.43.

The reason for the initial decrease in the speed of Cable 2 at t ≈ 3s is analogous to the initial increase in the speed of Cable 2 shown in Figure 5.11. The controller determines that the clamming device is not fully open by assessing the pressure differential. The fuzzy logic controller subsequently slows the downward progress of Cable 2 until the load is fully removed from Cable 1 at t ≈ 3.5s. At this point the fuzzy logic portion of the controller that works on Cable 2 brings its speed of descension to 15 rpm. The proportional, fuzzy and total control signals for Cable 2 are shown in Figure 5.45 while Figure 5.46 shows the PI control signals for Cable 1.

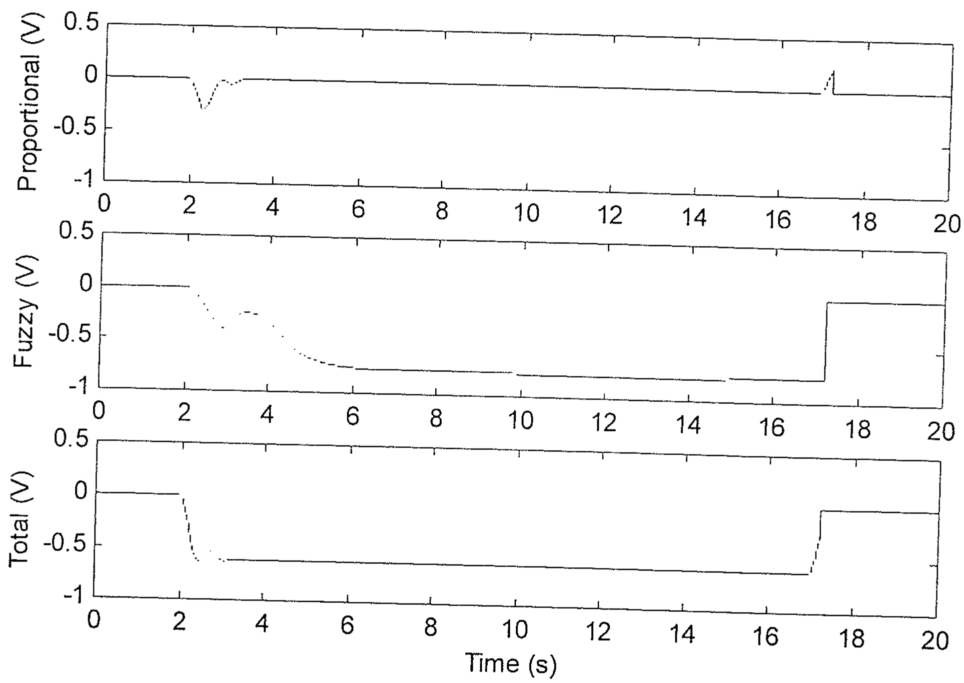


Figure 5.45 – Cable 2 control signals pertaining to Figure 5.43.

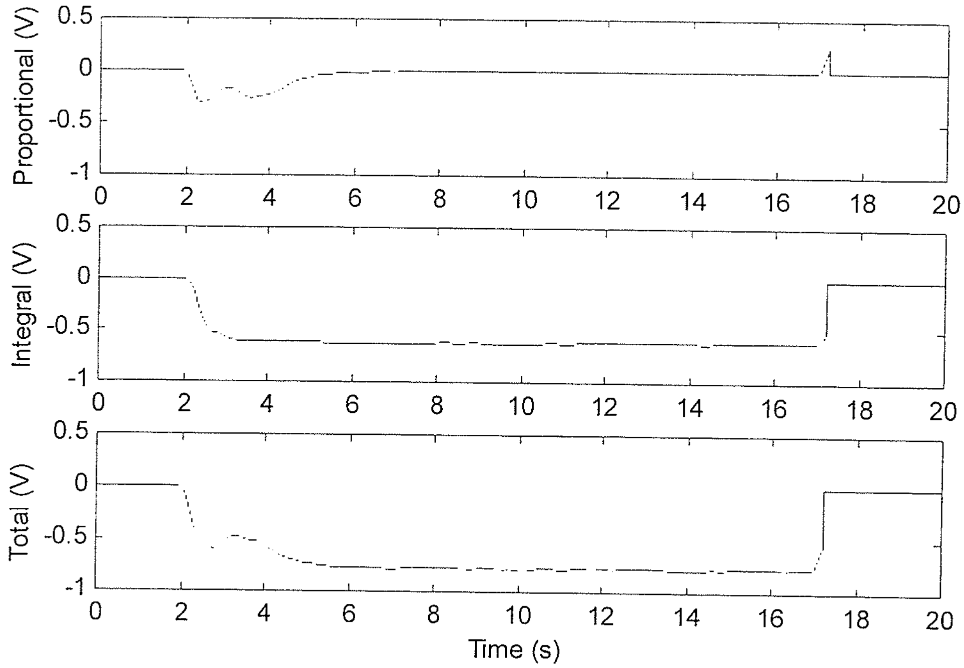


Figure 5.46 – Cable 1 control signals pertaining to Figure 5.43.

5.2 Test under external loading

This study is designed to show that the controller described in Section 5.1 can be sequenced and evaluated in the presence of an external load. A total of 40 pounds of cast iron plates were used in this study as load. The sequence of action simulates the lifting of trashes from the water using the up closed operating mode, lowering the clamming device down to a truck using the down closed operating mode, and dropping the trash into the bed of the truck by completely opening the clamming device. This sequence of events is summarized in Figure 5.47, and the speed responses of the cables are shown in Figure 5.48.

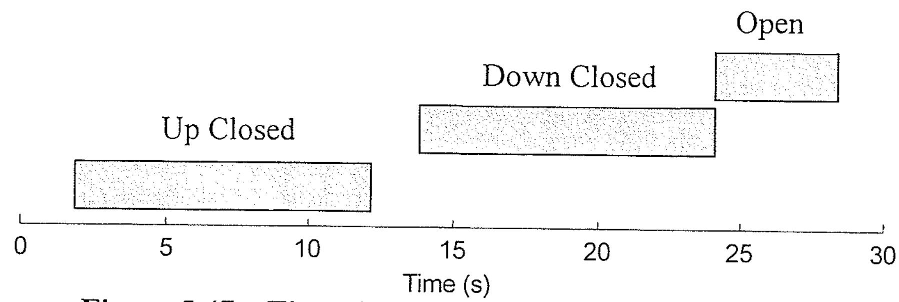


Figure 5.47 – Time chart for test with external load.

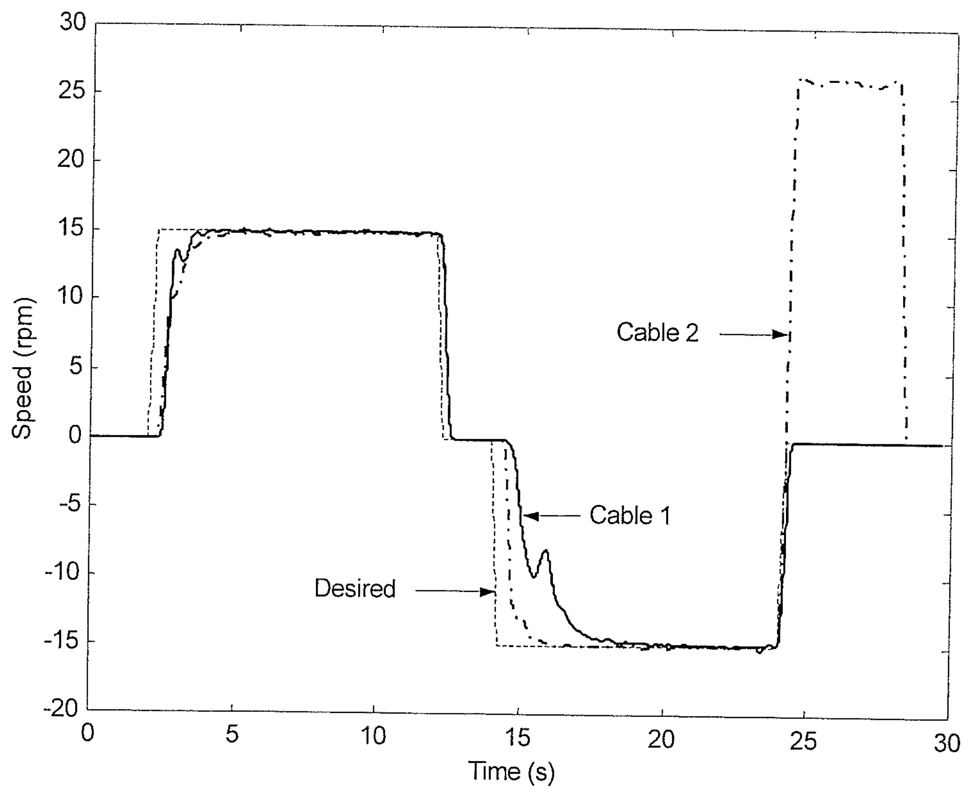
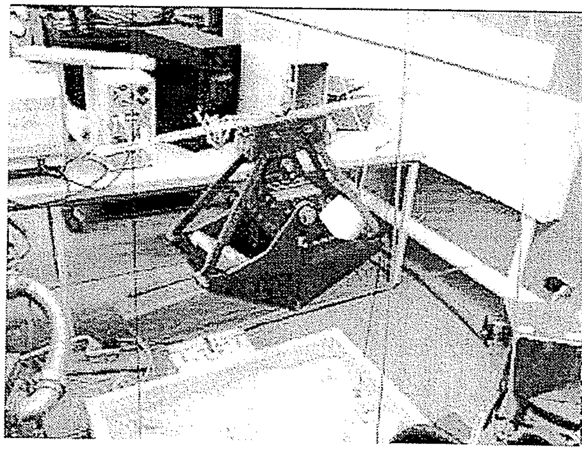


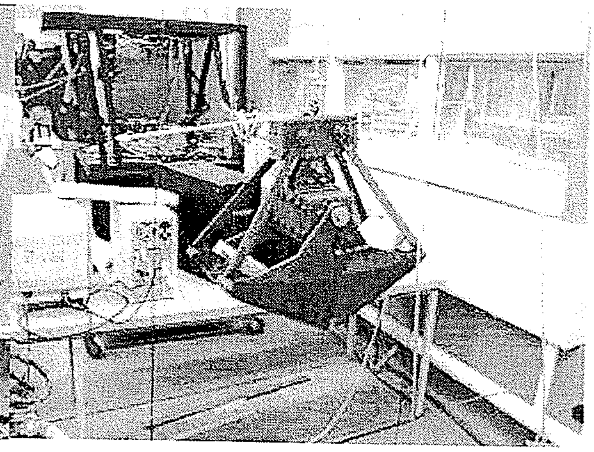
Figure 5.48 – Speed responses for test with external load.

Referring to Figure 5.48, from t ≈ 2s to t ≈ 12s the controller operates in the up closed mode while carrying the cast iron plates. The controllers keep the speeds of the two cables in close proximity to one another, even in the presence of an external load. The external load is not expected to cause any problems with the controller; this test was conducted simply to prove that assumption. The system dwells from t ≈ 12s to t ≈ 14s, then begins to descend while carrying the plates. The reason for the delay in the speed response of Cable 1 is found in Section 5.1.5, but this delay does not cause the clamming device to open. The large rise in the speed of Cable 2 at t $\approx$ 24s allows the clamming device to open, therefore dropping the plates to the ground.

Figure 5.49 shows the digital photograph sequence for this study at selected points in time. The first photograph (Figure 5.49a) shows the clamming device in its initial position, loaded with two cast iron plates. At t $\approx$ 12s, the clamming device is at its maximum height. Figure 5.49c shows the clamming device as it begins to return to its lowest point, at t $\approx$ 24s. The final two photographs (Figures 5.49e and 5.49f) show the clamming device opening and dropping the weights to the ground.

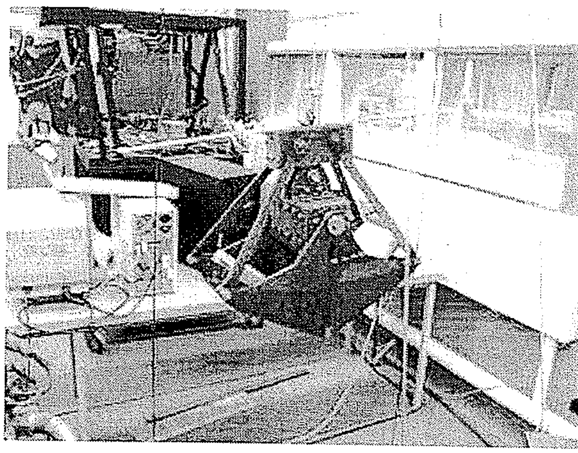
Figure 5.50 shows the control signals relayed to Cable 1 for the test under external load. At any time, the total control signal is calculated as the sum of the proportional, integral and/or fuzzy logic controllers. The controller switching rules, as shown in Figure 4.1, permits only the integral or fuzzy controller to be active for each cable at any time. The control signals for Cable 2 are shown in Figure 5.51.

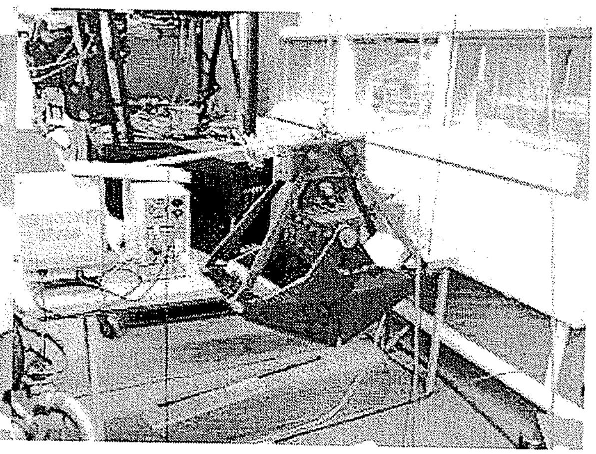




(a) t ≈ 0s

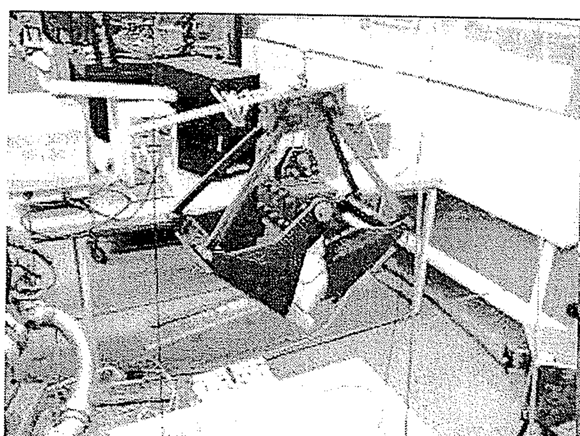
(b) t ≈ 12s

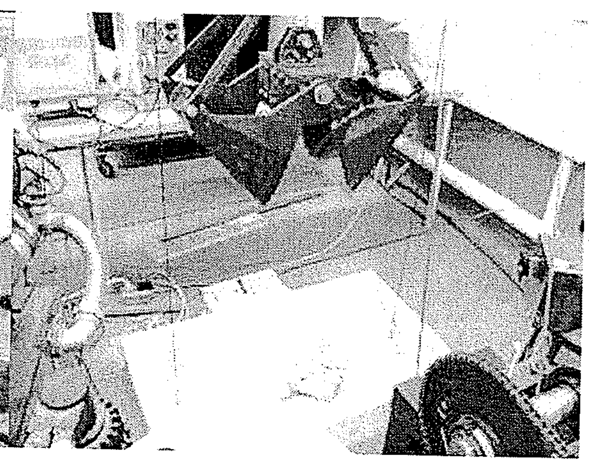




(c) t ≈ 16s

(d) t ≈ 24s





(e) t ≈ 26s

(f) t ≈ 30s

Figure 5.49 – Photo sequence for test under external load.

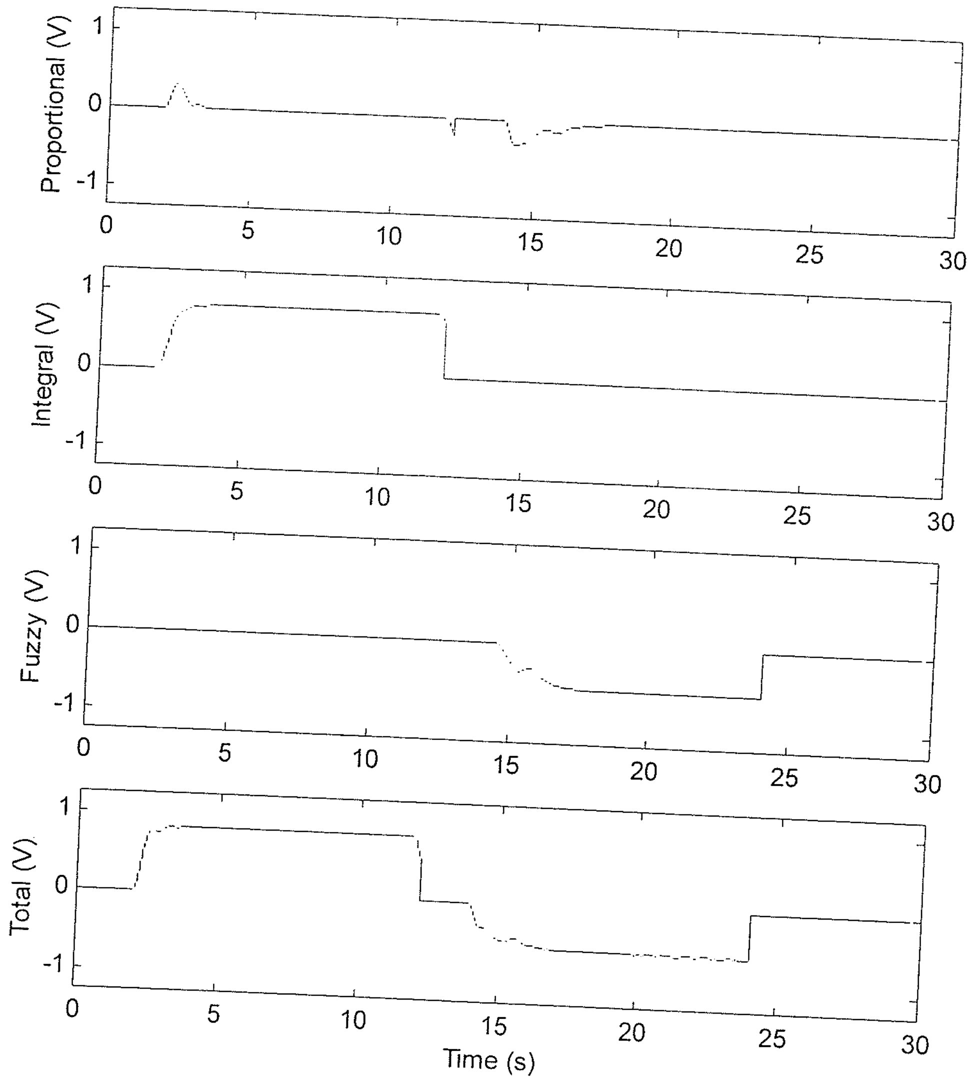


Figure 5.50 – Cable 1 control signals for test under external load.

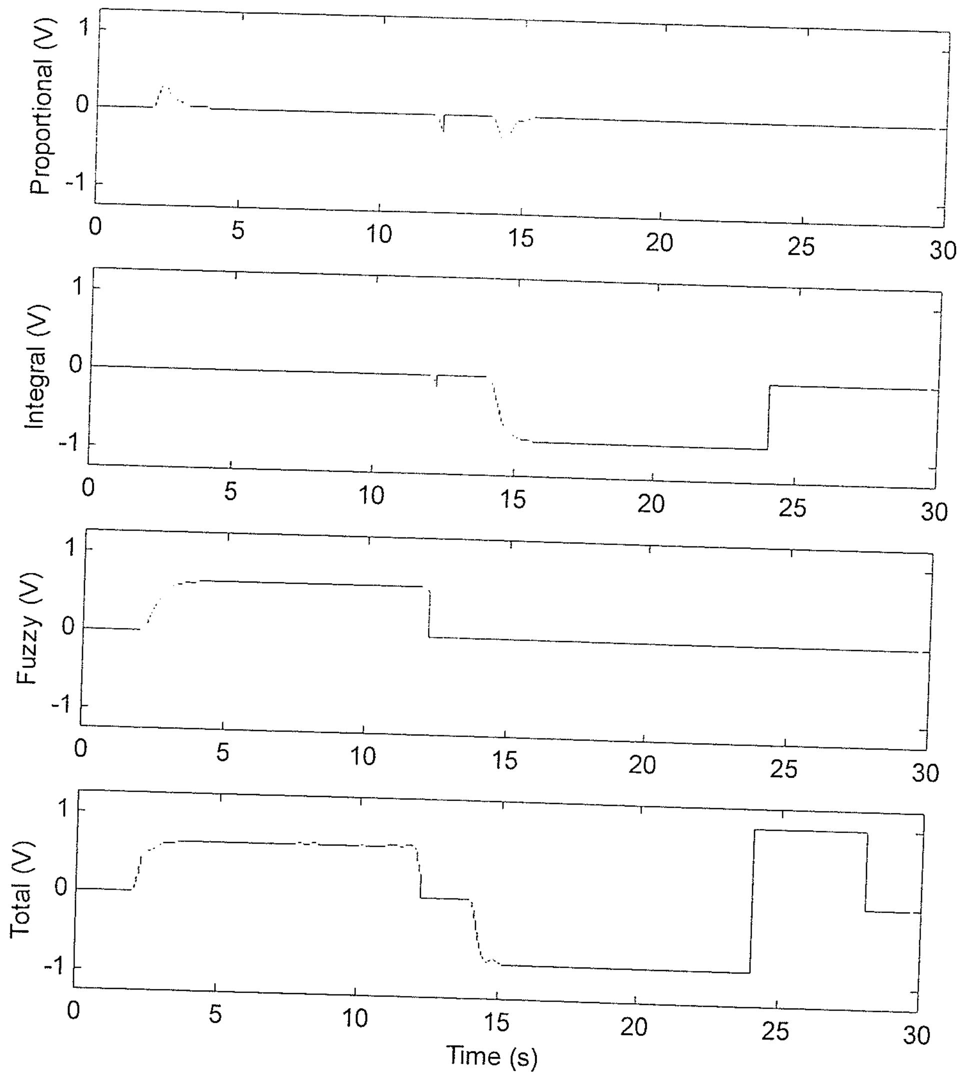


Figure 5.51 – Cable 2 control signals for test under external load.

Referring to Figures 5.50 and 5.51, the control signals for each specific operating mode within this study are similar to those previously presented in this chapter, regardless of the external load imposed on the system by the cast iron plates. In order to open the clamming device, an added control signal is required, however. This signal is superimposed onto the total control signal from t ≈ 24s to t ≈ 28s to open the clamming device, causing the cast iron plates to drop.

5.3 *Advanced Case Studies*

The following advanced case studies are designed to simulate specific components of typical trash removal operations. The results of these studies are documented through plots of the speed responses of the cables and the control signals that drive those cables, along with digital photograph sequences showing the experimental test rig in action.

5.3.1 – Case study 1

This first case study simulates lowering the clamming device below the surface of the water using the down open operating mode, locking onto a load by closing the clamming device and lifting it up using the up closed operating mode. This series of events is summarized in Figure 5.52, while the speed responses for this study are shown in Figure 5.53.

Referring to Figure 5.53, the fuzzy logic controller lowers the clamming device in the down open operating mode from $t \approx 2s$ to $t \approx 12s$ before halting. From $t \approx 13s$ to $t \approx 19s$, Cable 1 is commanded to rise while Cable 2 is held stationary. This causes the clamming device to close onto a 20 pound cast iron plate used to simulate external loading. At $t \approx 20s$, the controller begins to lift the clamming device. At this point in time, the controller observes that the clamming device is not fully closed by assessing the pressure differential applied to Cable 2. The controller subsequently arrests the progress of Cable 2 until the controller is satisfied that the clamming device is fully closed, before continuing to lift the clamming device at 15 rpm until $t \approx 30s$.

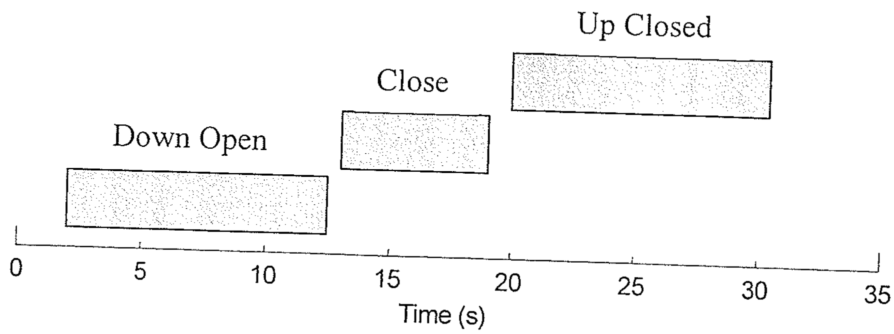


Figure 5.52 – Time chart for case study 1.

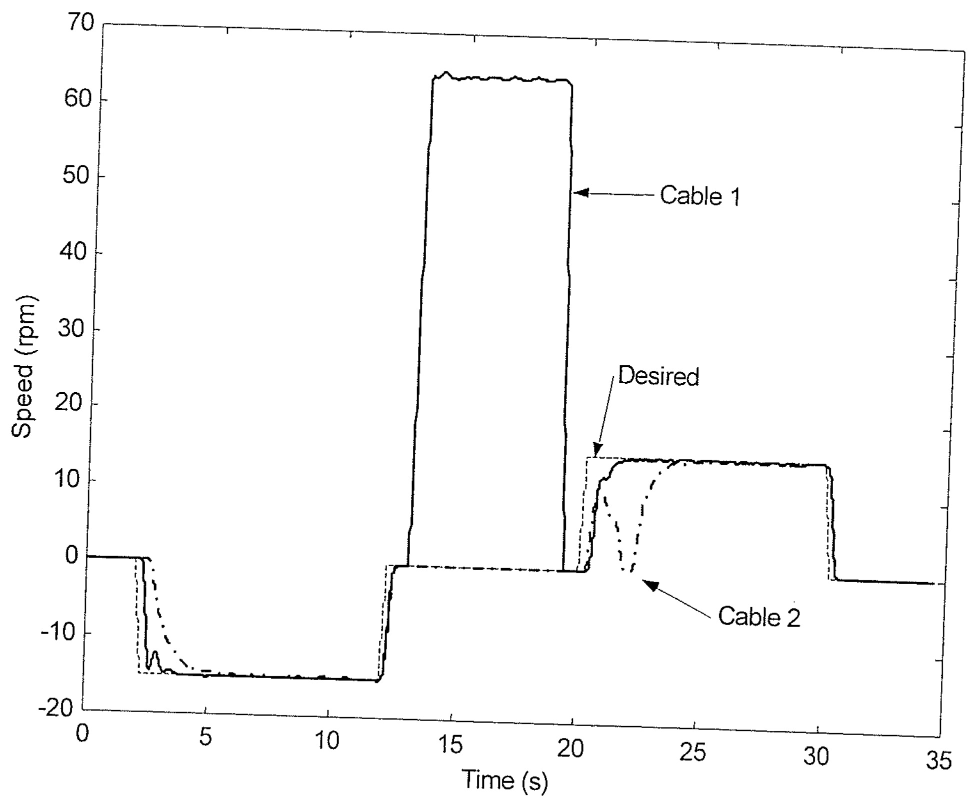
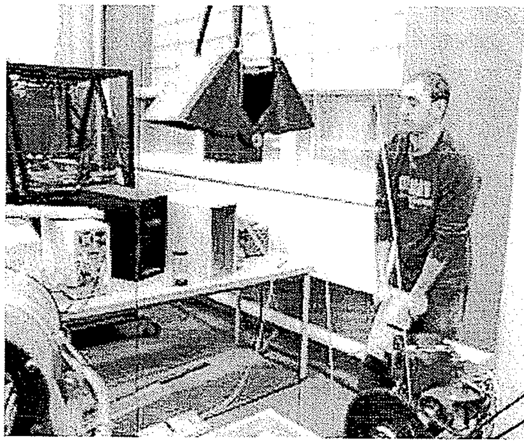
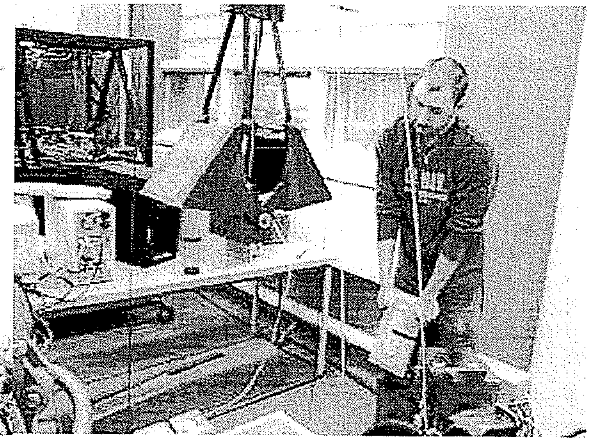


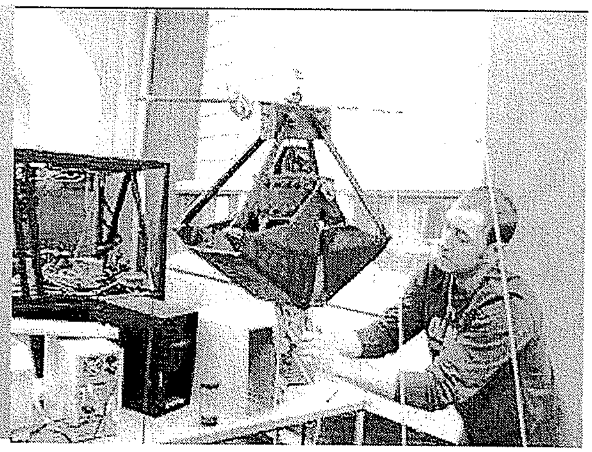
Figure 5.53 – Speed responses for case study 1.





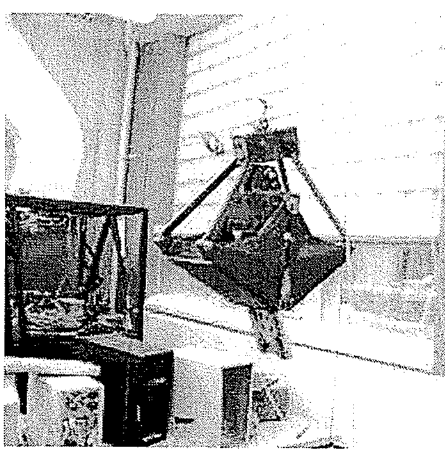
(a) t ≈ 0s

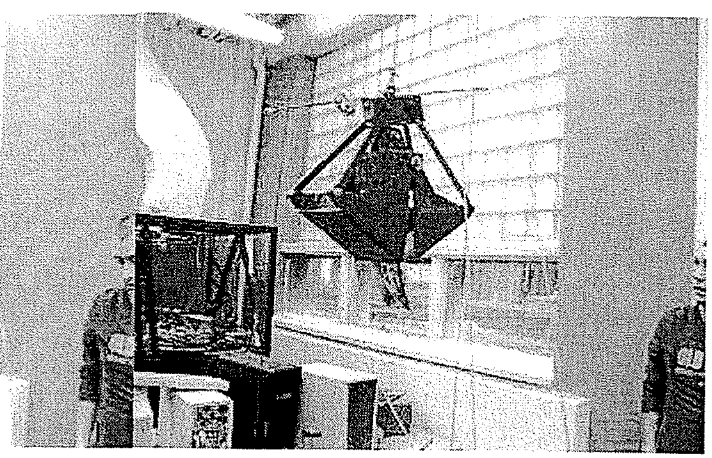
(b) t ≈ 10s



(c) t ≈ 16s

(d) t ≈ 18s





(e) t ≈ 22s

(f) t ≈ 28s

Figure 5.54 – Photo sequence for case study 1.

Figure 5.54 shows the events pictorially. Figure 5.54a shows the system in its initial position at t ≈ 0s. The second photograph shows the clamming device as it descends fully open before beginning to close at t ≈ 13s. Figures 5.54c and 5.54d shows the clamming device closing onto the plate and the last row of digital photographs shows the clamming device ascending while remaining fully closed and holding onto the plate. Figures 5.55 and 5.56 show the control signals for Cable 1 and Cable 2, respectively.

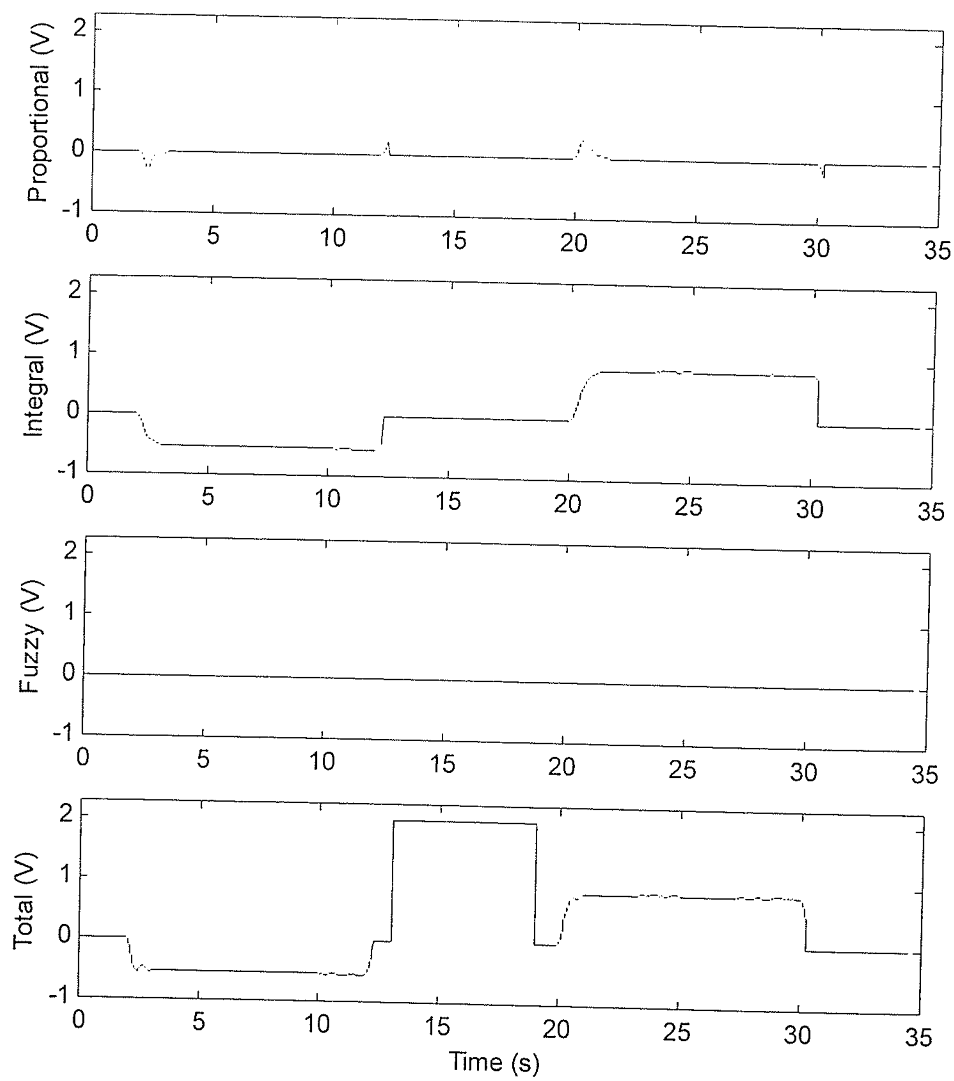


Figure 5.55 – Cable 1 control signals for case study 1.

Referring to Figure 5.55, the increase in the total control signal from t ≈ 13s to t ≈ 19s is responsible for closing the clamming device onto the cast iron plate used to simulate an external load. This extra control signal is similar to the control signal used in Section 5.2 to open the clamming device.

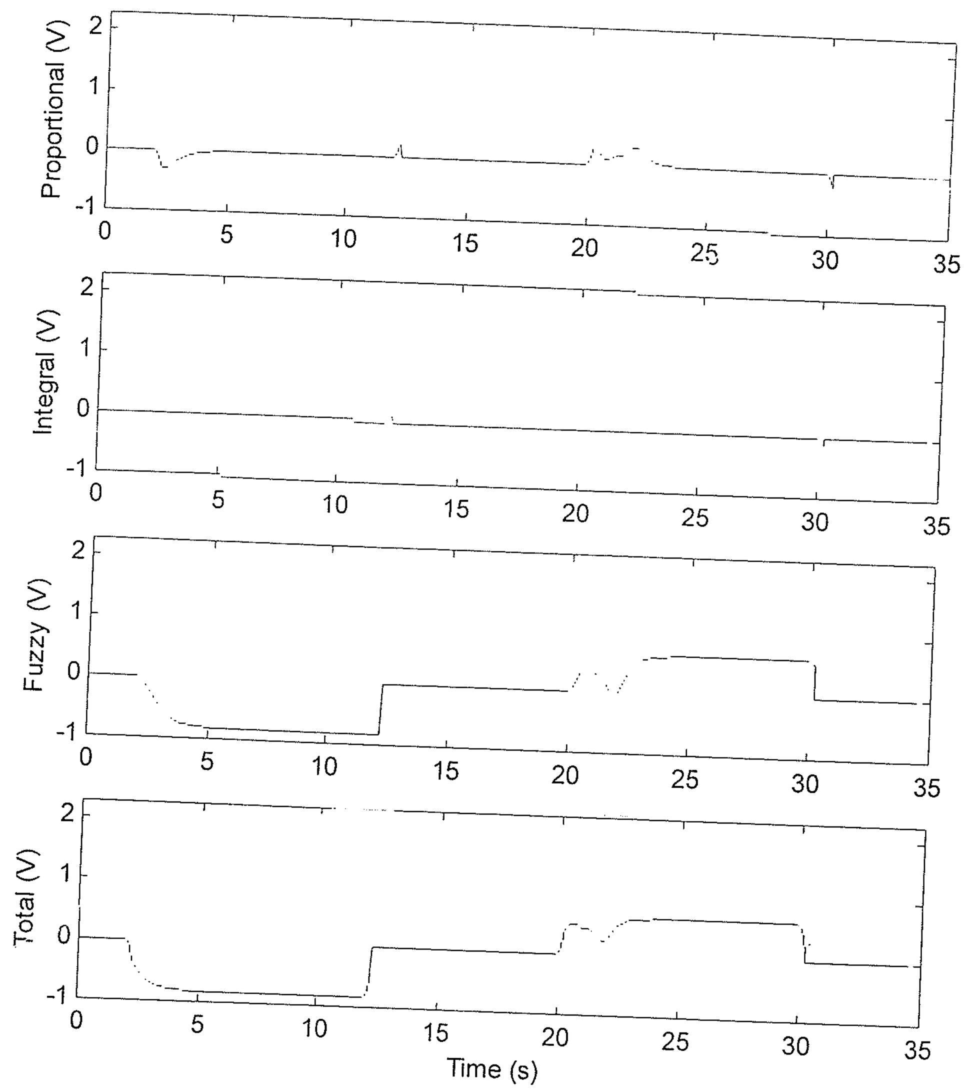


Figure 5.56 – Cable 2 control signals for case study 1.

5.3.2 – Case study 2

This case study is an extension of case study 1. In addition to the events which occur in case study 1, the down closed operating mode was included to simulate lowering the debris collected in case study 1 and releasing them onto the bed of a truck. This series of events is summarized in Figure 5.57, and the speed responses for this advanced case study are shown in Figure 5.58.

The down open operating mode of the controller recognizes that the clamming device is not fully open at t ≈ 2s and corrects for this error before returning to a steady rate of descension. The clamming device halts and subsequently closes from t ≈ 13s to t ≈ 19s. After ascending with the clamming device fully closed (up closed operating mode), the system pauses before the down closed operating mode is used to lower the clamming device from t ≈ 32s to t ≈ 42s. Once fully lowered, the clamming device is opened at t ≈ 43s. This sequence of events is summarized in Figure 5.58 and the digital photograph sequence pertaining to this case study is shown in Figure 5.59.

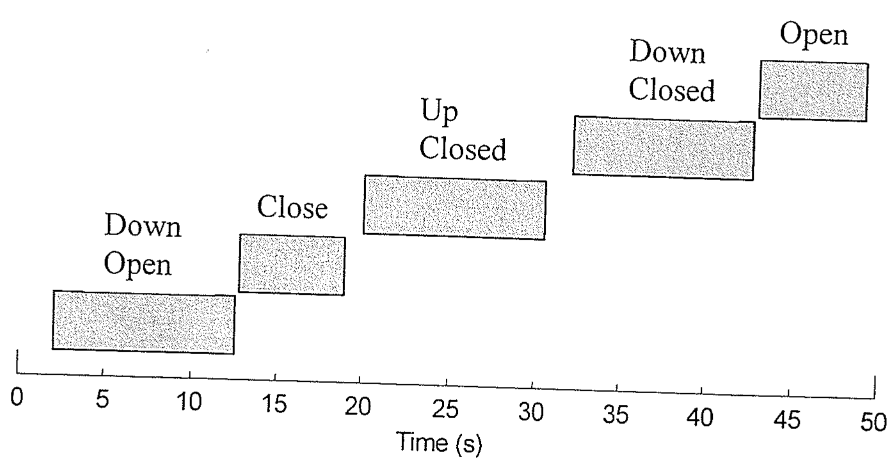


Figure 5.57 – Time chart for case study 2.

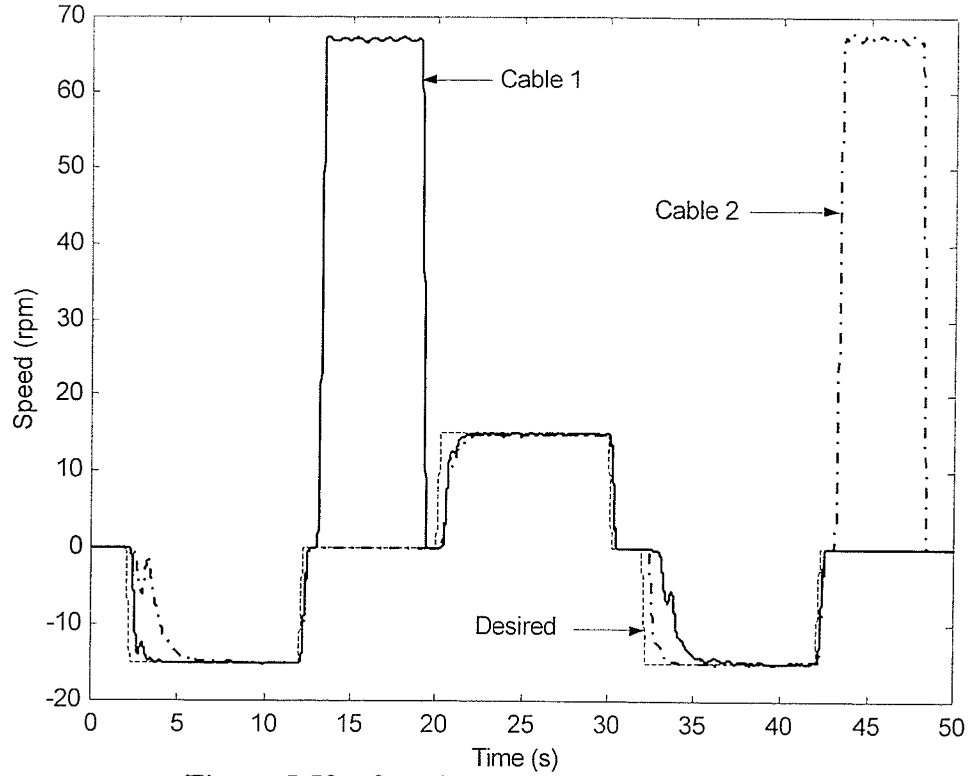
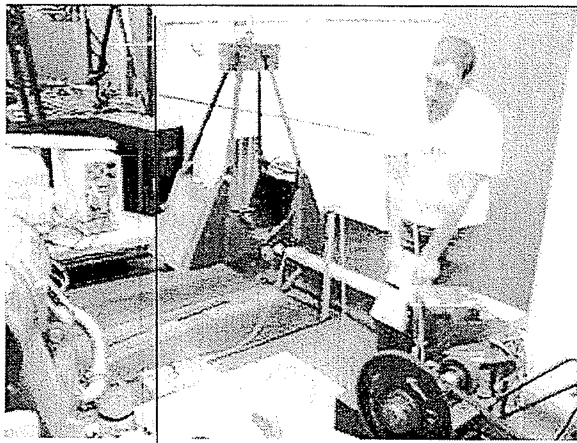
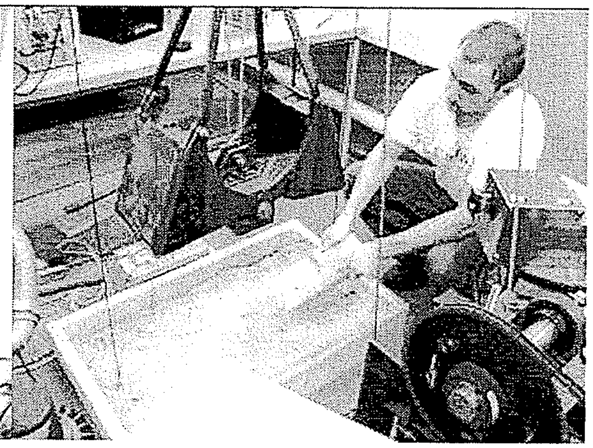


Figure 5.58 – Speed responses for case study 2.

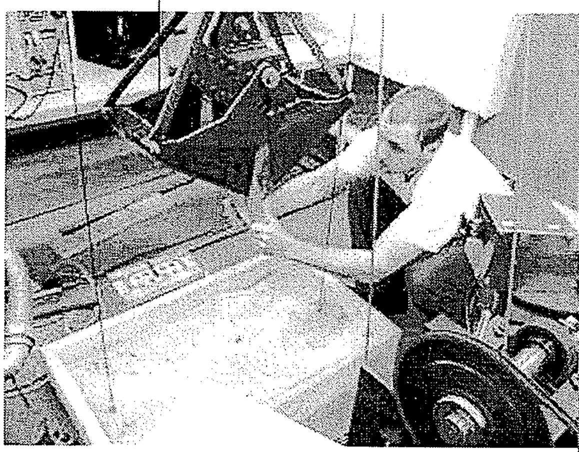
Referring to Figure 5.59, the first photograph shows the system in its initial position at t ≈ 0s before it descends to its lowest point at t ≈ 12 as shown in Figure 5.59b. The clamming device closes from t ≈ 13s to t ≈ 19s. Figure 5.59d shows the clamming device as it ascends to its highest point at t ≈ 30s. The fuzzy logic controller utilizes the down closed operating mode to return the clamming device to its lowest height at t ≈ 42s before opening fully from t ≈ 43s to t ≈ 48s. Figures 5.60 and 5.61 show the control signals for Cable 1 and Cable 2, respectively.



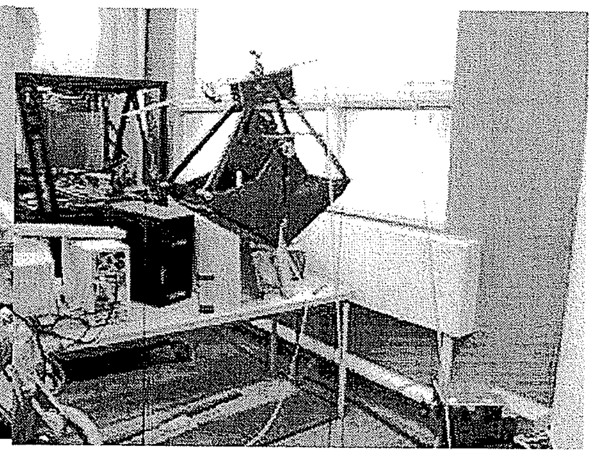
(a) t ≈ 0s



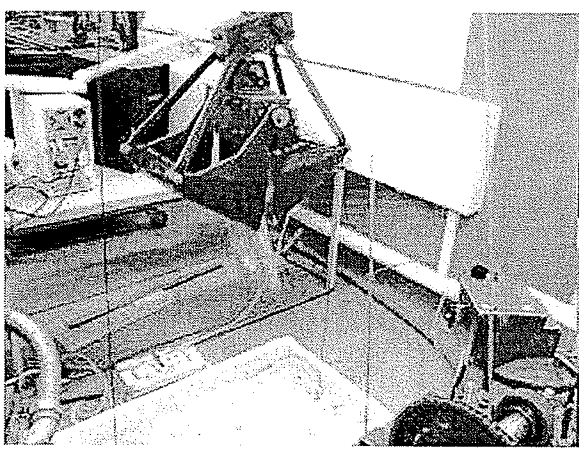
(b) t ≈ 12s



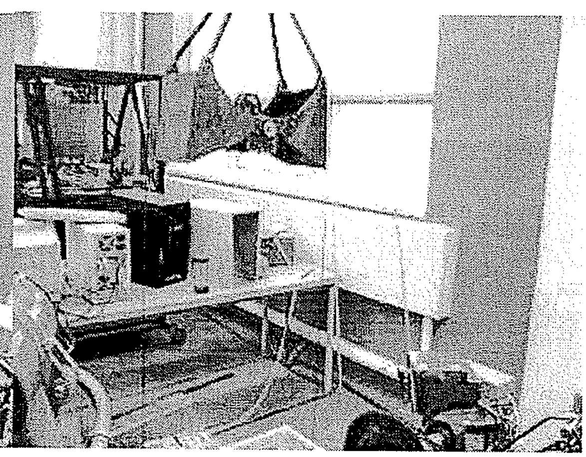
(c) t ≈ 18s



(d) t ≈ 30s



(e) t ≈ 42s



(f) t ≈ 46s

Figure 5.59 – Photo sequence for case study 2.

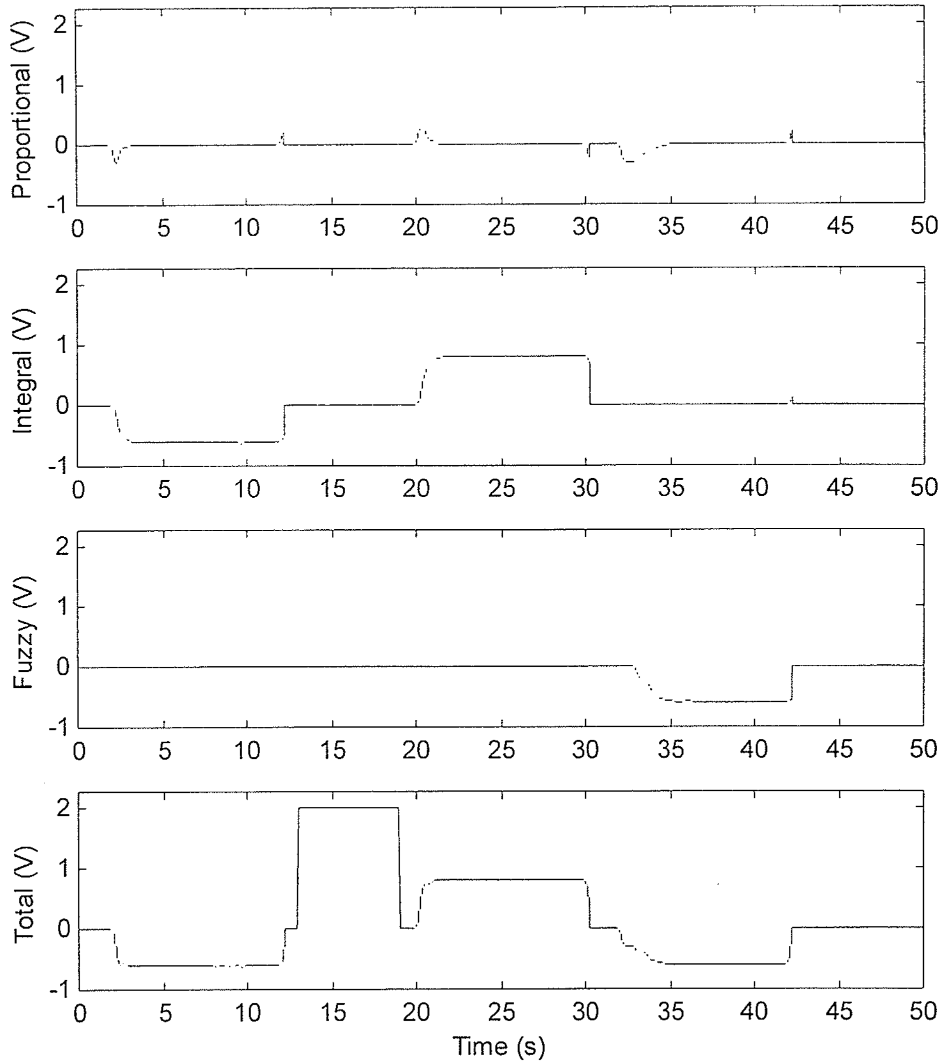


Figure 5.60 – Cable 1 control signals for case study 2.

Referring to Figure 5.60, the large increase in the total control signal from t ≈ 13s to t ≈ 19s closes the clamming device onto the cast iron plate used to simulate an external load. The increase in the total control signal in Figure 5.61 from t ≈ 43s to t ≈ 48s opens the clamming device to drop the cast iron plate.

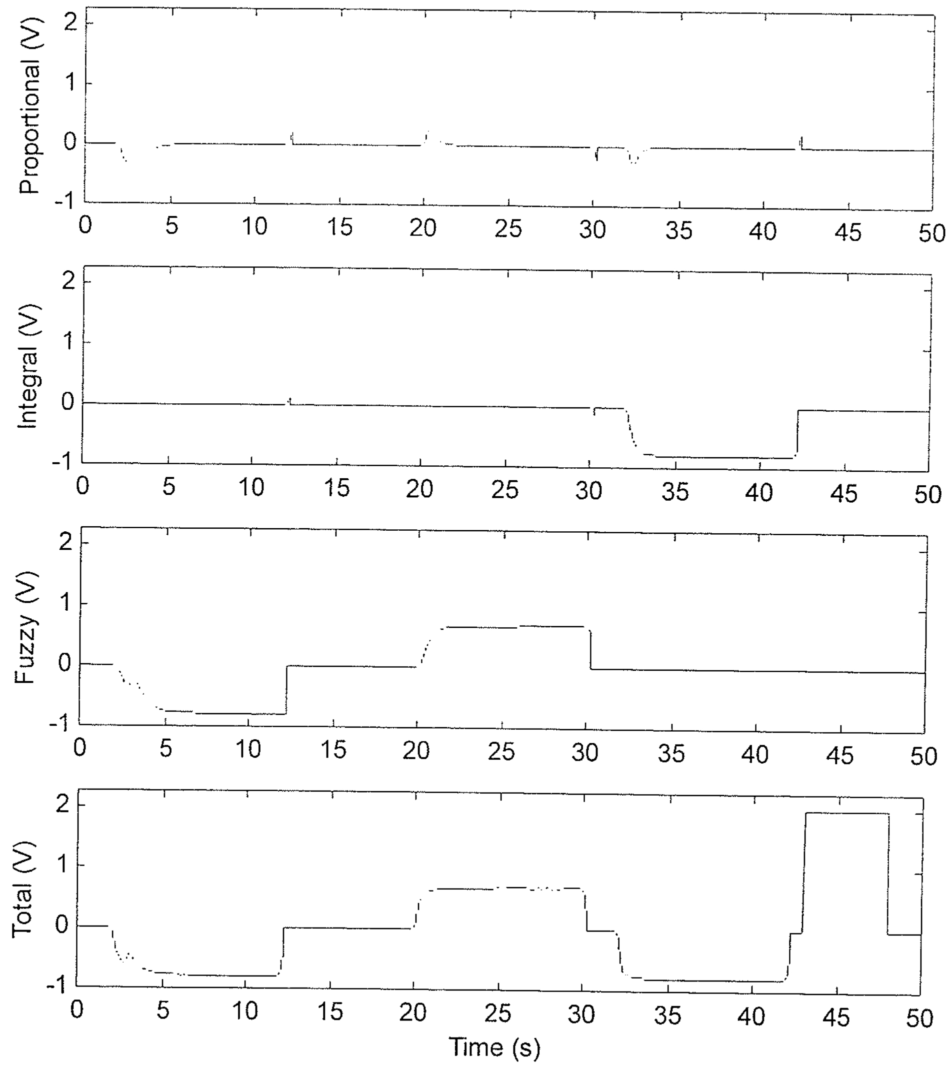


Figure 5.61 – Cable 2 control signals for case study 2.

5.3.3 – Case study 3

The final case study utilizes all four operating modes in sequence to simulate a full cycle of trash removal. It is a continuation of the previous case studies, where the up open operating mode has been included at the conclusion of the events in case study 2 to simulate the clamming device returning to its initial height after removing trashes from a trash rack at a hydroelectric generating station. The series of events is summarized in Figure 5.62. The speed responses of the cables are shown in Figure 5.63.

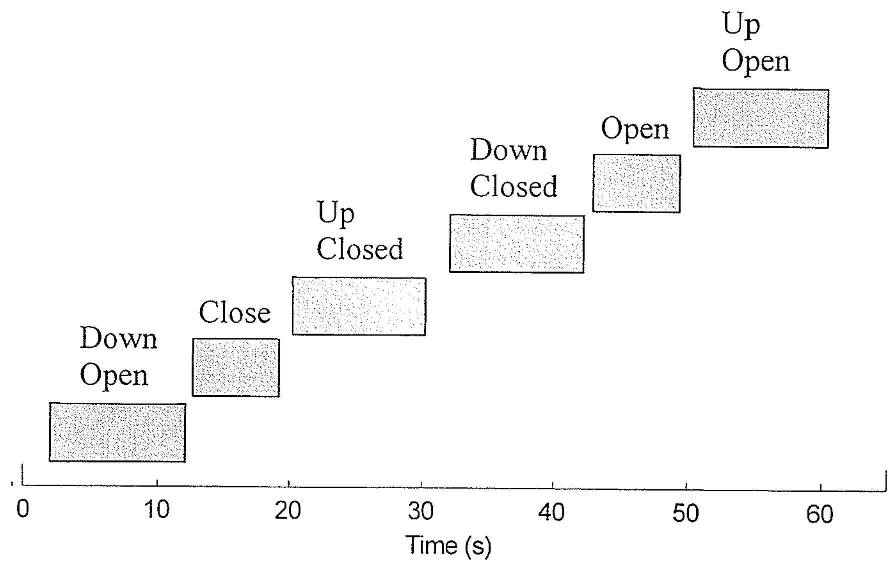


Figure 5.62 – Time chart for case study 3.

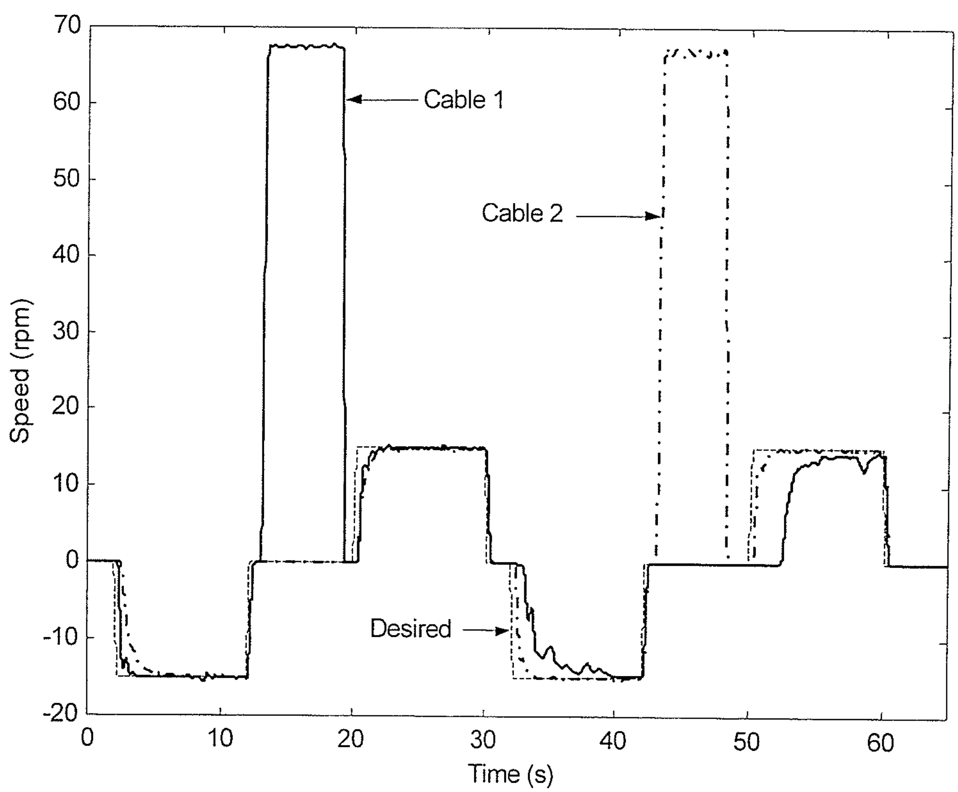
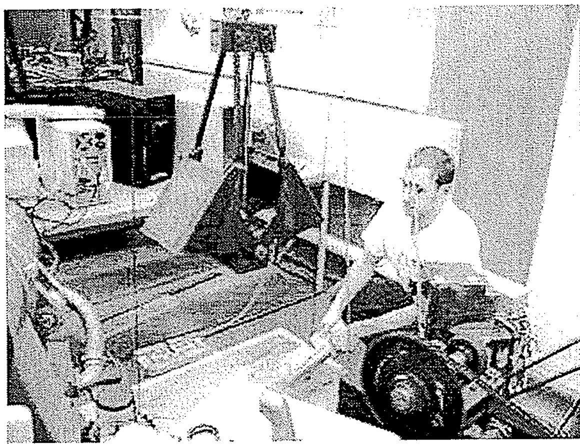


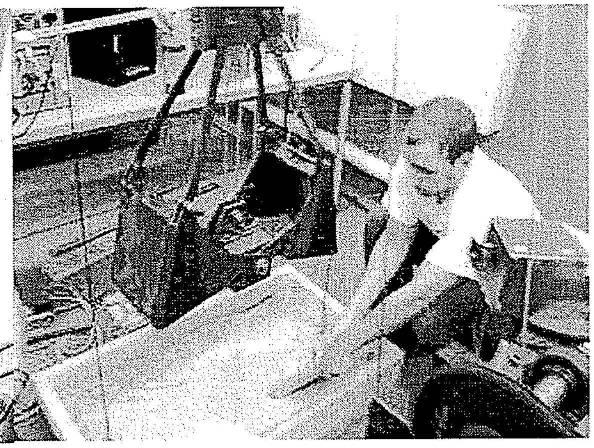
Figure 5.63 – Speed responses for case study 3.

Referring to Figure 5.63, the system initially functions in the down open operating mode before closing the clamming device onto a cast iron plate from t ≈ 13 to t ≈ 19s. The plate is raised using the up closed operating mode, then pauses before the clamming device is lowered through the utilization of the down closed operating mode. The clamming device then opens from t ≈ 43s to t ≈ 48s. At t ≈ 50s the fuzzy controller is in the up open operating mode and recognizes that the clamming device is not fully open by assessing the pressure differential as described in Section 5.1.4. The fuzzy logic controller compensates for the incorrect load by returning the full load to Cable 2 before arriving at a steady rate of ascension.

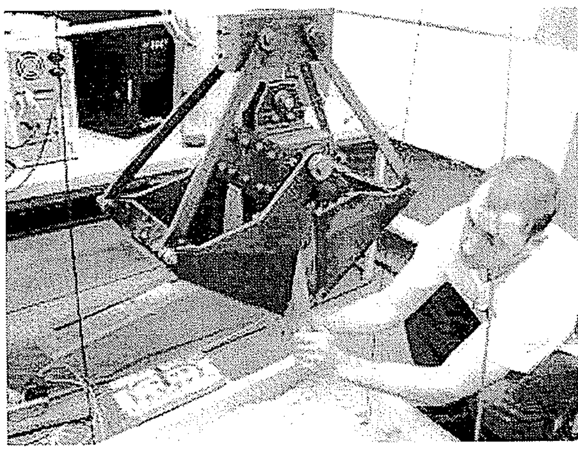
Figure 5.64 shows the digital photograph sequence for the final advanced case study. The Figure 5.64a shows the clamming device in its initial position at t ≈ 0s. After lowering the clamming device, the system pauses before closing into a cast iron plate from t ≈ 13s to t ≈ 19s (see Figures 5.64b and 5.64c). The fuzzy logic lifts the plate to its maximum height in Figure 5.64f. After a short pause the clamming device descends, and the clamming device is shown at its lowest height in Figure 5.64h before opening and dropping the plate to the ground (see Figures 5.64i). The fuzzy logic controller realizes that the clamming device is not fully open and halts Cable 1 until the full load has returned to Cable 2 at t ≈ 54s, shown in Figure 5.64k. The clamming device then ascends at a constant 15 rpm.



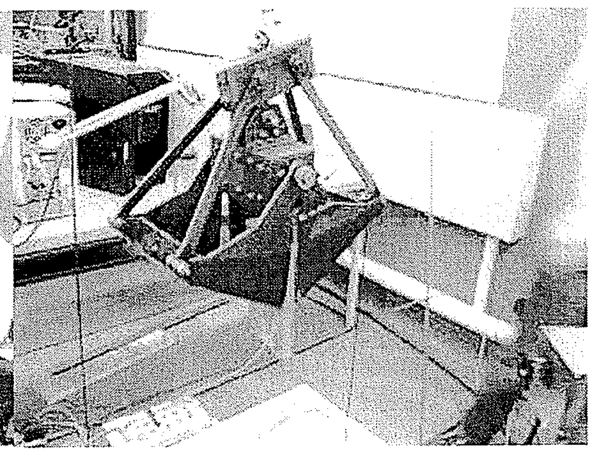
(a) t ≈ 0s



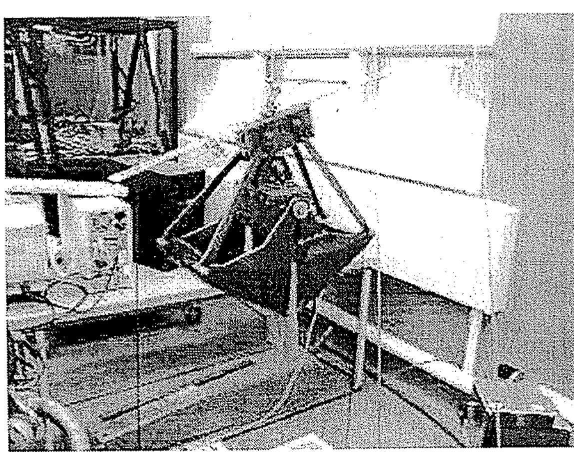
(b) t ≈ 12s



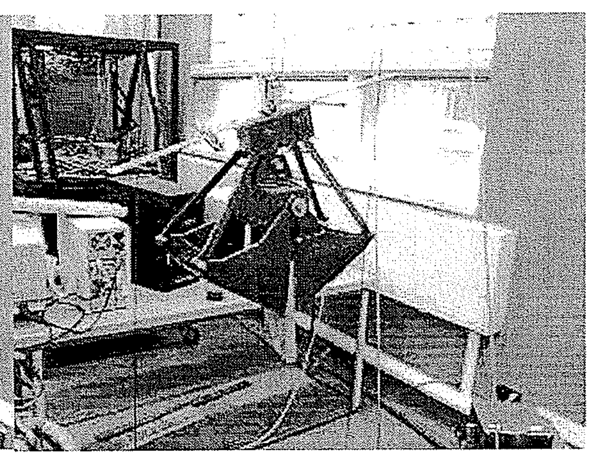
(c) t ≈ 18s



(d) t ≈ 22s

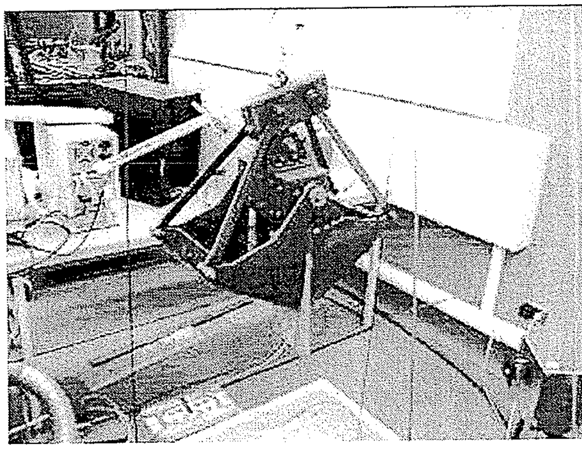


(e) t ≈ 26s

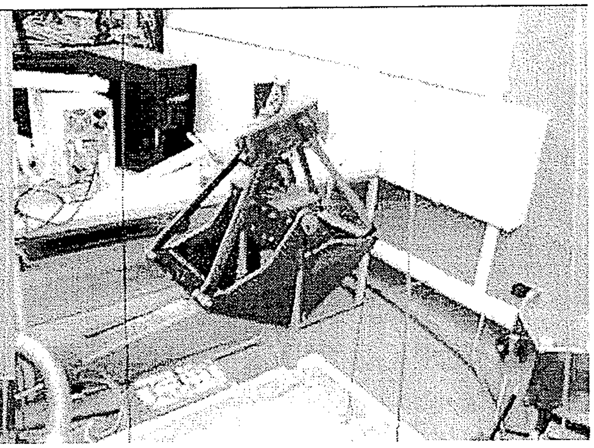


(f) t ≈ 30s

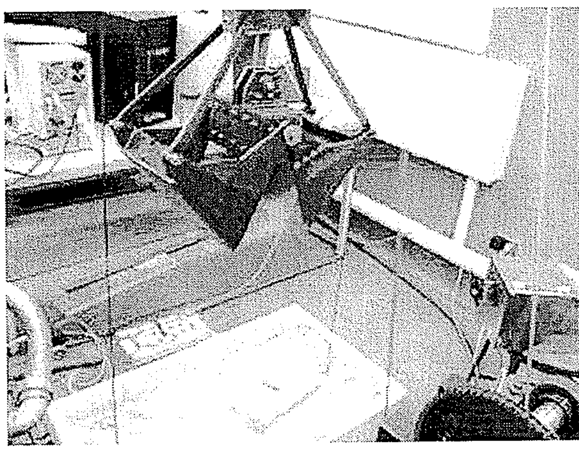
Figure 5.64 – Photo sequence for case study 3.



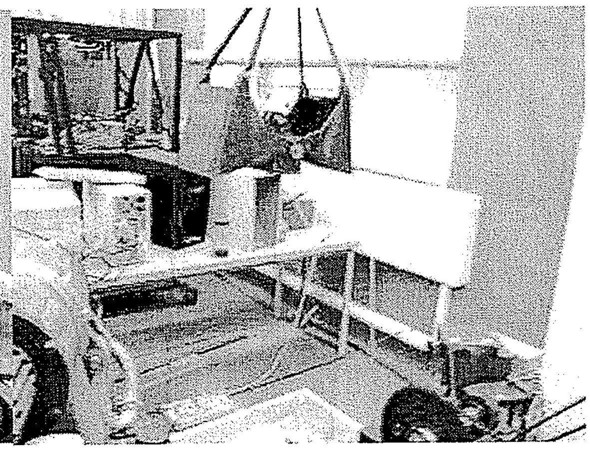
(g) t ≈ 38s



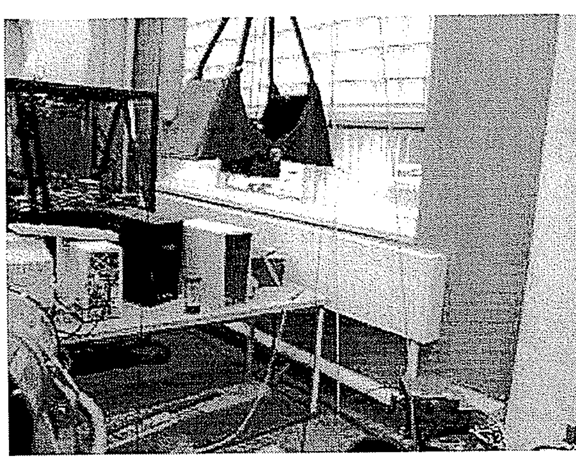
(h) t ≈ 42s



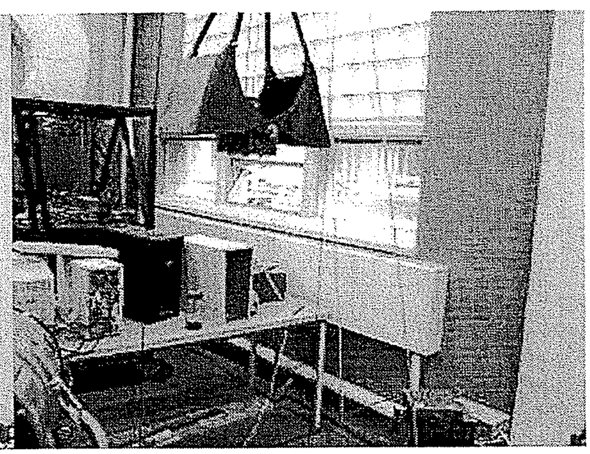
(i) t ≈ 44s



(j) t ≈ 50s



(k) t ≈ 54s



(l) t ≈ 60s

Figure 5.64 continued – Photo sequence for case study 3.

The control signals for Cable 1 are shown in Figure 5.65 and the control signals for Cable 2 are shown in Figure 5.66. Referring to Figure 5.65, the large increase in the total control signal from t ≈ 13s to t ≈ 19s closes the clamming device onto the cast iron plate while the increase in the total control signal in Figure 5.66 from t ≈ 43s to t ≈ 48s opens the clamming device to drop the cast iron plate. Also, Figure 5.65 shows the fuzzy logic controller correcting for the clamming device not being fully open to start the up open operating mode, between t ≈ 50s and t ≈ 54s.

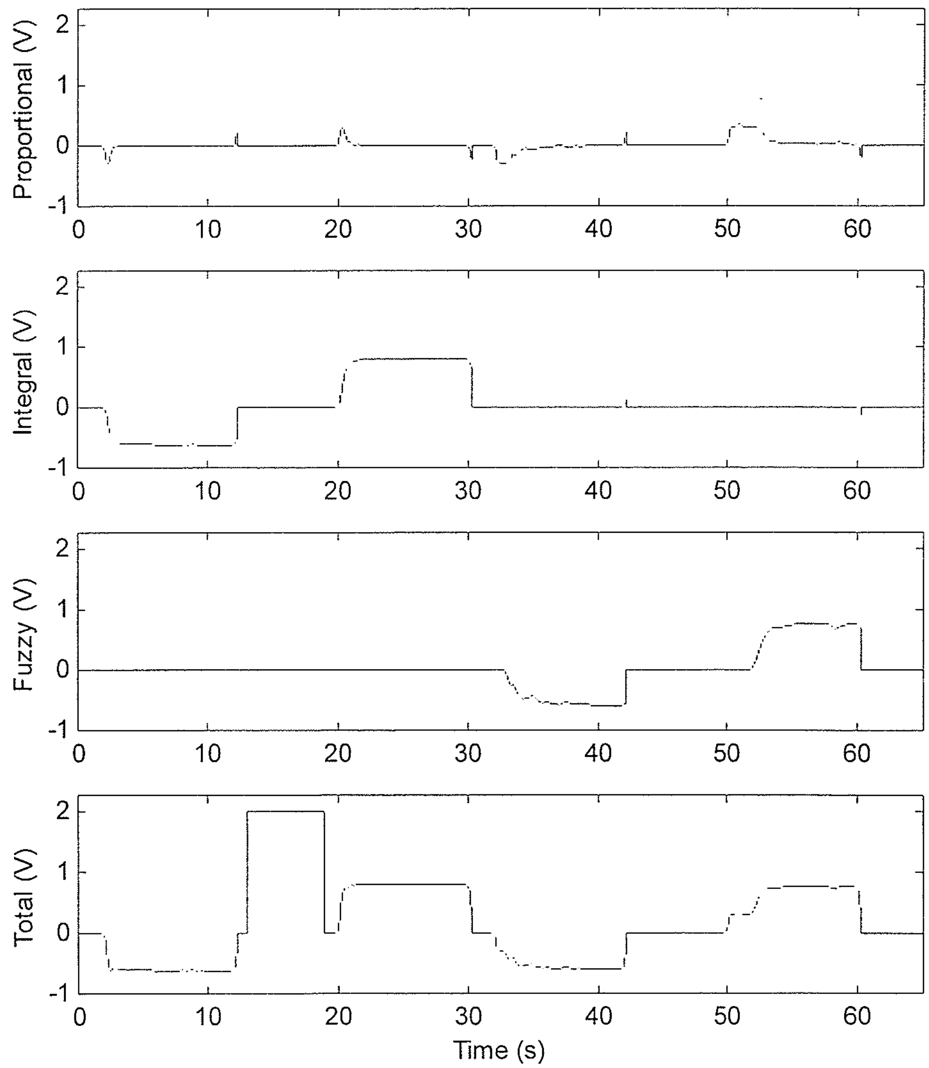


Figure 5.65 – Cable 1 control signals for case study 3.

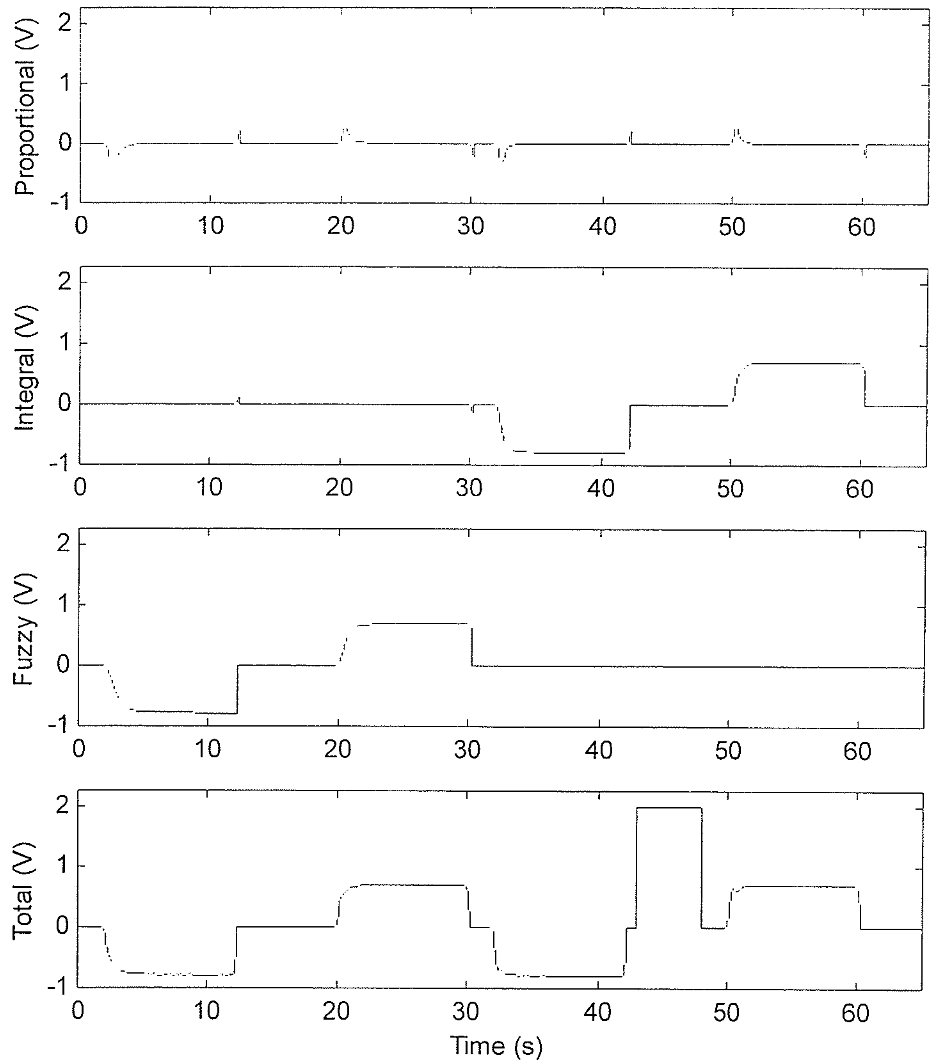


Figure 5.66 – Cable 2 control signals for case study 3.

Chapter 6

Contribution of this Thesis

This thesis presents the design and experimental evaluation of a fuzzy logic based controller for the purpose of closed-loop coordinated control of a cable-driven clamming device. Currently, the operators determine whether or not a cable is carrying the appropriate load by visually observing the slackness or tension of the cables carrying the clamming device. The task of coordinating the motion of the cables actuating the clamming device requires continuous attention from the operator. The goal of this research is to develop a controller to coordinate the motion of the cables to perform the task of handling the load and manipulating the clamming device. As a result, the operator is removed to a supervisory position in the control loop, easing the mental burden on the operator and making for a safer workplace. To meet this goal, the experimental test rig in the Experimental Robotics and Tele-operation Laboratory at the University of Manitoba was fully instrumented to create a full platform for testing novel control strategies.

The controller designed for this task allows for smooth control of the winch speeds from multiple inputs, i.e. the load state and speed error, for four distinct operating modes; up closed, up open, down closed and down open. The proposed control strategy cooperatively incorporates conventional control theory and the fuzzy logic based controller designed for this research into a novel controller. The specific control strategy proposed in this thesis represents a new development in the control of cable-driven heavy-duty equipment.

For each operating mode, a conventional PI type controller controls the speed of one cable, while the other cable is PF controlled. The controller is designed in such a way that the computer control algorithm closely follows the thought process of a human operator by keeping the speed of one cable constant and varying the speed of the other cable to correct for errors in the load state and speed error of the clamming device. This novel approach utilizes a PF controller to evaluate the current load state and speed error and determine, through fuzzy logic, the small incremental corrections that are required to coordinate the motion of the cables. The exact control structure, i.e. which cable is PI controlled and which is PF controlled, depends on which operating mode is being used.

The controllers for each individual operating mode were tested for various initial scenarios to simulate errors in the loading of the clamming device. The controller performed well in all scenarios for all operating modes. A successful study was performed to demonstrate that the controller would not react adversely in the presence of an external load. Several advanced case studies were also performed, simulating segments of typical trash removal operations. Each successive study built upon the previous, and the final advanced case study utilizes all four operating modes in sequence to simulate an entire cycle of trash removal.

The fuzzy logic controller keeps the appropriate tensions on each cable, depending on the specific operating mode being utilized. An operator would no longer be required to balance the loads on each cable during ascension and descension. He/she would simply use one single-axis joystick to impart a desired speed to the system while the fuzzy logic controller handles the small corrections required to coordinate the motion of the cables.

The controller presented in this thesis would be feasible to implement on the actual cranes operated by Manitoba Hydro for the purpose of clearing debris from hydroelectric generation stations. Sensors would be placed on the base of the crane to protect expensive data collection hardware, necessitating indirect assessments of the variables for load state and speed error. Pressure transducers on the hydraulic motors and optical encoders on the winches indirectly measure both the vertical speeds of the cables along with their load states, respectively. The final control system would consist of embedded supporting systems that will perform the advanced control of the clamming device, while the operator is removed to a supervisory position within the control loop. The controller presented in this thesis would require only minor modification to adapt to a different physical system than the experimental test rig, namely the actual cranes used by Manitoba Hydro. The cranes would require instrumentation in the form of optical encoders and pressure transducers, and the hardware and software required for computer control would have to be designed to be implemented in an embedded control system.

A limitation of the fuzzy logic controller presented in this thesis is that it is not capable of dealing with excessive slack in the cables. Such slack is dangerous to the operation of the clamming device, as excess cable could become tangled on unknown obstacles, or become severed. A vision-based system along with the controller presented in this thesis would address that issue. Also, to add to the controller design presented here, studies involving the effect of the motion of the boom of the crane could be conducted to investigate whether the controller could be expanded to include a control architecture capable of not only augmenting human control, but preventing unintentional errors such as tipping over from attempting to lift too much load or moving too fast. The feasibility of adaptive learning techniques for self-calibration of the fuzzy logic controller could also be investigated.

Chapter 7

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