Fuzzy logic control of a "smart" window

by

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A Thesis Submitted to the

Graduate Faculty in Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

Department: Mechanical Engineering
Major: Mechanical Engineering

Iowa State University
Ames, Iowa

1994

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1. INTRODUCTION

1.1 Impact of Windows on Building Energy

Windows have a significant impact on building energy usage. In the United States about 5% of national energy usage is attributable to windows.[1] "Typical windows admit large fractions of incident solar radiation, and allow relatively high rates of heat exchange with the surroundings, compared to other portions of the building envelope" [2, page 1]. "Window system properties, characteristics and designs have a significant impact on building energy requirements, building thermal performance, occupant comfort, and HVAC system sizing" [2, page 1].

Solar radiation consists of direct, diffuse, and reflected components. For a clear day the largest component of solar radiation is direct solar gain [3]. The direct component of solar radiation is the portion of the radiation that has the greatest effect on building energy usage. It also the easiest to control because the position of the sun is well documented for any time of the year for different locations and window orientations [3].

As radiant energy passes through glass, the contribution to heat gain from direct beam radiation is constantly changing due to solar angles and sky conditions. The shading coefficient (the percentage of solar BTU per hour that passes through a window into the conditioned spaces) depends on the layers of glass and the use of draperies or blinds [4]. Single pane glass has a shading coefficient of about 90% while a double paned window with closed, light-colored blinds has a shading coefficient of approximately 50% [5]. Factors that affect the solar gain include glazing types, orientation of windows, and outdoor obstructions to sunlight [4].

After a window has been installed, the only factor that can be changed is the shading coefficient. This can be done by means of various window treatments such as blinds or draperies. The ideal solution is an adjustable variable shading device such as venetian blinds. The effect of these shading devices is to change the shading coefficient with different adjustments of the louvers. It is then possible to optimize the energy based on current outdoor and building load conditions.

1.2 Shading Devices

Adjustable shading devices such as venetian blinds can have a significant effect on building energy requirements when used properly. One study by the NBS states "Adjustable devices allow the benefit of tailoring the thermal and solar characteristics of the window to match the current weather conditions and building HVAC load conditions" [2, page 5]. A detailed analysis of the heat transfer through a double-paned window with between glass venetian blinds has been done by Rheault and Bilgen [6]. This research shows that an energy economy of up to 36% during the winter and 47% during summer is possible for Canadian climactic conditions. The analysis was done with the blinds at optimum angles for the winter and summer. These savings were compared to a single paned window with no blinds [6].

Improper use of blinds can work against the performance of window units. For instance, during the summer if a building occupant with an east-facing window leaves the blinds in an open position overnight, by the time he or she returns in the morning, the space will already have received considerable heat gain. Another example is during the winter; if an occupant leaves the blinds open overnight more radiant heat is lost through the window than if the blinds were closed.

While blinds have the potential to be effective in optimizing solar gain through a window, building occupants generally do not use the blinds appropriately to conserve energy. "While adjustable solar shading devices have the potential for greater energy savings than fixed devices, studies have shown that in many cases adjustable devices are in fact left in fixed positions by the occupants for long periods of time. Automatically adjusting devices can overcome this limitation, however they tend to be more complex and expensive, and long-term durability may be a significant consideration" [7, page 5]. The study also states that the shading device should be judged on the balance between "heating efficiency" and "shading performance" [7].

Currently the use of passive shading systems is very common in the United States. In the light commercial market shade systems are used to control light and to reduce solar heat gain. However, passive shade systems have the disadvantage that they are seldom set at the optimum tilt angle which changes throughout the day. Because direct solar radiation has the greatest impact on building energy, this optimum angle depends primarily on the solar altitude angle and the solar intensity.

A case study on the use of window blinds as a potential energy saver conducted by the NBS indicates that building users do not change the positions of venetian blinds frequently during the course of a day or from day to day. "Of the approximately 700 blinds studied in each season, the photographic records showed that no more than 50 blinds were changed at all during the week before experimental treatment, or more than once during the following week" [2, page 29]. Researchers also found that "when a preferred placement was established, the blind was not likely to be moved, either from day to day, or within the course of a single day" [2, page 70].

1.3 Objective

Ideally, an inexpensive, reliable, automatically adjusting shading device needs to be developed. The device should be able to optimize the lighting and solar gain that comes through a window. Local climate conditions dictate that this optimization has two basic modes, one for winter and one for summer. During the winter, direct beam radiation could be used to reduce the heating load of a building and maximize the light. During the summer, direct beam radiation should be blocked but as much diffuse and reflected light should be allowed in the building as possible in order to reduce the lighting load. This would reduce building envelope energy requirements while maintaining occupant comfort. Recent research by the Architecture Department at Iowa State University has been directed toward quantifying the energy savings from such a system. Typical savings were found to be generally around 80,000 Btu per year per square foot of glazing [8]. This takes into account the energy kept out during the summer and the energy gained during the winter. However, this research does not account for savings due to lighting.

An automatically adjusting shading device incorporating a Pella Corporation Slimshade with a motor actuator is being developed. This shading device has been called a "smart" window. The controller is based on the response of thin-film photovoltaic material that has been developed by Iowa Thin Film Technologies, Inc. and the Center for Amorphous Semiconductors at Iowa State University. The response of the photovoltaics depends on the amount of light falling on the cells. Because of the unpredictability of the factors affecting the direct solar gain such as clouds, time of year, latitude, and window orientation, a mathematical model of the response of the photovoltaics is inaccurate at best. A controller based on this model would be complex and would necessarily be different for every window location and orientation. Since conventional control problems are usually based upon mathematical models, a different approach was needed for the control of the "smart" window.

Fuzzy logic is a control technique based on fuzzy sets which uses linguistically expressed rules to control a process. Fuzzy sets are the linguistically expressed values of control inputs. Control rules are found by talking to an expert operator and can then be used to find control outputs for certain system inputs. In the case of the "smart" window, the rule base is determined by the ideal response of a building occupant to certain environmental conditions. Fuzzy logic control can use important information for computer control that would otherwise be difficult or impossible to use.

The objective of this research was to develop a controller for the automatically adjusting Slimshade using the response of thin film solar cells and the control technique of fuzzy logic. The fuzzy logic controller was expected to give better performance than a controller based on crisp sets because of the subjective nature of the control problem. The variables for the control of the shading system were more appropriately expressed as fuzzy sets than as crisp sets. The performance of the fuzzy logic controller was compared to that of a more conventional controller based on crisp sets in order to validate the results.

2. FUZZY LOGIC OVERVIEW

2.1 Background

Some processes such as batch chemical reactors, blast furnaces, and cement kilns are difficult to accurately control automatically. This difficulty is due to the non-linear, time-varying nature of these processes [9]. As stated by Zadeh "... as the complexity of a system increases, our ability to make precise and yet significant statements about its behavior diminishes until a threshold is reached beyond which precision and significance (or relevance) are mutually exclusive characteristics" [10, page 28].

Human operators have often been able to control processes that cannot be described sufficiently by a model. The operators use qualitative concepts such as "high", "low", "very low", "somewhat high", etc., to control these processes. In conventional control methods this valuable information would not be used because it cannot be expressed by precise equations. Fuzzy logic provides a means to utilize this qualitative knowledge in computer control.

Fuzzy logic is a control technique based on the concept of "fuzzy sets" as presented by Zadeh [10,11] in the mid 1960's. Fuzzy set theory makes it possible to use imprecise concepts in a mathematically strict sense [11]. Conventional logic is based on a yes or no two-valued logic. Either an element is a member of a set or it is not. There are two major problems with this type of logic, real situations often cannot be described precisely and the complete description of a system contains too many details for a human operator to process, yet the operator still makes appropriate control decisions [12]. Fuzzy sets allow an element to be a member of a set to a certain degree. Fuzzy logic uses fuzzy sets as a basis to control a process using the same concepts as a human operator.

The basic steps in fuzzy logic are as follows: Important system inputs and outputs are decided upon and are considered to be linguistic variables. Linguistic values (or fuzzy sets) of these linguistic variables are determined and membership functions for the values developed. A fuzzy rule base is created using human operator actions to certain linguistic values of the input linguistic variables. After the rule base and membership functions are determined, if crisp input variables are available they are "fuzzified" using the membership functions. Then certain rules of the rule base are "fired" by means of an inference mechanism to obtain fuzzy outputs. Finally the outputs are "defuzzified" to obtain crisp output values. If fuzzy subsets of the linguistic values are input, such as with a qualifier "very" or "somewhat", then the compositional rule of inference is applied to determine the fuzzy output value. Most often the input variables are crisp values and the compositional rule of inference is not applied.

2.2 Fuzzy Sets and Linguistic Variables

"A fuzzy set is a class of objects with a continuum of grades of membership" [2, page 338]. That is, there is no sharp transition from membership to non-membership [13]. Many concepts in the real world do not have well-defined boundaries. The sets of beautiful, small, large, hot, cold, etc., do not have crisp boundaries. A fuzzy set, F, in a universe of discourse, U, is characterized by a membership function, μ_F, which takes values between zero and one. A fuzzy set can be seen as a generalization of an ordinary set whose membership takes on values of only zero and one [14]. Fuzzy sets are linguistic values of linguistic variables.

A linguistic variable is characterized by the name of the variable, the set of names of linguistic values of the variable, the universe of discourse of the variable, the rules for generating the names of the values of the variable, and the fuzzy subsets of the universe of discourse [12]. Linguistic variables are generally system outputs or inputs. Significant linguistic variables and linguistic values for these variables can be determined by talking to a knowledgeable system operator. States of the system and actions to the system are described using values of linguistic variables. Much of the same information is used to determine the rule base for the fuzzy logic system. Often the rule base information and the linguistic variable information are obtained simultaneously.

The membership functions (fuzzy sets) for the linguistic values of the linguistic variables are also determined from operator knowledge. Typically, to simplify calculations, the membership functions of fuzzy sets are represented as straight lines, however, almost any shape of membership function is admissible so long as it meets the requirements as stated by Zadeh [11]. Some different possibilities for membership functions are shown in Figure 2.1. The shape of a membership function is not as important as the boundaries of the fuzzy set. The support of a fuzzy set (any values of the universe of discourse where the fuzzy membership function is not zero) and where the peak value ($\mu=1$) occurs are the important characteristics of the membership functions.

A hypothetical system is described to further the understanding of linguistic variables and fuzzy sets. The output of a thin-film photovoltaic could be a voltage proportional to the amount of light falling on the solar cells. A linguistic variable for this system could be the change in voltage from the last time it was checked (old voltage - new voltage). Input values of this linguistic variable are precise values. Using this variable, the operator should be able to determine whether the blinds should be moved. The name of the linguistic variable is then "change in voltage" and linguistic values of this variable could be "negative", "zero", and "positive". These are also the names of the fuzzy sets of the variable. A fuzzy set can be represented as a set of ordered pairs of values of the linguistic variable and their grades of

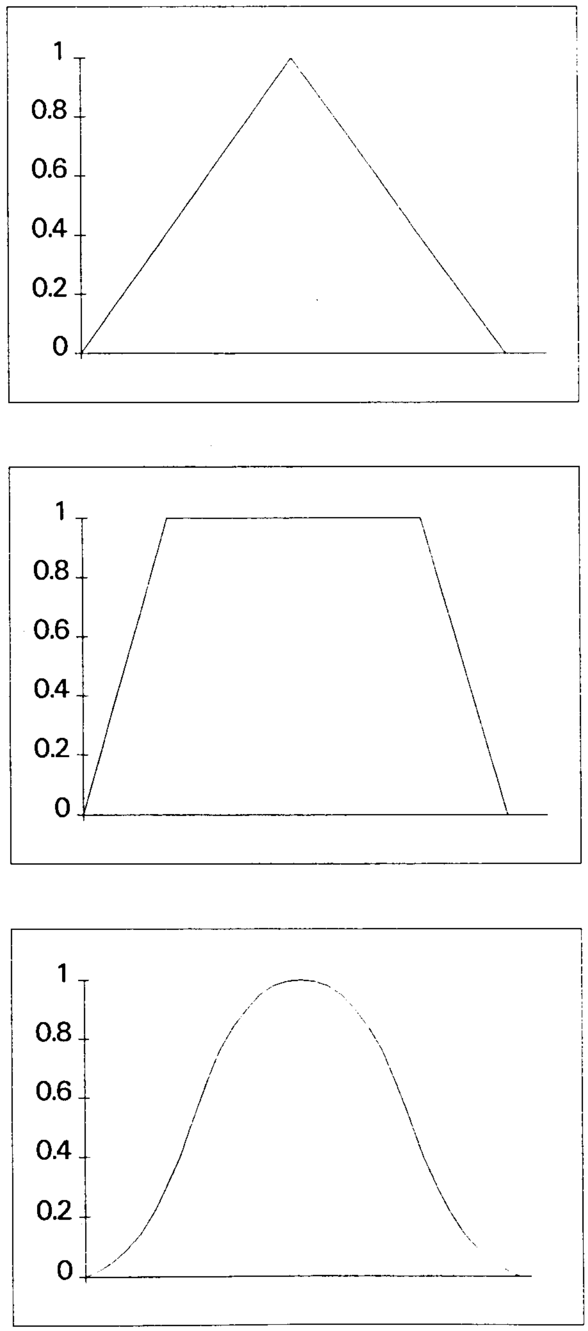


Figure 2.1: Possible shapes for fuzzy set membership functions

membership. The universe of discourse of the "change in voltage" is the range of all possible values for the voltage difference. The universe of discourse can be either discrete or continuous. If the universe is discretized, a look-up table which defines the output of the controller for each possible combination of input values can be created in order to decrease run time of the controller. The fuzzy sets of "change in voltage" might be similar to Figure 2.2 for a continuous universe of discourse. The value of the variable "change in voltage" can belong to more than one fuzzy set at a time. For instance, a change in voltage value of 0.15 volts is a member of "zero" to a degree 0.5 and a member of "positive" to a degree 0.5. This process of assigning membership values of certain variables is called "fuzzifying" the input.

The output variables are also expressed as linguistic variables in terms of fuzzy sets. For the system introduced earlier, the motor position voltage corresponds to a certain blind angle that controls how much light reaches the photovoltaics. Therefore, a change in motor position voltage corresponds to a change in the photovoltaic voltage. Figure 2.3 shows the fuzzy sets of the output variable, change in motor position voltage, with linguistic values of "zero", "small", and "large". A certain change in motor position voltage will change the amount of light reaching the photovoltaics. This idea is used in developing the rule base.

2.3 Rule Bases

A rule base or fuzzy algorithm must be established to determine appropriate outputs for certain inputs. The rule base relies on information obtained from a knowledgeable operator. Questions are asked of the operator about actions taken at certain states of the system. All actions to states are expressed as linguistic rules called fuzzy implications and are usually of the form:

IF X=(antecedents) THEN Y=(consequences)

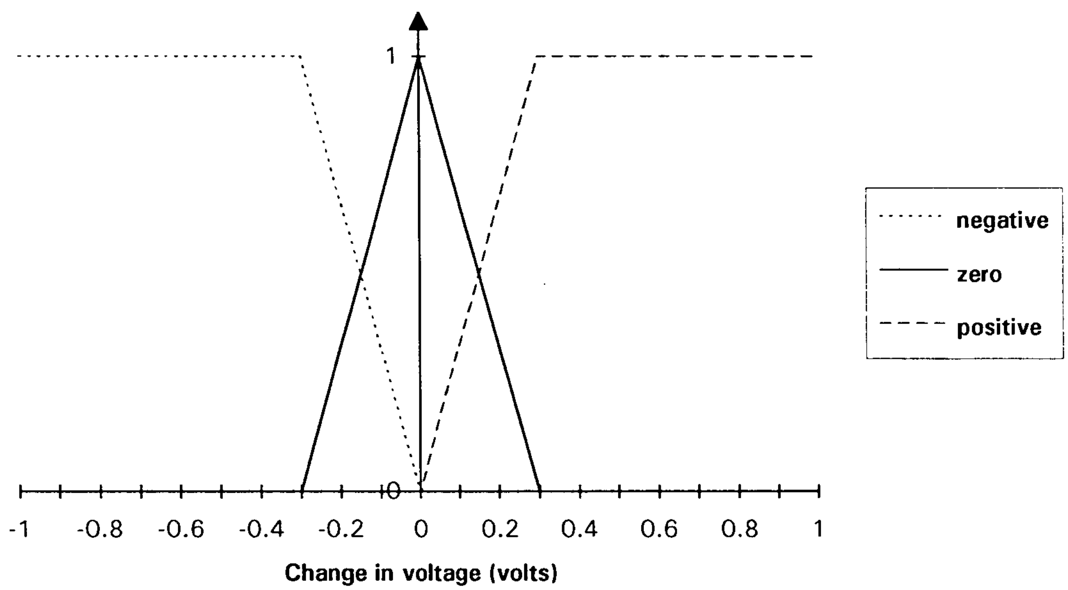


Figure 2.2: Membership functions for input variable fuzzy sets of example system

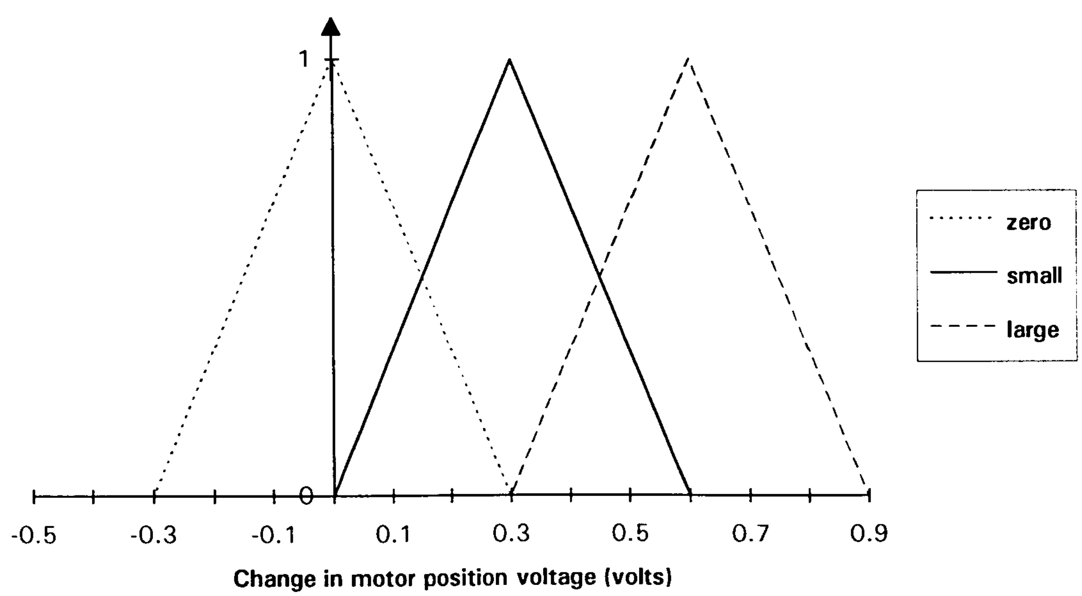


Figure 2.3: Membership functions for output variable fuzzy sets of example system

The rules are interpreted as: If the antecedents of the rule are met, then apply the consequences. The antecedents can be interpreted as process inputs and the consequences as process outputs. The antecedents and the consequences of these rules are expressed in linguistic terms and are often called fuzzy conditional statements [14]. If several linguistic variables are included in the antecedents and the consequences of these rules, the system is a multiple-input multiple-output system. If X and Y are scalars, the system reduces to a single-input single-output system. The complete set of rules that covers all possible inputs and outputs makes up the rule base.

Consider the hypothetical fuzzy sets introduced in section 2.2. The goal of this system is to maximize the voltage output of the photovoltaic cells. A change in motor position voltage corresponds to a change in the light level causing the voltage output. For this hypothetical system, a rule might be stated as:

If Δvoltage is "positive" then the Δmotor position voltage is "large".

If the voltage has decreased from the last time it was checked, the blinds need to be moved. Both "positive" and "large" have fuzzy meanings as described in the fuzzy sets of section 2.2.

A complete rule base for the system would specify the change in motor position voltage for all possible linguistic values of change in voltage. The change in voltage has three "values" expressed by "negative", "zero", and "positive", therefore, there will be three rules in the rule base. The rules might be stated as:

1. If Δvoltage is "negative" then the Δmotor position voltage is "zero".
2. If Δvoltage is "zero" then the Δmotor position voltage is "small".
3. If Δvoltage is "positive" then the Δmotor position voltage is "large".

For a more complex system there could be more inputs and outputs for each rule. Once the rule base has been established and all the linguistic variables and fuzzy sets are determined, the next step is decision making. An inference mechanism is used to determine fuzzy outputs for fuzzy inputs.

2.4 Decision Making Logic

The heart of fuzzy logic control is the decision making logic. Composition is the mechanism by which decisions are made when several rules are fired simultaneously to a degree less than one. The result of this composition is a fuzzy possibility distribution that must then be interpreted as a single crisp output. Several methods are available for defuzzification and some of the more common techniques will be discussed.

2.4.1 Inference Mechanism

As was discussed in section 2.3, fuzzy conditional statements provide the basis for decision making in fuzzy logic controllers. The main tools of reasoning in conventional logic are tautologies such as the *modus ponens*. It consists of a premise, an implication, and a conclusion, such as:

Premise: x is A

Implication: If x is A then y is B

Conclusion: y is B [12]

When the modus ponens is generalized to include fuzzy sets, it is called the *generalized modus ponens* [11]. With these generalizations, the premise, implication, and conclusion can be stated as:

Premise: x is A'

Implication: If x is A then y is B

Conclusion: y is B' [12]

Where A' is a fuzzy subset of the fuzzy set A, usually with a qualifier such as "very" or "somewhat". The implication forms a two-dimensional fuzzy relation, R, in the product space of A and B. The membership function of R is given as:

$$\mu_R(u,v) = \mu_{AxB}(u,v) = \min[\mu_A(u); \mu_B(v)],\ u \in U,\ v \in V \qquad [9]$$

If the implication is rule 2 from the rule base presented in section 2.3, then U is the universe of discourse of change in voltage, u is a value of this universe, V is the universe of discourse of change in motor position voltage, v is a value of this universe, A is the fuzzy set of "zero", and B is the fuzzy set of "small". The fuzzy relation R can be represented graphically as in Figure 2.4. The universes of discourse for the change in voltage and the change in motor position voltage had to be discretized which causes the fuzzy relation to be discretized.

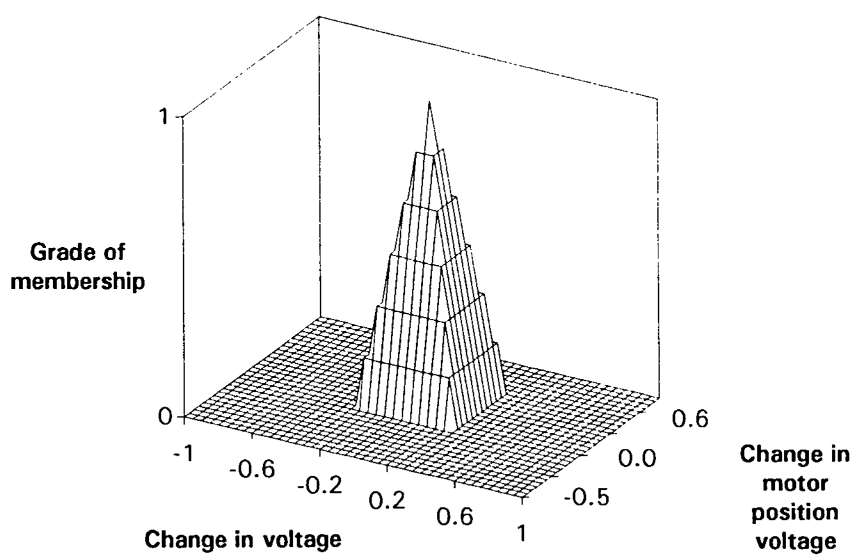


Figure 2.4: Graphic representation of the fuzzy relation

The rule base or fuzzy algorithm generally contains more than one rule. The concept of "fuzzy composition" is needed to combine all the rules in a useful manner. Using the "or" connective between rules of the rule base, the fuzzy relation is formed by the union of the different rules. The membership function for this fuzzy relation is given by:

$$\mu_R(v,u) = \max[\min[\mu_{A1}(u);\mu_{B1}(v)];\min[\mu_{A2}(u);\mu_{B2}(v)];\ldots\min[\mu_{AN}(u);\mu_{BN}(v)]] \quad [9,16]$$

Where N is the number of rules, A_i is the antecedent of rule i, and B_i is the consequent of rule i. Given R, the fuzzy relation, and A', a fuzzy subset value of A, the relation is used to infer the corresponding value B' by the use of the compositional rule of inference [9]. Zadeh's compositional rule of inference is the most widely used form of composition for fuzzy algorithms [10]. Given the fuzzy implication, if A then B, the fuzzy subset B' inferred from a given fuzzy input set A' has a membership function defined by:

$$B' = A' \circ R \qquad [9]$$

The operator "$\circ$" indicates the composition which can take many forms. The most commonly used composition operation is the max-min composition. The membership function of this composition is defined by:

$$\mu_{B'}(v) = \max_u \min[\mu_{A'}(u);\ \mu_R(u,v)] \quad [9]$$

where the $\max_u$ operator indicates the maximum over the universe of discourse U. This composition is only used if the input variables are fuzzy inputs. In most applications, including the example presented above, the inputs are precise values. There is no need then to use the compositional rule of inference and the composition of the rule base reduces to:

$$\mu_{B'}(v) = \mu_R(v,u_0) \qquad [16]$$

The composition of the three rules introduced in section 2.3 can be seen graphically in Figure 2.5. Again, the universes of discourse were discretized making the fuzzy relation discretized. Given an input of change in voltage, a slice of the graph can be taken to obtain the output possibility distribution. For instance, an input change in voltage value of 0.2 volts has an output possibility distribution as shown in Figure 2.6.

2.4.2 Defuzzification

An example of a fuzzy possibility distribution is shown in Figure 2.6. The output is not useful in this form; it must be converted to a single crisp value. The most commonly used defuzzification strategies are the Max Criterion Method, the Mean of Maximum Method (MOM), and the Center of Area Method [17].

The Max Criterion Method simply uses the first point in the output universe of discourse where the possibility distribution reaches a maximum value. The output that would be obtained by this method is marked in Figure 2.7 by MAX.

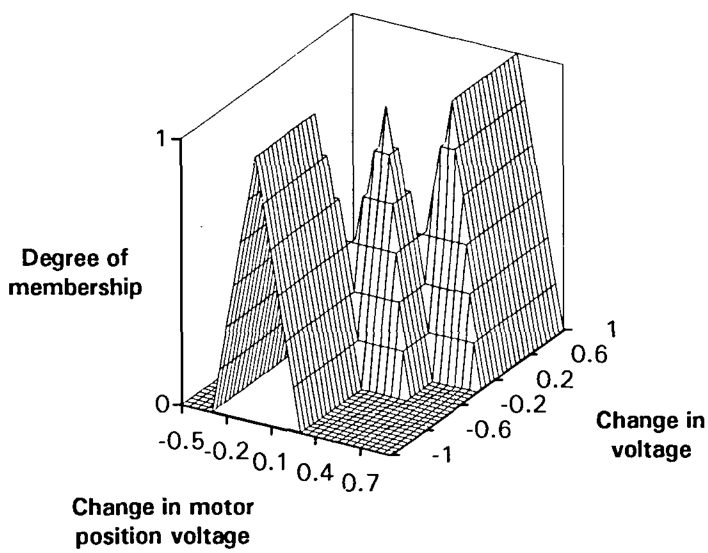


Figure 2.5: Max-min composition of the rule base

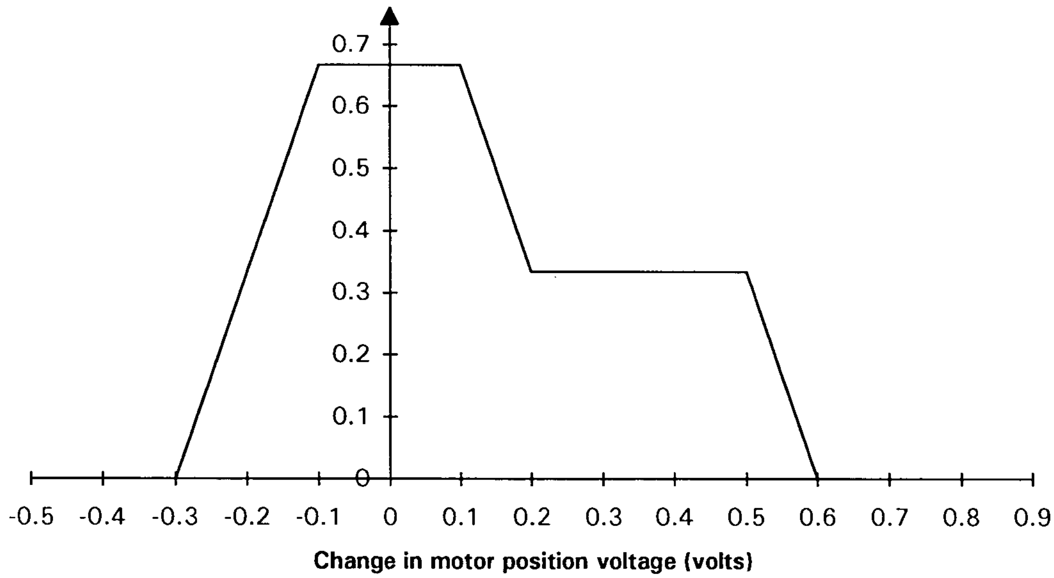


Figure 2.6: Possibility output distribution for 0.2 input change in voltage

The MOM method uses the average value of all the outputs which have the maximum value of the possibility distribution. In the case of a discrete universe of discourse for the output control actions the output can be expressed as:

$$z_0 = \sum_{j=1}^{l} \frac{w_j}{l} \qquad [17]$$

where the w_l is the support value at which the membership function reaches the maximum value, $\mu_Z(w_l)$, and l is the number of support values that have the maximum value of $\mu_Z(w_i)$. The output generated by this method is indicated on Figure 2.7 as MOM.

The center of area method takes into account values of the output universe of discourse that do not have the maximum possibility distribution value. This strategy provides as the output the center of gravity of the output possibility distribution. For a discrete universe this value can be obtained from:

$$z_0 = \frac{\sum_{j=1}^{n} \mu_z(w_j) * w_j}{\sum_{j=1}^{n} \mu_z(w_j)} \qquad [17]$$

where $\mu_Z(w_i)$ is the possibility distribution value of the control value w_i and n is the number of output actions in the universe of discourse. The output from this method is indicated on Figure 2.7 as COA.

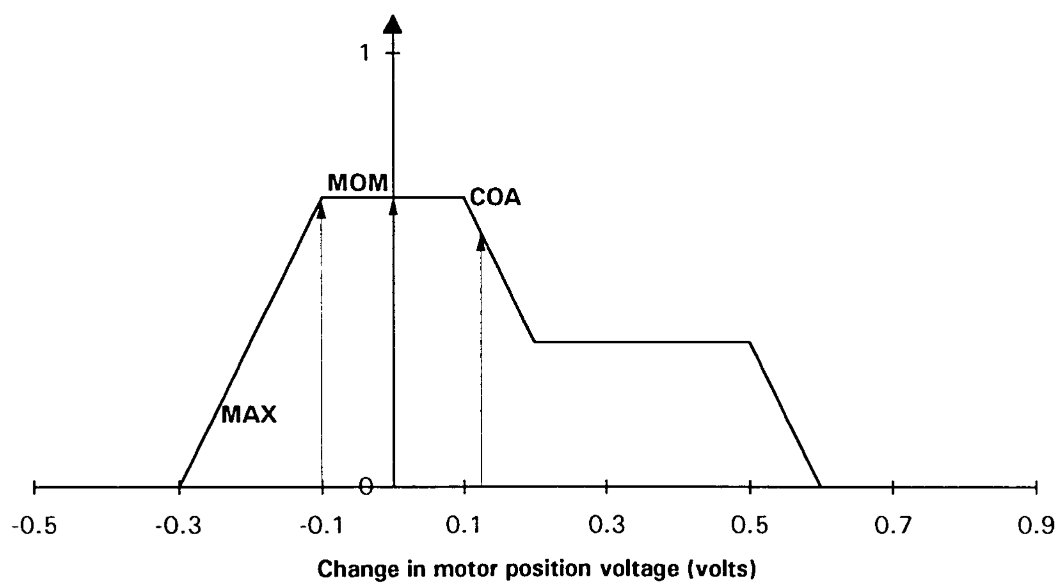


Figure 2.7: Results of various defuzzification strategies

The most commonly used defuzzification strategy is the Center of Area Method. Many sources have found the COA method to give better results than the MOM method because it takes into account values of the output possibility distribution with degrees of membership less than the maximum [17]. Both the MOM and the COA methods give better results than the Max Criterion method.

2.5 Application

The previous sections describe the development of a fuzzy logic control algorithm that derives control actions from rules obtained from expert knowledge. This system consists of a rule base expressed using linguistic variables, fuzzy membership functions of the linguistic variables, fuzzy relations derived from the control rules, an overall fuzzy relation, and a defuzzification interface. There are basically two methods of implementing fuzzy logic control when precise inputs are available. The first method calculates the control action during run time. Only the rules having an effect on the output at that particular instant are used. This process is repeated at each control instant. The second method involves creating a look-up table that contains the control actions for all possible values of inputs. The table is then used for referencing at appropriate input values during process control. The first method is preferable if the rule base and the fuzzy sets are subject to change. However, this method can involve more computer memory and run time than the second method. If the rule base and fuzzy sets are well established, the second method may be more appropriately used.

Fuzzy logic control has been applied to many different control problems. Some early applications of fuzzy logic control include cement kiln operation [18], warm water plant [16], and activated sludge wastewater treatment [19]. In more recent years the use of fuzzy logic control has become widespread and is used in items as common as cameras, trains, air conditioners, and vacuum cleaners [20].

Many software and hardware tools have been recently developed to simplify the application of fuzzy logic. A few of the more common software packages are Fuzzy-C, TIL Shell, and FIDE. A comprehensive description of recent software and hardware developments is presented by Jamshidi [21].

3. EXPERIMENTAL APPARATUS

The automatically adjusting shading device consists of thin-film photovoltaics for sensing the light level and a Pella Corporation window with between-glass window blinds to adjust the shading coefficient to desired levels. The blinds can be electrically operated by means of a motor actuator located between the glass and attached directly to the blinds. A personal computer with a data acquisition board is currently being used to control the shading system and an external power supply is being used to provide power for the system.

3.1 Slimshade and Motor Actuator

The window being used is the Pella Corporation aluminum-clad "SmartSash II" casement window with Pella's between glass low-emissivity Slimshades. Pella Slimshades consist of a series of narrow, individual aluminum louvers that are located between the window panes, are interconnected, and can be tilted to any angle from -90 to +90 degrees with angles defined as shown in Figure 3.1. Slimshade blinds are easy to operate and, since the blinds are encased in glass, they are free from dust accumulation and virtually maintenance free [4].

Pella Corporation has also developed a low-voltage direct current servo-motor for use with the Slimshades. The servo-motor measures 2 x 3 x 3/4 inches and is located between the two panes of glass. The electric motor is typically powered with 12-15 volts but can be operated using a 9 volt battery. At full load the motor draws 0.5 amps. The motor is directly attached to the lower operating rail of the Slimshade and moves the louvers from

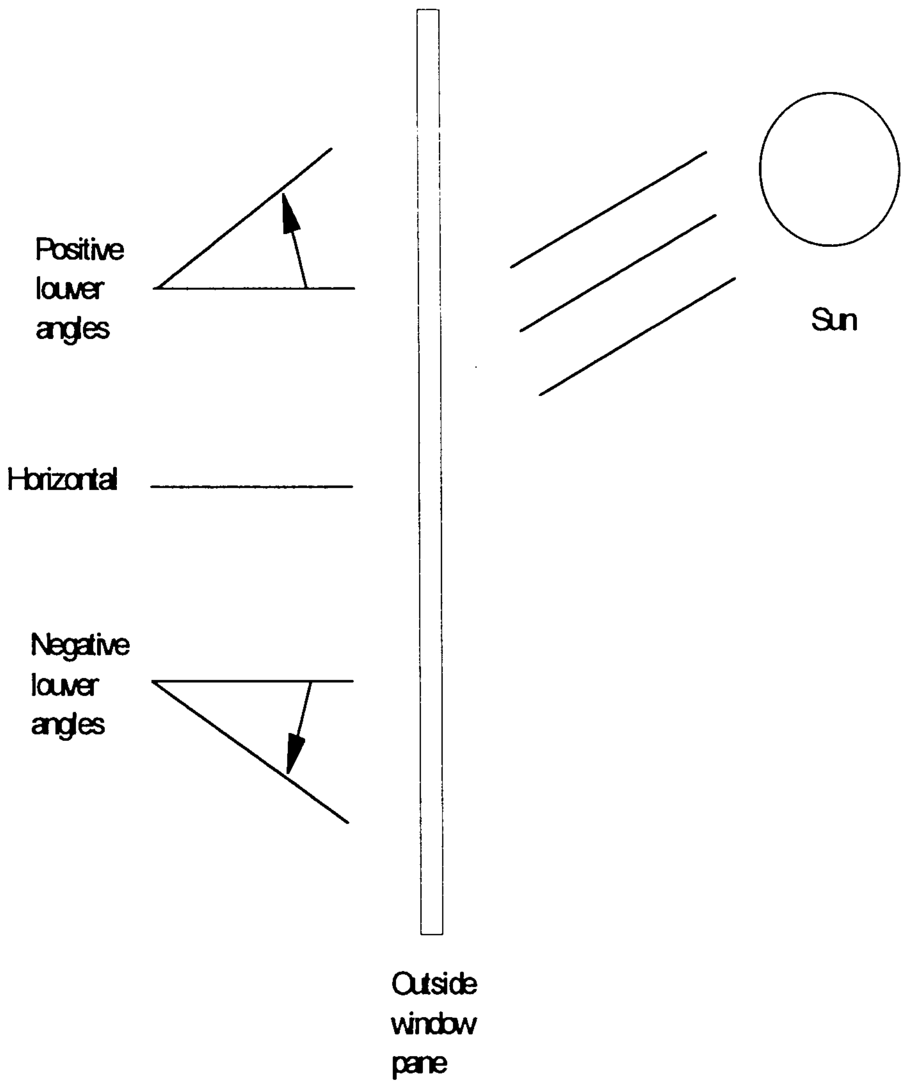


Figure 3.1: Definition of louver angles

approximately -90 to +90 degrees. The output shaft of the motor rotates at approximately 15 revolutions per minute.

There are three input wires to the motor: a ground wire, a wire for the positive end of the power supply, and a control input wire. A power supply of 12 volts input to the motor was used. With this input voltage, the control voltage ranges from approximately 3 to 8 volts with 3 volts being +90 degrees and 8 volts corresponding to a -90 degree tilt angle The current window/actuator design provides the control voltage by means of an adjustable potentiometer. The tilt angle of the shade varies linearly with the voltage in this range. This relationship is used to determine the desired control voltage. The smallest change in voltage that consistently changes the louver angle is 0.2 volts. This corresponds to a change in angle of approximately 7 degrees. Voltage changes below 0.2 volts may or may not change the motor position. To get a better idea of the motor response to various input voltages, the motor was sent voltages in increments of 0.05 volts and the photovoltaic output voltage read at each step to determine when the motor moved. Figure 3.2 shows the results of this operation.

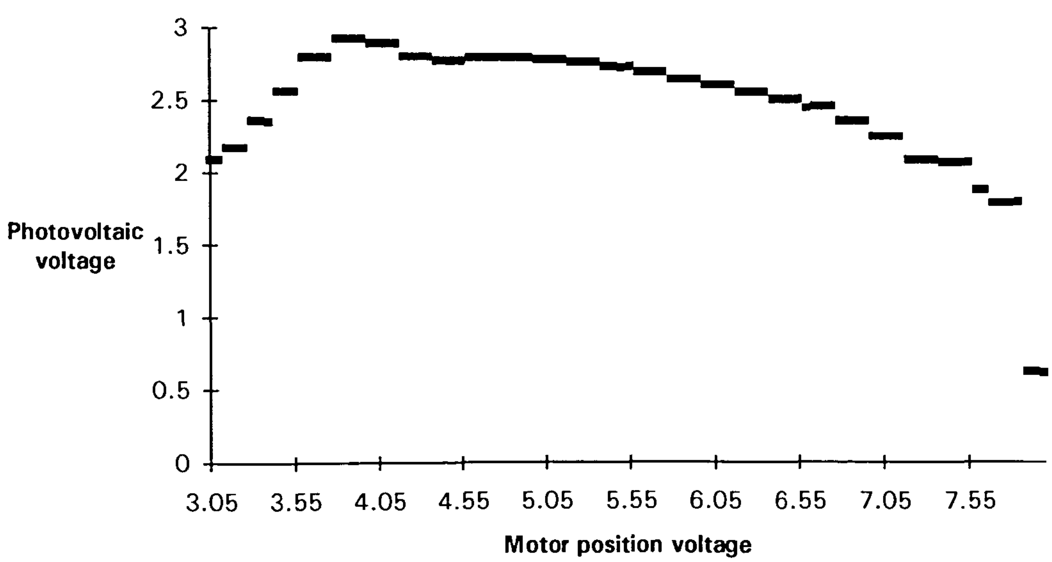


Figure 3.2: Motor response to small voltage steps

3.2 Thin-film Photovoltaics

Iowa Thin Film Technologies, Inc. and the Center for Amorphous Semiconductors at Iowa State University have developed flexible substrate, thin film solar cells that can be custom fabricated for specific applications. The solar cells are made on flexible polyimide substrates by a roll-to-roll manufacturing process. The proper interconnect arrangement to provide the desired current and voltage characteristics is accomplished by programming the computer that controls the laser scriber and automated silk-screen system for the desired pattern. The thin film cells (2 mils thick) can be mounted between the panes of glass in the window or built into the frame of the window as desired [4].

The thin-film photovoltaic power output is proportional to the amount of light falling on the cells. For the experimental setup the sensing cells did not draw any current, so the voltage used in the control operations is the open circuit voltage. The maximum power output occurs when the blind angle is equal to the solar altitude angle and maximum direct beam radiation is admitted. The response of the photovoltaics as the blinds were moved from -90 to +90 degrees in increments of approximately 15 degrees can be seen in Figure 3.3. More extensive curves of this type with different light angles and levels can be found in Figure 4.1. The nature of this response is the basis for control of the Slimshades.

3.3 Data Acquisition Hardware

A National Instruments MC-MIO-16 board was used for the data acquisition operations. The MC-MIO-16 is a high-performance multifunction analog, digital, and timing input/output board for the IBM Personal System/2 computer. It has 16 analog input channels

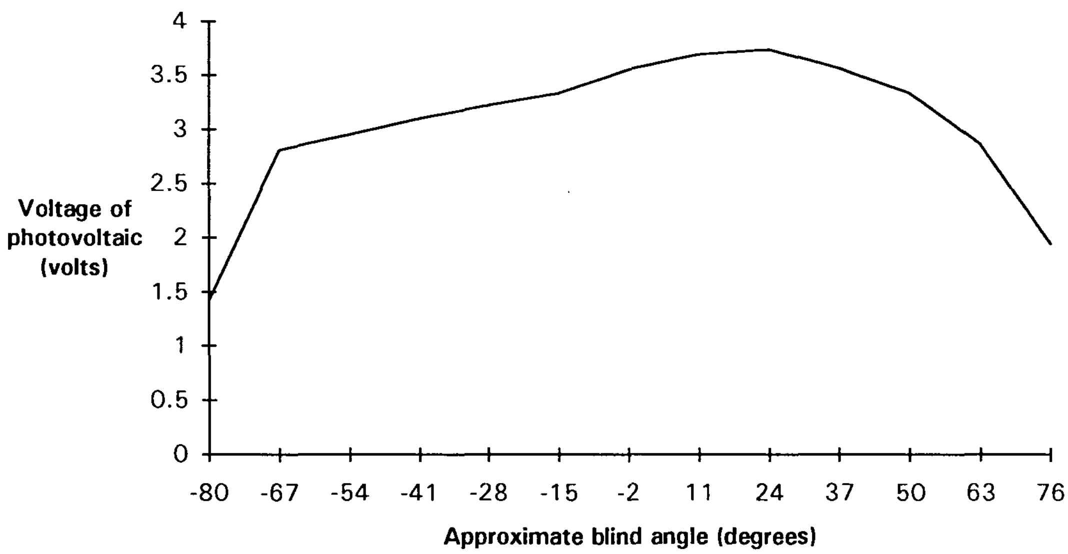


Figure 3.3: Response of the photovoltaics to different blind angles

and 12-bit A/D conversion. The 12-bit resolution allows the converter to resolve the input range into 4096 different levels. Three input ranges are allowable by jumper settings on the MC-MIO-16 board: -10 to +10 V, -5 to +5 V, or 0 to +10 V. The input range used was 0 to +10 V. The smallest possible input increment is 2.44 mV at this setting. The analog output circuitry has two channels of 12-bit D/A output. The internal voltage reference of the board was used with unipolar settings. This provides an output range of 0 to +9.9976 V in steps of 2.44 mV [22].

The MC-MIO-16 board was installed in an IBM PS/2 Model 50 Z computer. The board was controlled using programs created in QuickBasic 4.5 and library functions included in software for the MC-MIO-16.

3.4 Experimental Setup

The Pella window and Slimshade were set up parallel to an existing building window that received many hours of direct solar gain during a day. The photovoltaic outputs were read by the data acquisition board in the personal computer. A 12 volt direct current power supply provided power to the motor actuator and the personal computer with the data acquisition board provided the control voltage to the motor for control of the blinds. The total experimental equipment was set up as shown in Figure 3.4.

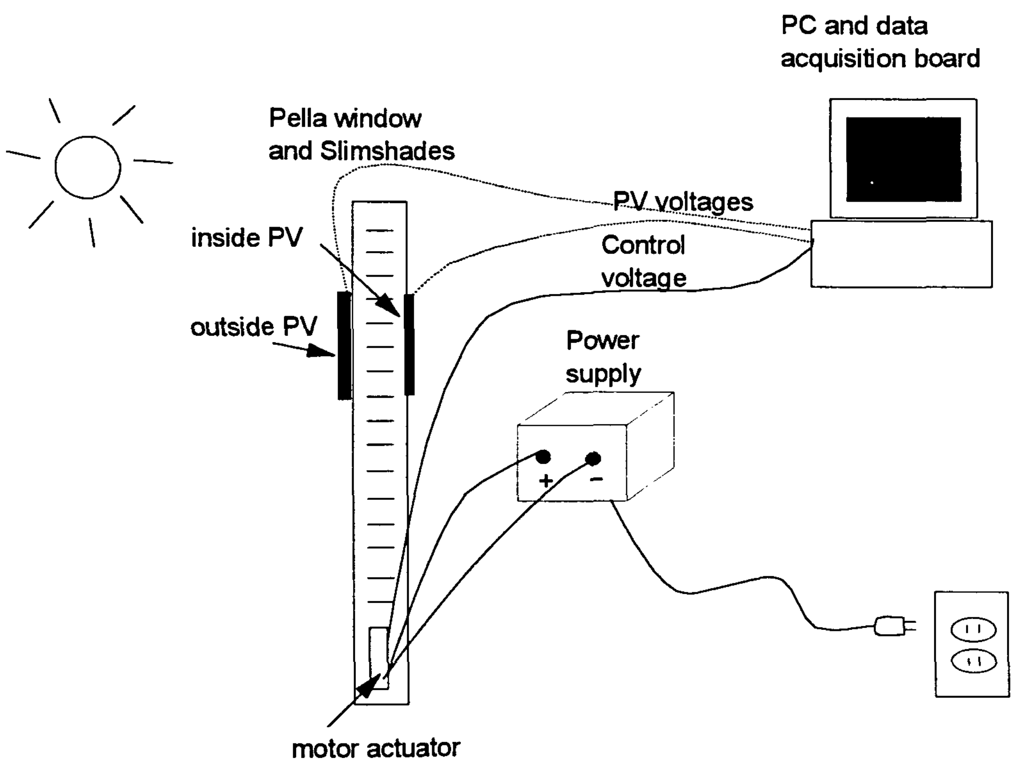


Figure 3.4: Experimental setup

4. EXPERIMENTAL PROCEDURE

4.1 Principles of Operation

The power output of the photovoltaic solar cells changes with the intensity of light that falls on them. The amount of light that falls on the photovoltaics changes with the blind position. The most light falls on the solar cells when the louver angle is equal to the solar altitude angle. To characterize this response, the blinds were moved from -90 to +90 degrees in increments of approximately 15 degrees while at various sun levels. The data acquisition board in the personal computer recorded the open-circuit voltage at each increment. Some typical curves from this data acquisition are shown in Figure 4.1. Over the course of a day, the position of the peak of the curve and the height of the curve changes but the general shape remains the same.

For the winter mode the ideal operation would have the blind angle always equal to the solar altitude angle with blind angles as defined in Figure 3.1 to let the maximum amount of direct solar gain through the window. This optimum operating point for the winter mode would always be at the peak of the curves shown in Figure 4.1 because maximum lighting corresponds to the maximum voltage of the photovoltaic cell. Empirical equations are available to calculate the solar altitude angle [3] but a controller based on these equations would be complex and difficult to keep synchronized with real time. Operation at the optimum position was accomplished by using the change in voltage from one sample time to the next and calculating approximately how much the motor should move by means of fuzzy

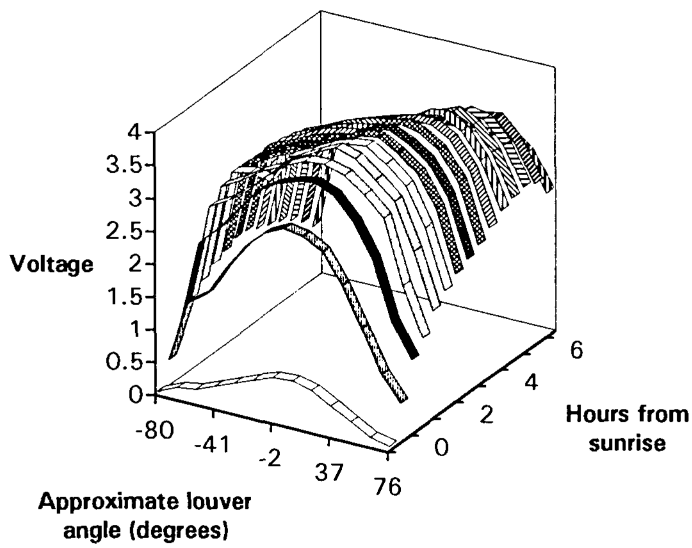


Figure 4.1: Response of photovoltaics to different blind angles throughout a day

logic or the error-feedback controller. The sample time between voltage checks is five minutes. As shown in Figure 3.2, the resolution of the motor does not allow for small increments of motion. Five minutes is much less time than it takes for the sun to move by an angle greater than the smallest motor increment. The reason for the small time step is to determine how consistently the controllers maintain the correct positions without searching. After the motor moves to a new position, the voltage is checked again to determine if the blinds moved in the right direction and if they moved the correct amount. The controllers continue to check the voltage until the blinds are in the right position and then the process repeats at five minute intervals.

For the summer mode, the blinds are supposed to be open as far as possible while blocking out the direct solar gain. On the voltage output curves in Figure 4.1 this point is not well defined, because a gradual voltage increase from closed blinds occurs. If the louvers are modeled as flat, thin slats with the width equal to the spacing between them, the relationship between the blind angle and the solar altitude angle is constant as demonstrated in Appendix B. However, to use this relationship the controller would have to be programmed to calculate the solar altitude angle at any instant. Equations are available for these calculations [3] but a controller based on these equations would be quite complex and difficult to keep synchronized with real time.

A different approach was needed for the summer mode controller. Most of the sun's intensity comes from beam radiation. Diffuse and ground reflected components can be assumed to be uniformly distributed with little error [3]. If both the inside and outside photovoltaic cells receive the same amount of diffuse and ground reflected radiation, the difference between the output of the cells is due to the difference in beam radiation reaching each cell. The assumption of the same amount of diffuse radiation reaching both the inside and outside photovoltaics is not valid for early mornings and late afternoons. At these times the correct louver angle is almost closed which allows little diffuse radiation to reach the inside photovoltaic cells. Data was taken to find the ratio of the inside voltage to the outside voltage when the shades were at the correct angle. The correct shade angle was determined by moving the blinds until the direct sunlight was just blocked by the blinds and then taking voltage readings. The data from these tests can be seen in Figure 4.2 for a southeast facing window. With exceptions occurring in the early morning and late afternoons, a consistent ratio of approximately 0.85 corresponds to the desired position. This ratio is used to determine if the blinds are open enough or too far and the blinds are adjusted accordingly. The controller allows beam radiation to enter the building envelope during early mornings and late afternoons. The radiation which enters the building during these periods is not considered critical because of the lower intensity of the radiation when the sun is near the horizon due to the increased atmosphere through which the radiation must travel.

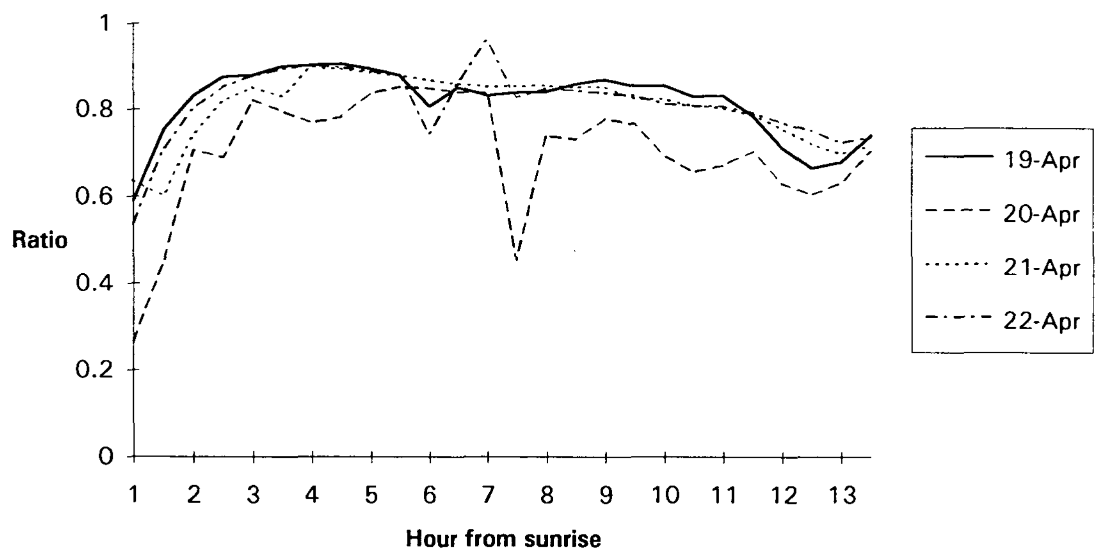


Figure 4.2: Ratio of inside to outside photovoltaic voltage for a southeast facing window

4.2 Test Procedures

The tests were set up in two locations with different orientations. The first was located in 593 College of Design in a southeast facing window. The second location was in the hallway of Black Engineering facing west. Both these locations had large windows with few outside obstructions to sunlight. The test window was set up parallel with and as close as possible to the existing building window. The pane of glass from the existing building window does not affect the validity of the test results because all were performed under the same test conditions. The only effect of the extra pane of glass is to reduce the photovoltaic output because of the radiation reflected and absorbed by the glass.

Criteria for comparison of the controllers had to be established. Because of the difference in cloud cover and available solar radiation on different days, the data could not be compared directly. Some of the comparison criteria were how well the controller maintained the desired position of the blinds, the number of times it took the controller to establish the correct louver position, and the responses of the controllers to different lighting conditions such as clouds.

Each controller was set up to run all day, close at night, and resume operation in the morning when the light level reached a threshold value. The threshold value was set at 0.5 volts output from the photovoltaic cells located on the outside of the blinds. This value was chosen because it is significantly lower than the voltage produced at midday on very cloudy days and this is approximately the voltage observed near sunset on clear days. As the controllers are further developed, it may become necessary to change this threshold value.

The data taken from the winter mode tests and from the summer mode tests was essentially the same. The computer programs were set up to count the number of times the blinds moved before settling in the correct position. This number was then written to a data file along with the motor voltage at that position, the inside voltage, and the outside voltage. Additionally, for the summer mode controller, the ratio of inside voltage to outside voltage was also recorded.

Each summer mode controller ran for five days during late April and early May in the southeast location with the aforementioned data being gathered during this period. Each winter controller ran for three days during May and June in the southeast orientation with data being gathered during this period. The controllers were also observed during operation to determine their responses under various sky conditions. The collected data and these observations were used to determine which controllers performed best. The west facing location was used to determine how well the controllers operated a different orientation.

4.3 Fuzzy Logic Controller

4.3.1 Linguistic Variables and Fuzzy Sets

Two linguistic variables were used for the winter mode of operation. The input variable was the change in voltage and the output variable was the change in motor position voltage. These variables were chosen because this information is sufficient to determine whether the blinds are in the correct position and also because of the simplicity of the resulting rule base and control actions. The fuzzy sets or "values" associated with the change in voltage are "negative", "zero", and "positive". The output variable, change in motor position voltage, has the fuzzy sets "zero", "small, and "large". The direction of motion of the motor was determined by the direction of the previous motion and whether the inside voltage increased with this motion. The membership functions of these variables can be seen in Figures 4.3 and 4.4. The membership functions were determined by using Figure 4.1 to determine how much the voltage changes with a certain change in the louver angle. Straight line functions were used for the membership functions because the shape of the membership function curve does not have as much of an effect on the results as the boundaries of the curve.

Two linguistic variables, one input and one output variable, were used for the summer mode of the controller. The input linguistic variable is the ratio between the inside and outside photovoltaic open-circuit voltages and the output linguistic variable is the change in motor position voltage. The ratio of inside to outside photovoltaic voltage was used as the input variable because a reasonable solution using only the inside voltage could not be found and also the resulting rules were quite simple. The "values" of the ratio are "low", "OK", and "high". The "values" of the change in motor position voltage are "negative", "zero", and

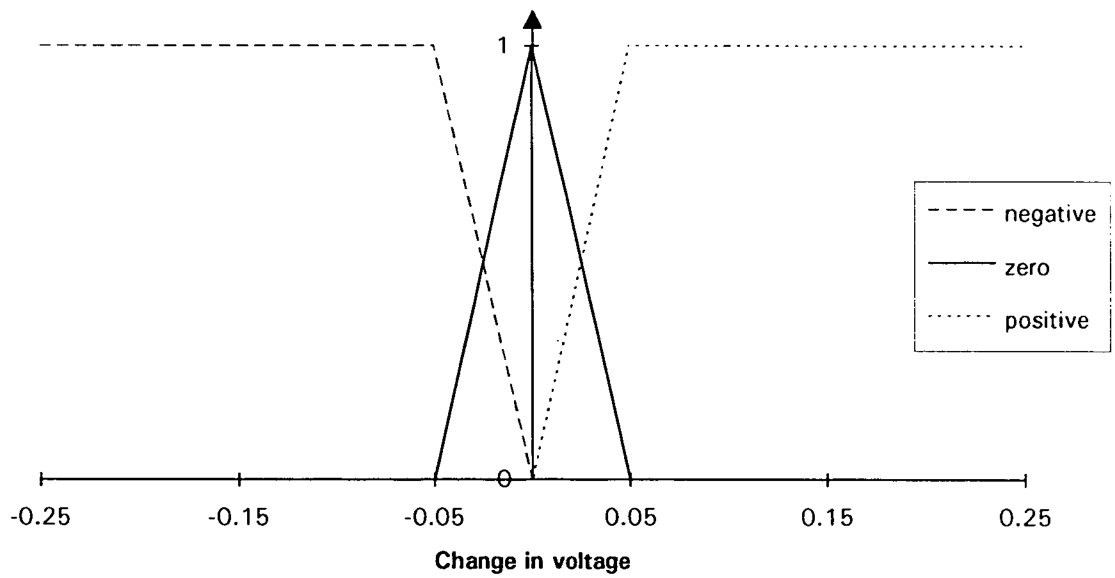


Figure 4.3: Membership functions for winter mode input variable

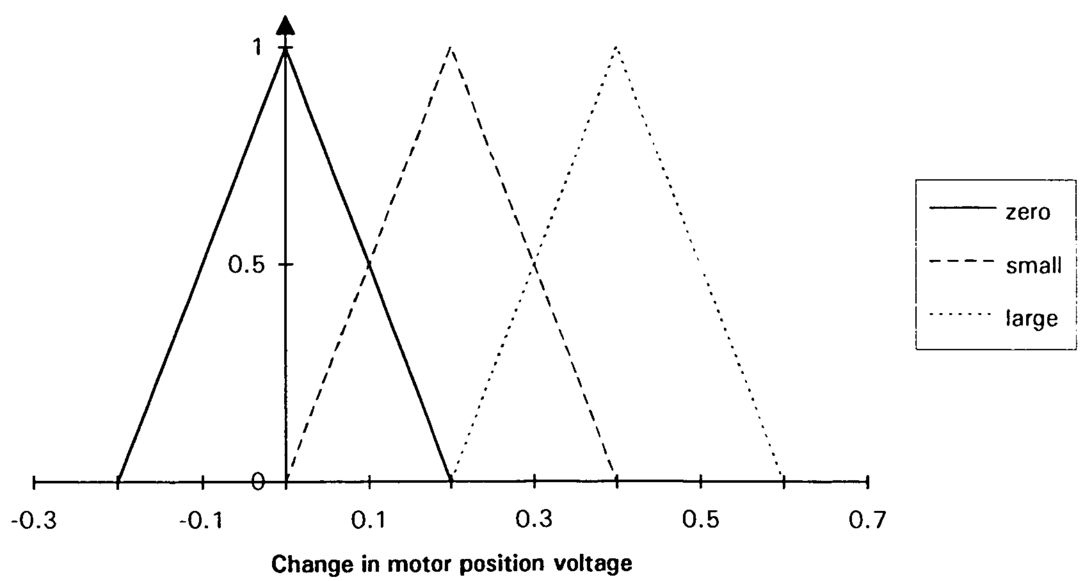


Figure 4.4: Membership functions for winter mode output variable

"positive". These "values" were chosen because the blinds will need to open further, close further, or not move at all. The membership functions for the fuzzy sets of the variables can be seen in Figures 4.5 and 4.6. The membership functions for the input variable, ratio, were determined using the ratio versus time curves shown in Figure 4.2. The change in motor position voltage membership functions were determined by observation of the required motion of the motor to get the desired change in position.

4.3.2 Fuzzy Rule Bases and Relation Matrices

The fuzzy rule base for the winter mode of operation of the controller consists of three rules which provide a simple and effective control strategy for the controller. These rules are based on the desired response of the controller to the information known about the change in the photovoltaic voltage. The response of the motor to the change in voltage information

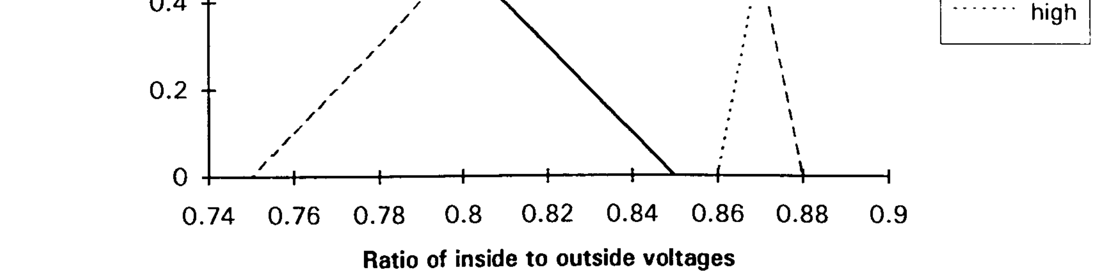


Figure 4.5: Membership functions for summer mode input variable

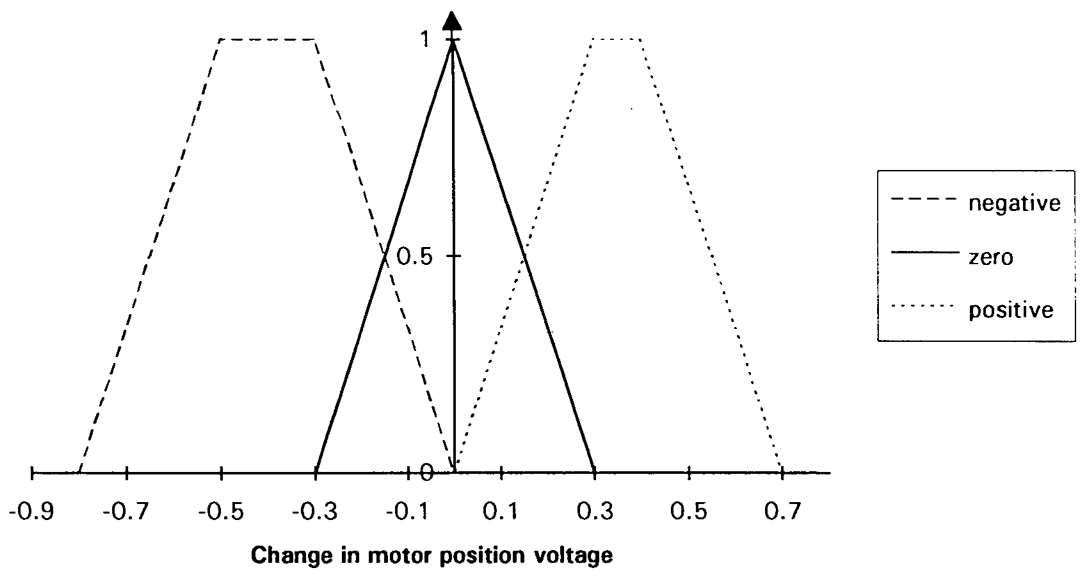


Figure 4.6: Membership functions for summer mode output variable

should be the same response as that of a human operator given the same information. The rule base is as follows:

1. If the change in voltage is "negative" then the change in motor position voltage is "zero".
2. If the change in voltage is "zero" then the change in motor position voltage is "small".
3. If the change in voltage is "positive" then the change in motor position voltage is "large".

The relation matrix is determined using the max-min composition of the rules using methods from section 2.4.1 and the fuzzy sets and linguistic variables described in section 4.3.1. A graphical representation of the relation matrix is shown in Figure 4.7.

The fuzzy rule base for the summer mode of operation of the controller consists of three rules. This rule base provides a simple but effective control strategy for the summer mode controller. The rules were determined by the desired motor response to known ratio inputs. The motor should produce the same response as a human operator given the same information. The rules are as follows:

1. If the ratio is "high" then the change in motor position voltage is "positive".
2. If the ratio is "OK" then the change in motor position voltage is "zero".
3. If the ratio is "low" then the change in motor position voltage is "negative".

Relation matrices were determined using the max-min composition of rule bases as described in section 2.4.1 and the fuzzy sets and linguistic variables described in section 4.3.1. A graphical representation of the relation matrix is shown in Figure 4.8.

4.3.3 Operation of FLC

Both the winter mode controller and the summer mode controller were implemented by creating look-up tables of the output variable for discrete values of the input variable. This method of applying the fuzzy logic control has benefits as described in section 2.5. The look-up tables were created using the membership functions as defined in section 4.3.1 to assign degrees of membership to each input linguistic value. The max-min composition of the rule base as described in section 2.4.1 and the output variable membership functions were used to obtain output possibility distributions. The possibility distributions were then defuzzified using the Center of Area defuzzification method described in section 2.4.2. This process was repeated for each discrete input variable value and the crisp outputs written to an external file. Implementing the fuzzy logic control in this way reduces the length of the necessary computer code in the control programs and, for applications with more extensive rule bases, reduces the computation time. The computer programs used to generate the look-up tables are listed in Appendix A. By creating separate look-up tables, the membership functions were easily modified without changing the control programs.

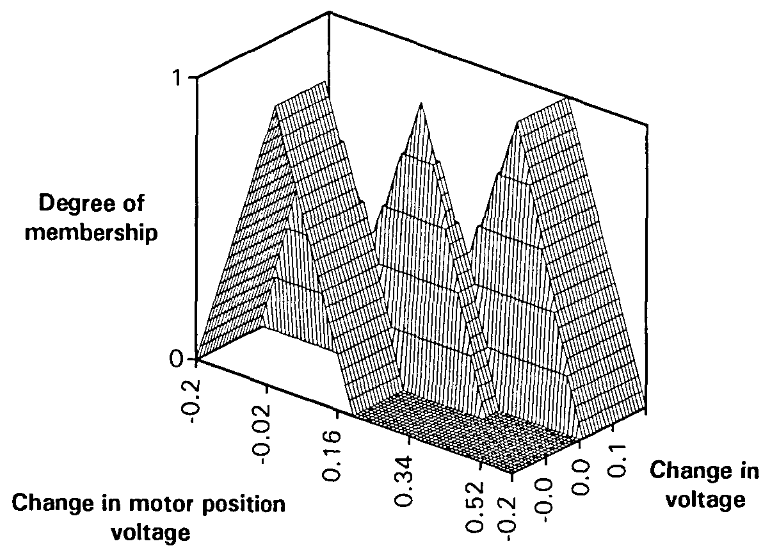


Figure 4.7: Relation matrix for winter mode controller

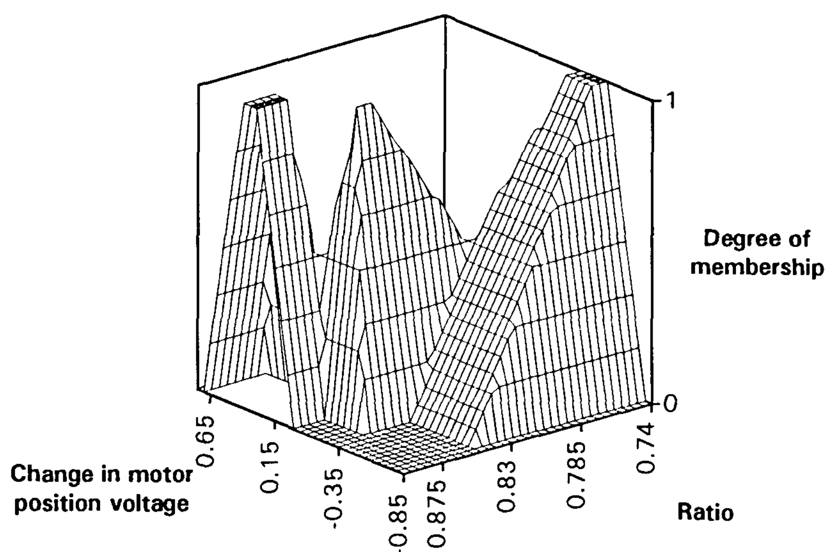


Figure 4.8: Relation matrix for summer mode controller

The output values from the winter look-up table are read from a data file into the control program during run time. The voltage from the photovoltaic cells on the outside of the blinds is read to determine whether it is day or night. If it is night, the controller keeps checking at five minute intervals until the voltage is above the day threshold. During the day, the voltage is checked at five minute intervals. The change from the last voltage reading is computed. From this input value of the change in voltage, the appropriate change in motor voltage is found from the look-up table values. The direction of motor motion is determined by the previous direction of motion. After the new motor voltage is sent, the inside voltage is again checked and the change in voltage computed. If the voltage has decreased from the last value, the direction of motor motion is reversed and the new motor voltage sent. When the change in motor voltage from the look-up table is less than 0.1 volts, the blinds are near the correct position and the interval checking resumed. If a position cannot be found where the change in motor voltage is below the threshold in five tries, the position with the highest voltage is chosen and the interval checking resumed. The flow chart in Figure 4.9 shows the steps taken in the control of the winter mode. Appendix A lists the control program code.

For the summer mode controller the output values from the look-up table are read from a data file into the control program during run time. The outside voltage is checked to determine whether it is day or night. If it is night, the controller checks the voltage at five minute intervals until it is above the day threshold. When it is day, the ratio of the inside voltage to the outside voltage is checked at five minute intervals. Using this value, a change in motor position voltage is found in the look-up table. After the new motor voltage is sent, the ratio is checked again. When the change in motor position voltage output falls below 0.1 volts, the checking of the ratio is resumed at five minute intervals. A flowchart of the summer mode fuzzy logic controller is shown in Figure 4.10. Appendix A lists the computer code for this controller.

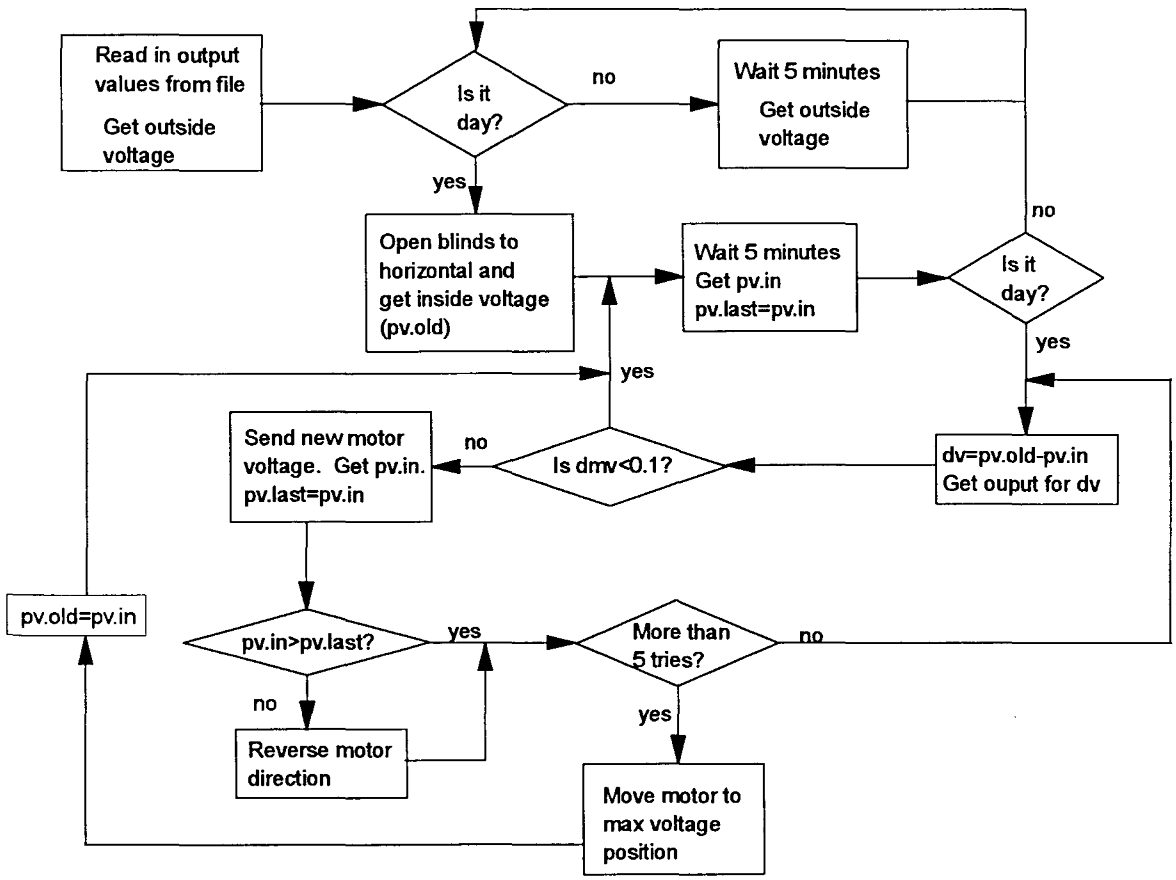


Figure 4.9: Flow chart for winter mode of the FLC

4.4 Error-feedback Controller

4.4.1 Operating Parameters

The winter mode controller was based on the response of the photovoltaic cells to different light levels and louver angles as shown in Figure 4.1. The controller compares the current voltage value with the last voltage value and calculates the percentage change. Limits defining acceptable percent voltage changes have been established. If the percent voltage change is outside this range, the motor is adjusted accordingly. The acceptable percent

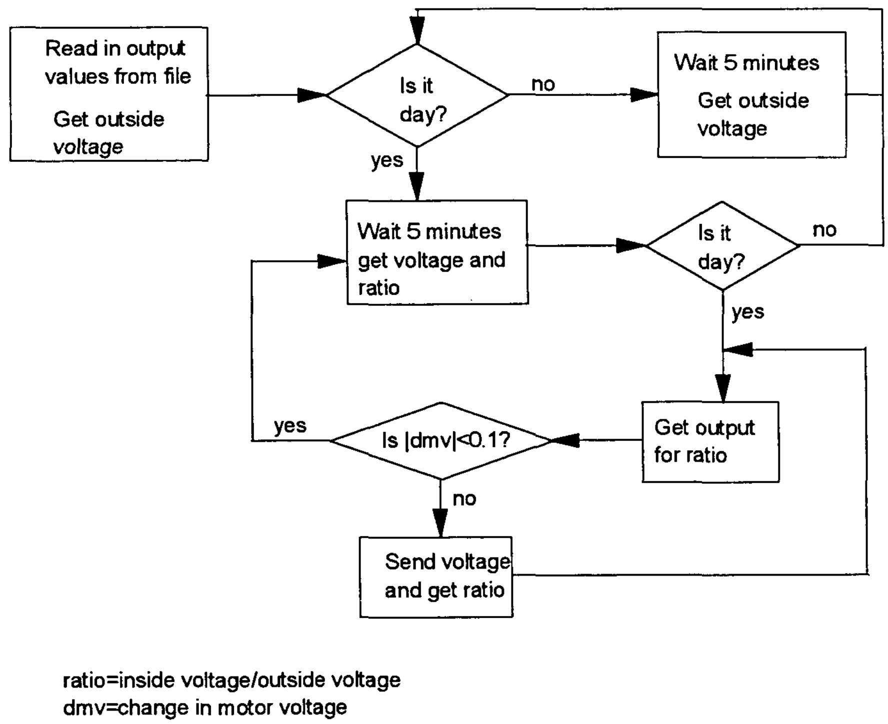


Figure 4.10: Flow chart for summer mode of the FLC

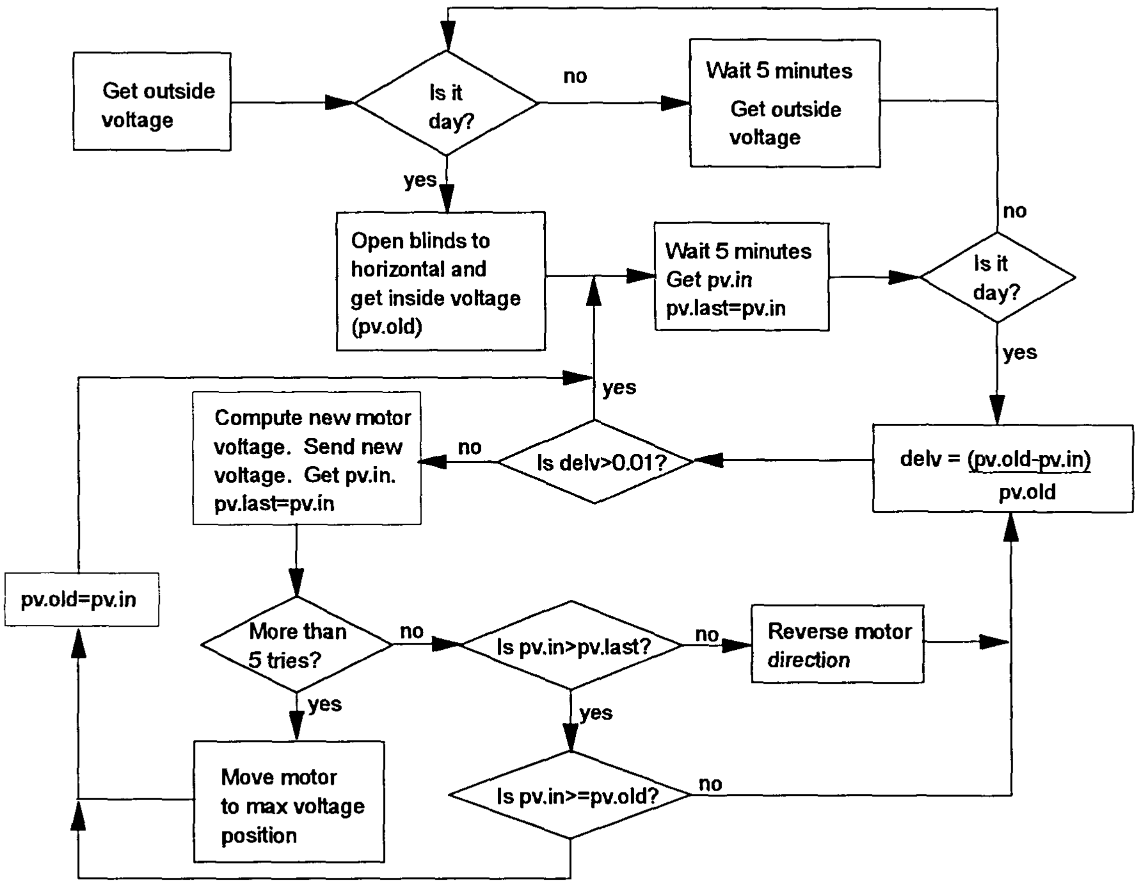
change in voltage range is a 1% voltage drop. If the voltage has increased or remains the same, no action is taken. If the voltage drop is greater than 1%, then the motor is adjusted by an amount proportional to the voltage change. The parameters to calculate the motor adjustment were determined from Figure 4.1.

The summer mode of the controller is based on the ratio of inside to outside voltages of the photovoltaic as shown in Figure 4.2. The controller checks to see if the ratio is within an acceptable range. If the ratio is outside this range, the blinds are adjusted accordingly. The acceptable range of ratios is from 0.80 to 0.87. If the ratio is within this range, no action is taken. If the ratio is below this range, the blinds are opened by a set amount. If it is above this range, the blinds are closed by a set amount.

4.4.2 Operation of Error-feedback Controller

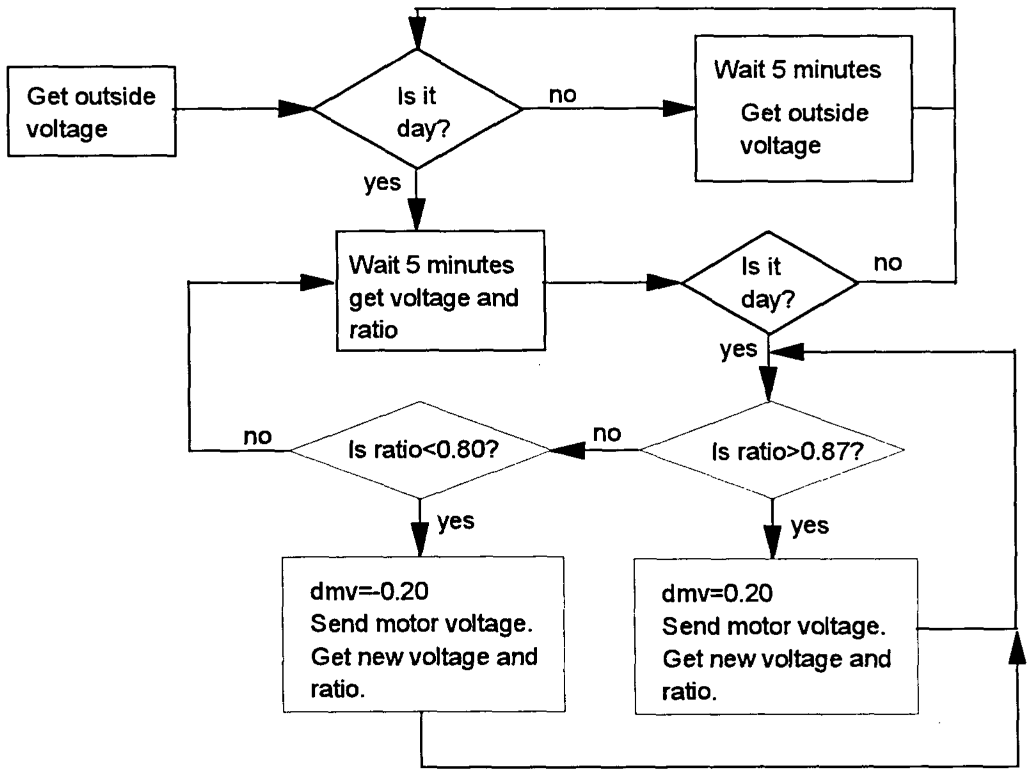
Figure 4.11 shows the flow chart for the winter mode of operation. The outside phototvoltaic voltage is read to determine whether it is day or night. If it is day, and the voltage change from the previous check time was more than a 1% drop, the blinds are moved by an amount proportional to the change in voltage. The voltage is then checked again. If the new voltage is lower than the previous voltage, the direction of motion of the blinds is reversed and the process of checking repeated. The new voltage should be within a threshold value of the old voltage before resuming the five minute check time. If a suitably high voltage cannot be found within five motions of the blinds, they settle in the position corresponding to the highest voltage found in those five tries.

The summer mode of operation has the same five minute check time as the winter mode and is based on the ratio between the voltage of the photovoltaic cells on the outside of the window and the voltage of the photovoltaic cells behind the blinds. The outside voltage is checked to determine whether it is night or day. If it is day, the controller checks the ratio at five minute intervals to see if it is within an acceptable range. The upper limit of this range is 0.87 and the lower limit is 0.80. If the ratio is above the upper limit, the blinds need to be closed and the motor is moved by +0.1 volts. If the ratio is below the lower limit the blinds need to be opened and the motor is moved by -0.1 volts. If the new motor position voltage corresponds to a blind angle greater than horizontal, the blinds are left at horizontal. A flowchart of this controller is shown in Figure 4.12.



pv.old=old inside voltage
pv.in=current inside voltage
pv.last=last inside voltage
delv=% change voltage

Figure 4.11: Flow chart for winter mode of the error-feedback controller



ratio=inside voltage/outside voltage
dmv=change in motor voltage

Figure 4.12: Flow chart for the summer mode of the error-feedback controller

5. RESULTS AND DISCUSSIONS

The results presented here are in the form of data taken while the controllers were operating over the course of several days as described is section 4.2. Three sunny days of operation for each winter mode controller were chosen from the College of Design location. The fuzzy logic controller ran from May 25 to May 27 and the error-feedback controller data is from June 3, 4, and 6. The data taken for the winter mode controllers was the number of times the blinds moved to find the correct position, the motor voltage at that position, the inside voltage, and the outside voltage. The number of times to move to the correct position shows which controller has better logic for determining the necessary motor motion. The fuzzy logic controller moved an average of 4.6 times to find the correct position and the error-feedback controller moved an average of 0.93 times. As shown from these values, the error-feedback controller has better logic for determining the correct motor motion. The fuzzy sets for the motor position voltage and the change in voltage need to be modified to improve the change in motor position voltage calculation.

The motor position voltage at each check time can show how smoothly the controllers tracked the sun. The theoretical motor position voltage was calculated over a sunny day assuming that the blind angle should be equal to the solar altitude angle and using equations from Duffie and Beckman [3]. These calculations are shown in Appendix C. Figure 5.1 shows the theoretical motor position voltages over a day. Figure 5.2 shows the motion of the motor for the fuzzy logic controller and Figure 5.3 shows the motion of the motor for the error-feedback controller. Both controllers followed the general shape of the theoretical

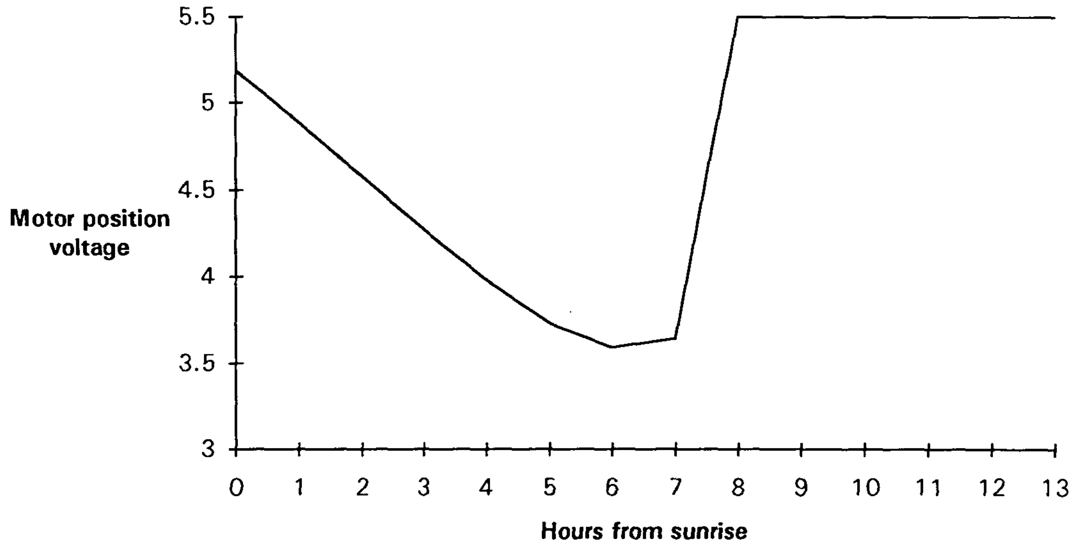


Figure 5.1: Theoretical motor position voltages throughout a day for the winter mode

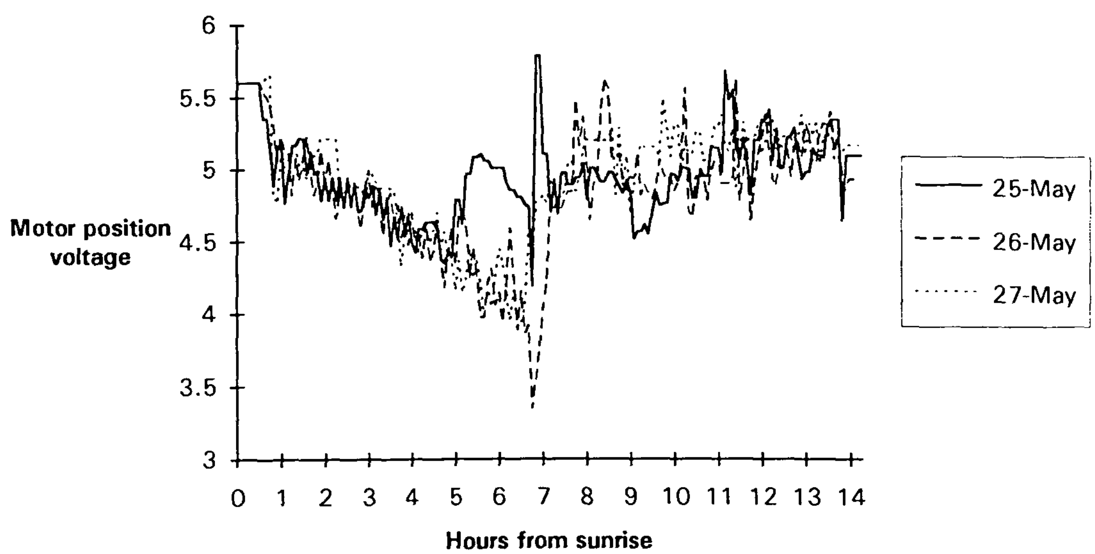


Figure 5.2: Actual motor position voltages for the FLC winter mode

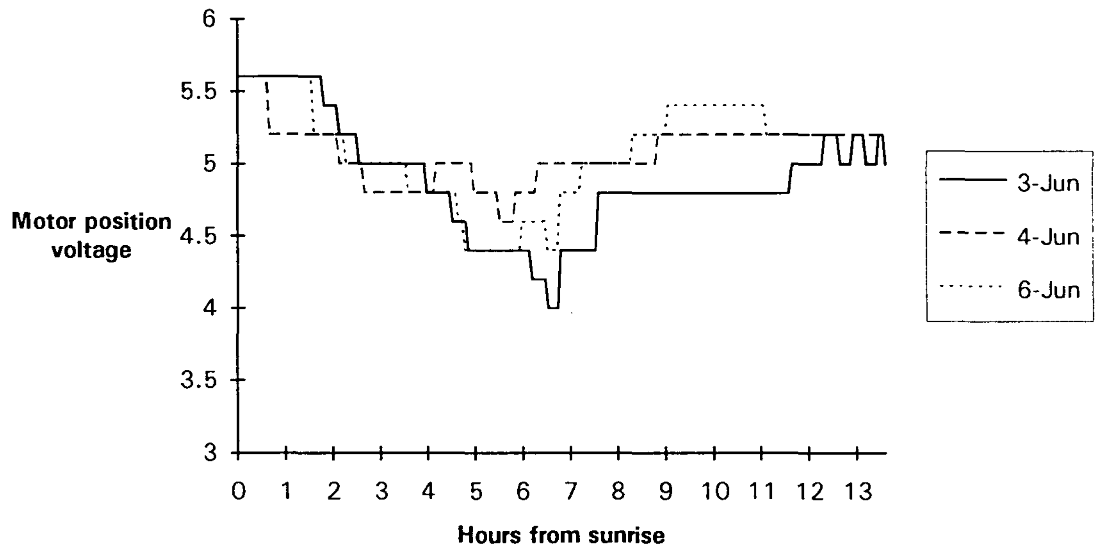


Figure 5.3: Actual motor position voltages for the error-feedback winter mode controller

curve. The FLC seemed to move more often but in smaller increments than the error-feedback controller. The error-feedback controller tends to remain in fixed positions for longer periods of time. The FLC needs to be made less sensitive to the smaller changes in input voltage.

The inside and outside voltages can be compared to determine how well the controllers kept the louver angle equal to the solar altitude angle. Figures 5.4 and 5.5 show the ratios of the inside to outside voltages. The FLC does a fair job of keeping the inside voltage as high as possible. The ratios in Figure 5.4 level out around unity. The ratios in Figure 5.5 for the error-feedback controller also level out around unity but are more consistent about remaining at this level.

The fuzzy logic controller collected data from April 29 to May 3 and the error-feedback controller ran from May 7 to May 11. Data gathered for the summer modes of the

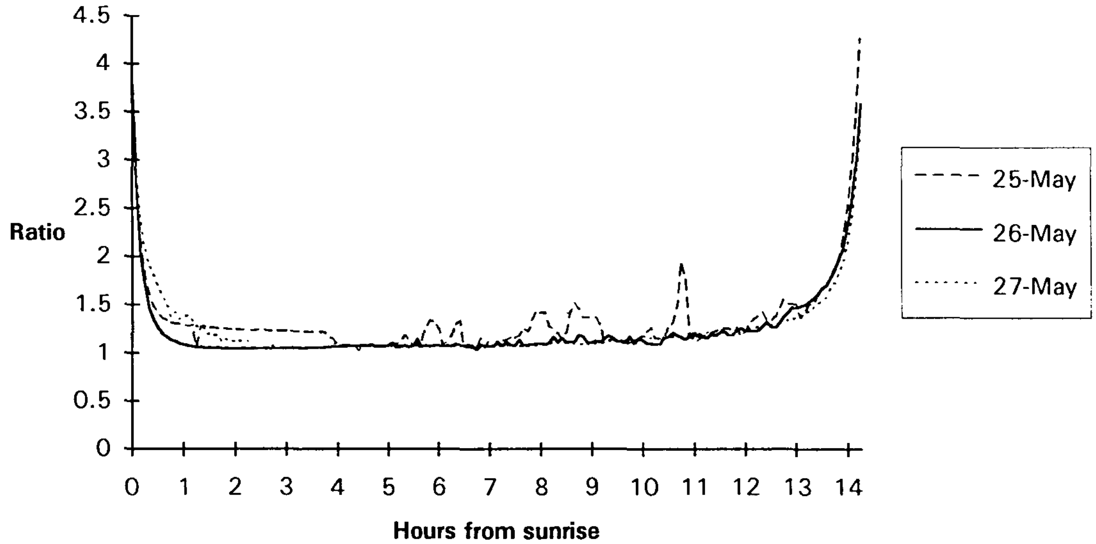


Figure 5.4: Ratio of inside to outside voltages for winter mode of FLC

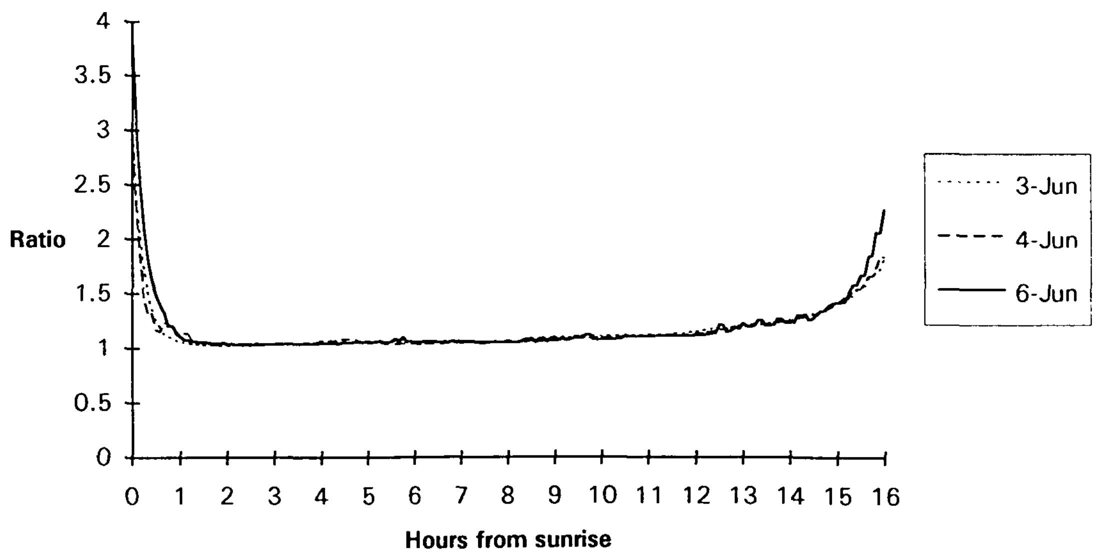


Figure 5.5: Ratio of inside to outside voltage for winter mode of error-feedback controller

controllers were the number of times the blinds moved to achieve the correct position, motor voltage at this position, inside voltage, outside voltage, and the ratio of inside to outside voltage. The number of times the blinds moved can be compared for each controller to determine which method better determines the correct motor motion. For the fuzzy logic controller the average number of times the motor moved was 0.523 and for the error-feedback controller the average number of time the motor moved was 0.381. The error-feedback controller has somewhat better logic for calculating the required change in motor position voltage. However, both these controllers find this value faster than either winter mode controller. With a little modification of the fuzzy sets, the summer mode FLC could find the correct motor position just as well as the error-feedback controller.

The motor voltages at each position can show how smoothly the blinds followed the sun. The theoretical motor position voltage was calculated over a sunny day using the relationship between blind angle and solar altitude angle as calculated in Appendix B and equations from Duffie and Beckman [3]. These calculations are shown in Appendix C. Figure 5.6 shows the theoretical curve for the motor position voltages. Figure 5.7 shows the actual motor position voltages for the FLC and Figure 5.8 shows the actual motor position voltages for the error-feedback controller. The motor position voltage for the FLC changed more gradually than the motor position voltage for the error-feedback controller. Shown in Figure 5.7 are two cloudy days, April 29 and May 1, on these days, the motor position voltage remained constant at 5.6 volts. In Figure 5.8, May 7 and May 8 are mostly cloudy days with the motor position voltage remaining at 5.6 volts.

The ratio values and the voltage values can be used to determine how well the controllers kept the ratio within an acceptable range. The acceptable range of ratios was determined using the curve in Figure 4.2. The ratios are expected to be lower during the early morning and late evening but during the day should be around 0.85. As seen in Figures 5.9

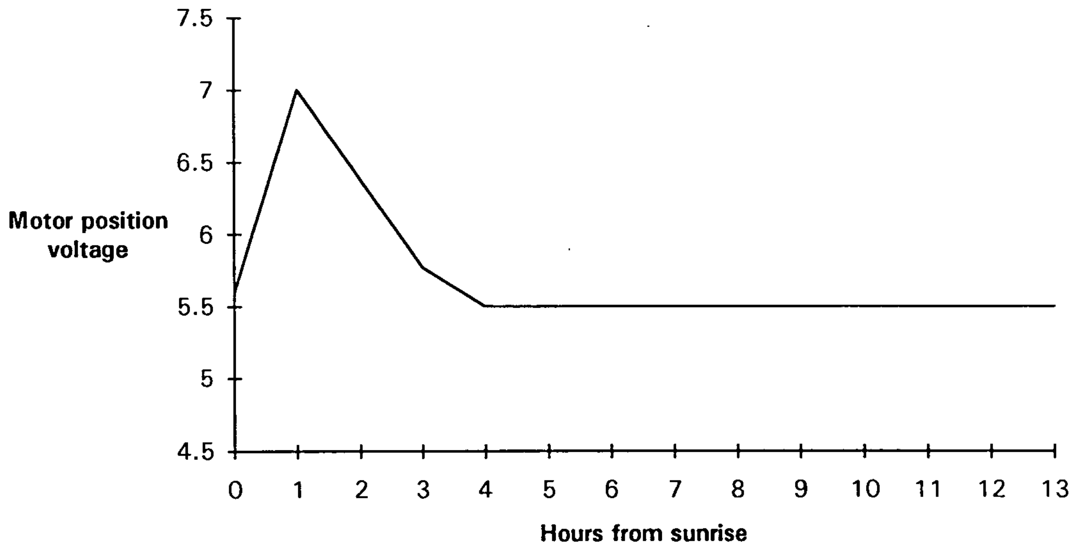


Figure 5.6: Theoretical motor position voltages throughout a day for the summer mode

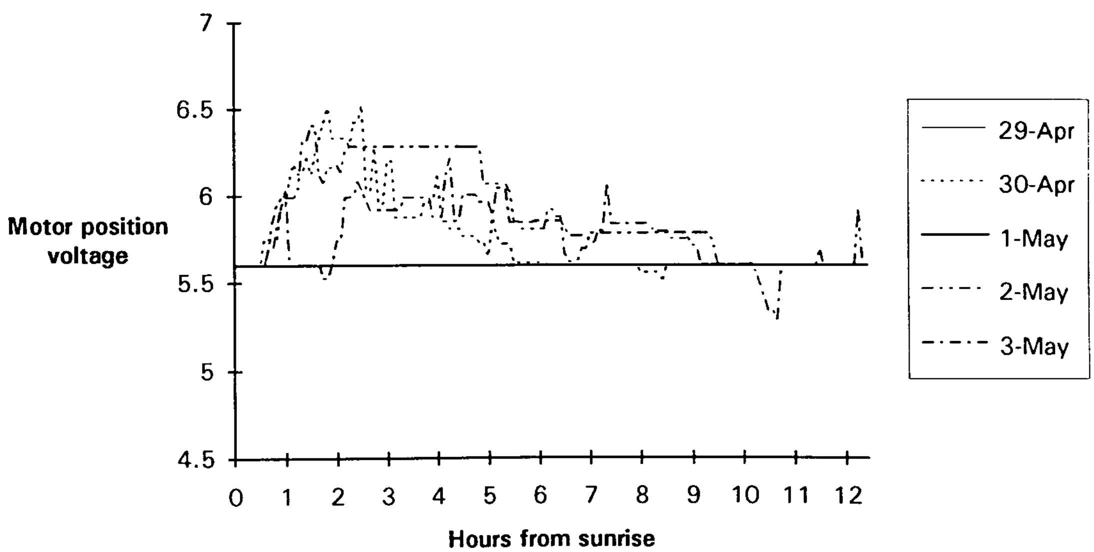


Figure 5.7: Motor position voltages for summer mode of the FLC

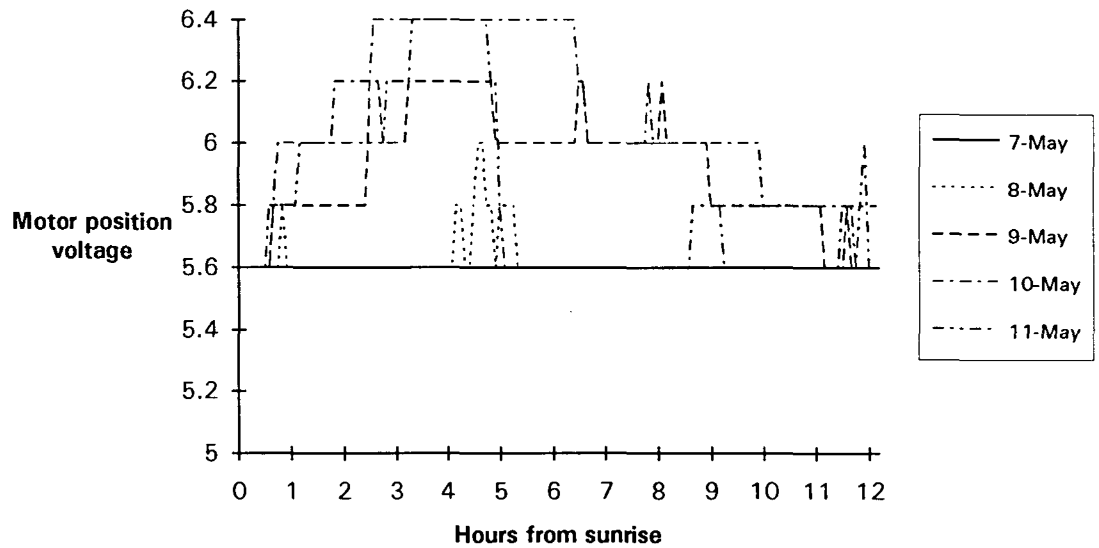


Figure 5.8: Motor position voltages for summer mode of the error-feedback controller

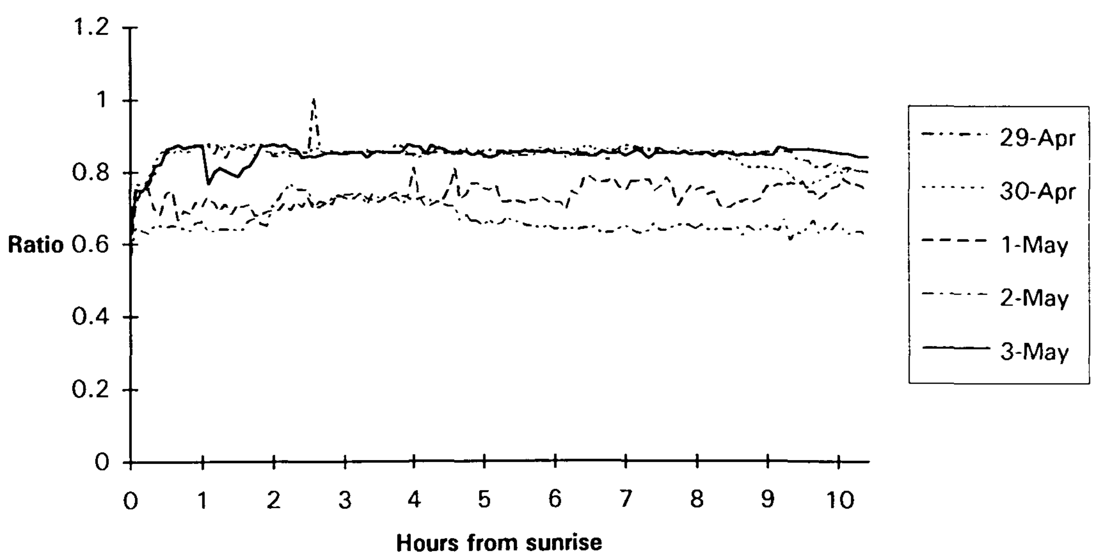


Figure 5.9: Ratio of inside to outside voltage for summer mode of the FLC

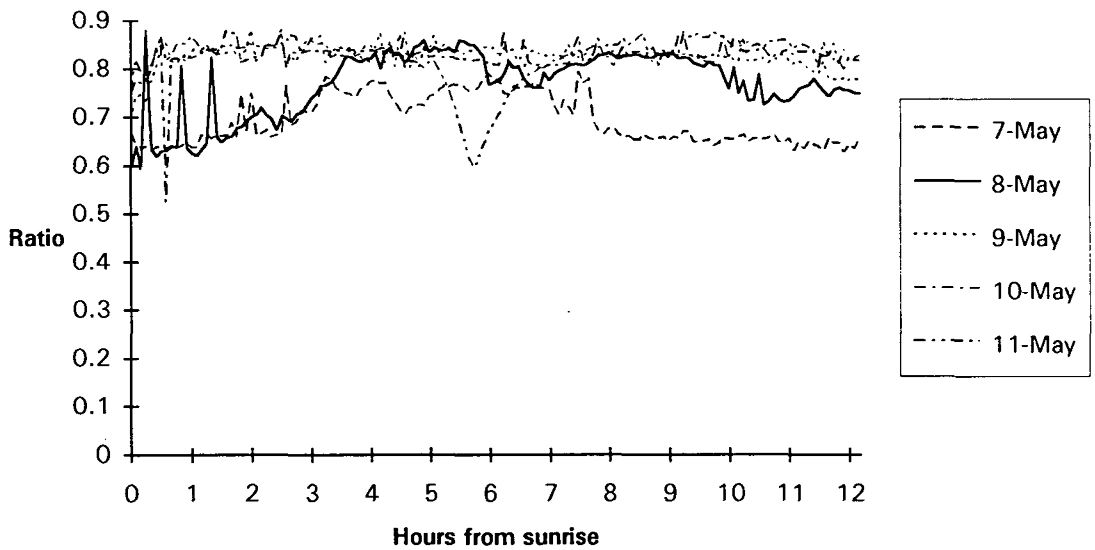


Figure 5.10: Ratio of inside to outside voltage for summer mode of error-feedback controller

and 5.10, the FLC maintains a more constant ratio of voltages with generally smoother curves and fewer drastic changes.

Because the summer mode controller was determined to have the greatest impact on building energy usage [8], tests to quantify these energy savings were done at the Lawrence Berkeley Laboratory Mobile Window Thermal Test facility (MoWiTT) located in Reno, Nevada. This facility consists of two room-sized calorimeters capable of measuring the net heat transfer through two windows exposed to the same climate conditions for comparison purposes [23]. Tests for the "smart" window were run for ten days from June 20 through June 30. The tests were done in two orientations including southeast and west for five days each. Three days were compared to a fixed shade at horizontal and the remaining two days were compared to a window with no shades. Data gathered from these tests consists of various temperatures, light levels, and energy needed to maintain constant room temperatures in both test chambers. Any energy used by equipment in the test chambers was accounted for in the energy analysis.

Some very valuable information about the nature of the response of the photovoltaic sensors was discovered during the tests. In general, two strips of photovoltaic cells will not have the same open-circuit voltage response. Only two well-matched strips, like the ones used in the Iowa tests, will produce the same response. During the tests at MoWiTT, one of the photovoltaic strips that had been used for the tests in Iowa stopped working correctly. New photovoltaic strips had to be used to control the blinds. The open-circuit voltages of the new strips were not well matched and were not stable enough to control the blinds at low light levels. The current produced by the photovoltaic cells is very stable, so 50 ohm resistors were used to close the circuit with the photovoltaic strips as shown in Figure 5.11. The voltage drop across the resistors is proportional to the current produced by the solar cells and can be used for the control of the blinds.

The winter mode of operation will not be affected by this change as the voltage will still need to be maximized. However, the ratio values used for the summer mode controllers will need to be re-determined using the same methods as described in section 4.1. The basic algorithm will remain the same for all controllers.

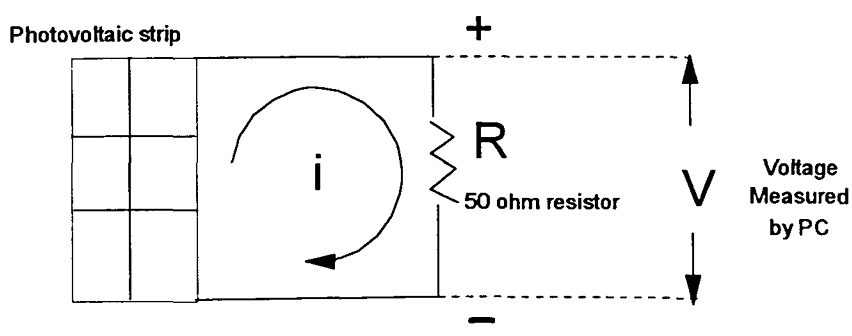


Figure 5.11: New circuit used in control strategy at MoWiTT facility

6. CONCLUSIONS

Both the fuzzy logic controller and the error-feedback controller performed satisfactorily for the control of the "smart" window. The main criteria for judging the performance of the controllers were: how well the controller maintained the desired position of the blinds, number of times the controller moved before achieving the correct position, and the response of the controllers to different lighting conditions such as clouds.

For the winter mode, the FLC moved a greater number of times than the error-feedback controller to find the correct position. Both controllers followed the predicted motor position voltage reasonably well. The FLC tended to change more frequently but with smaller motor voltage changes. If the fuzzy sets of the FLC were modified, the controller could be made to find the correct blind position quicker and move more smoothly.

For the summer mode, the FLC maintained the blind position more consistently than the error-feedback controller and did not seem to have many adverse responses to cloud cover. However, the FLC did move a greater number of times to achieve the desired position in the summer mode with this number reaching levels as high as 45. This problem can be remedied by a simple loop in the control program to limit the number of times it can move per check time.

With the information found from the MoWiTT tests about the performance of the photovoltaics, the summer control programs must be modified for the new voltage values when the resistors are in place. The ratio used to control the blinds will change along with the day to night threshold value. These are the only modifications to the programs that are needed to make the controllers work using the more stable voltage readings.

While both the error-feedback controller and the FLC have potential in this particular application, it appears that the FLC gives more promising results. The FLC provides the opportunity for more flexibility in the variables used for the control and gives smoother blind motion. As the "smart" window is further developed, more information may be needed to control the blinds, such as outside temperature. More variables are easily added to the FLC controller while the error-feedback controller gets much more complicated as the number of variables increases.

Future work on the "smart" window should include a more extensive study of the closed-circuit response of the thin-film photovoltaics and modifications to the control strategy which occur because of this change. Because it is the most critical mode of operation to energy savings, the summer mode of the controller should be the main focus of future research. More work needs to be done to determine if using a ratio of inside to outside responses is a valid control method. The fuzzy logic controller option should be considered for future work in the control of the "smart" window because of its flexibility.

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APPENDIX A: QUICKBASIC 4.5 CODE

A1 Look-up table calculation for winter mode of the FLC

```
DECLARE FUNCTION max! (a1!, a2!, a3!, a4!)
DECLARE FUNCTION min! (x1, x2)
' Assign values of input variables

OPEN "fuzz1.dat" FOR OUTPUT AS #1

FOR dv = -2 TO 2 STEP .02

IF dv < -.05 THEN
   neg = 1
   zero = 0
   ps = 0
ELSEIF dv < 0 THEN
   neg = -1 / .05 * dv
   zero = 1 / .05 * (dv + .05)
   ps = 0
ELSEIF dv < .05 THEN
   neg = 0
   zero = -1 / .05 * (dv - .05)
   ps = 1 / .05 * dv
ELSE
   neg = 0
   zero = 0
   ps = 1
END IF

sum = 0
sums = 0

FOR dmv = -.2 TO .6 STEP .01
   IF dmv < 0 THEN
      m = min(neg, 1 / .2 * (dmv + .2))
   ELSEIF dmv < .2 THEN
      m = max(min(neg, -1 / .2 * (dmv - .2)), min(zero, 1 / .2 * dmv), 0, 0)
   ELSEIF dmv < .4 THEN
      m = max(min(zero, -1 / .2 * (dmv - .4)), min(ps, 1 / .2 * (dmv - .2)),
   ELSE
      m = min(ps, -1 / .2 * (dmv - .6))
```

```
   END IF

   sum = sum + m
   sums = sums + m * dmv

NEXT dmv
   delv = sums / sum
   WRITE #1, delv

NEXT dv
END


FUNCTION max! (a1, a2, a3, a4)
tmax = a1
IF tmax < a2 THEN tmax = a2
IF tmax < a3 THEN tmax = a3
IF tmax < a4 THEN tmax = a4
max = tmax
END FUNCTION


FUNCTION min! (x1, x2)
IF (x1 < x2) THEN
   tmin = x1
ELSE
   tmin = x2
END IF
min = tmin
END FUNCTION
```

A2 Look-up table calculation for summer mode of the FLC

```
DECLARE FUNCTION max! (a1!, a2!, a3!, a4!)
DECLARE FUNCTION min! (x1, x2)
' Assign values of input variables

OPEN "fuzz2.dat" FOR OUTPUT AS #1

FOR ratio = 0 TO 1 STEP .005

IF ratio < .75 THEN
   low = 1
   ok = 0
   high = 0
ELSEIF ratio < .85 THEN
```

```
  low = -1 / .1 * (ratio - .85)
  ok = 1 / .1 * (ratio - .75)
  high = 0
ELSEIF ratio < .86 THEN
  low = 0
  ok = 1
  high = 0
ELSEIF ratio < .88 THEN
  low = 0
  ok = -1 / .02 * (ratio - .88)
  high = 1 / .02 * (ratio - .86)
ELSE
  low = 0
  ok = 0
  high = 1
END IF

sum = 0
sums = 0

FOR dmv = -.8 TO .7 STEP .01
  IF dmv < -.5 THEN
    m = min(low, 1 / .3 * (dmv + .8))
  ELSEIF dmv < -.3 THEN
    m = min(low, 1)
  ELSEIF dmv < 0 THEN
    m = max(min(low, -1 / .3 * dmv), min(ok, 1 / .3 * (dmv + .3)), 0, 0)
  ELSEIF dmv < .3 THEN
    m = max(min(ok, -1 / .3 * (dmv - .3)), min(high, 1 / .3 * dmv), 0, 0)
  ELSEIF dmv < .4 THEN
    m = min(high, 1)
  ELSE
    m = min(high, -1 / .3 * (dmv - .7))
  END IF

  sum = sum + m
  sums = sums + m * dmv

NEXT dmv
  dv = sums / sum
  WRITE #1, dv

NEXT ratio
END


IF (x1 < x2) THEN
  tmin = x1
ELSE
  tmin = x2
```

```
END IF
min = tmin
END FUNCTION


IF (x1 < x2) THEN
   tmin = x1
ELSE
   tmin = x2
END IF
min = tmin
END FUNCTION
```

A3 Control code for winter mode of the FLC

```
DECLARE FUNCTION round! (x#)
DIM dv(250), vm#(10), r(10)
REM   $INCLUDE: 'c:\nidaqdos\basic ex\nidaq.inc'

heap.size = SETMEM(-7000)
board% = 1

err.num% = Init.DA.Brds(1, brd.code%)
'IF (err.num%) THEN
'  PRINT "Error from Init.DA.Brds is "; err.num%
'END IF

OPEN "fuzz1.dat" FOR INPUT AS #1
OPEN "a:\fuzzy1.dat" FOR OUTPUT AS #2

FOR i = 0 TO 200
   INPUT #1, dv(i)
NEXT i

outchan% = 0
inchan% = 0
vmotor# = 8!
dir = -1

GOSUB sendvlts

PRINT "Hit any key to exit"

'   Is it night or day?
```

```
15 GOSUB getvolts
IF pv.out < .5 THEN
  start = TIMER
  DO
  IF INKEY$ <> "" THEN
    c = 1
    EXIT DO
  END IF
  LOOP WHILE ABS(TIMER - start) < 300!
  IF c = 1 THEN GOTO 50
  GOTO 15
END IF
PRINT "It is day"

vmotor# = 5.6
GOSUB sendvlts
GOSUB getvolts
pv.old = pv.in

'   Check the voltage every b minutes

10 start = TIMER
y = 0
DO
IF INKEY$ <> "" THEN
  c = 1
  EXIT DO
END IF
LOOP WHILE ABS(TIMER - start) < b
IF c = 1 THEN GOTO 50
GOSUB getvolts

'  Check to see if it is night

IF pv.out < .5 THEN   'It is night
  PRINT "It is night"
  vmotor# = 8!
  GOSUB sendvlts
  GOTO 15
END IF

pv.last = pv.in
diff = pv.old - pv.in

PRINT "diff="; diff

IF INKEY$ <> "" THEN GOTO 50

20 i = round(diff + 2) * 50
vmotor# = vmotor# + dir * dv(i)
```

```
IF ABS(dv(i)) < .1 THEN
   WRITE #2, vmotor#, y, pv.out, pv.in
   pv.old = pv.in
   GOTO 10
END IF

IF INKEY$ <> "" THEN GOTO 50
y = y + 1
GOSUB sendvlts
GOSUB getvolts
vm#(y) = vmotor#
r(y) = pv.in
IF pv.in < pv.last THEN dir = -dir

IF y > 5 THEN
   m = 1
   FOR i = 2 TO y
      IF r(i) > r(m) THEN m = y
   NEXT i
   vmotor# = vm#(m)
   GOSUB sendvlts
   GOSUB getvolts
   WRITE #2, vmotor#, y, pv.out, pv.in
   pv.old = pv.in
   GOTO 10
END IF

diff = pv.old - pv.in
PRINT "diff="; diff
GOTO 20

IF INKEY$ <> "" THEN GOTO 50

50  PRINT "Goodbye!"
err.num% = Init.DA.Brds(board, brdcode%)
END

getvolts:
   inchan% = 0
   err.num% = AI.Read(board%, inchan%, 1!, value%)
   IF (err.num%) THEN
      PRINT "Error from AI.Read is "; err.num%
   END IF

   err.num% = AI.VScale(board%, channel%, 1!, 1!, 0!, value%, pv.new#)
   IF (err.num%) THEN
      PRINT "Error from AI.VScale is "; err.num%
   END IF
   pv.in = round(pv.new#)
```

```
  inchan% = 1
  err.num% = AI.Read(board%, inchan%, 1!, value%)
  IF (err.num%) THEN
     PRINT "Error from AI.Read is "; err.num%
  END IF

  err.num% = AI.VScale(board%, channel%, 1!, 1!, 0!, value%, pv.new#)
  IF (err.num%) THEN
     PRINT "Error from AI.VScale is "; err.num%
  END IF
  pv.out = round(pv.new#)

RETURN

sendvlts:
'  err.num% = AO.Configure(board%, outchan%, 1, 0, 0, 0)
'  IF (err.num%) THEN
'     PRINT "Error from AO.Configure is "; err.num%
'  END IF

  err.num% = AO.VWrite(board%, outchan%, vmotor#)
  IF (err.num%) THEN
     PRINT "Error from AO.VWrite is "; err.num%
  END IF

  pause = TIMER
  DO
  LOOP WHILE (TIMER - pause) < 1.2
RETURN
FUNCTION round! (x#)
round = INT((x# + .005) * 100!) / 100
END FUNCTION
```

A4 Control code for summer mode of the FLC

```
DECLARE FUNCTION round! (x#)
DIM dv(250), vm#(10), r(10)
REM  $INCLUDE: 'c:\nidaqdos\basic ex\nidaq.inc'

heap.size = SETMEM(-7000)
board% = 1

err.num% = Init.DA.Brds(1, brd.code%)
'IF (err.num%) THEN
'  PRINT "Error from Init.DA.Brds is "; err.num%
'END IF
```

```
OPEN "fuzz2.dat" FOR INPUT AS #1
OPEN "a:\fuzzy2.dat" FOR OUTPUT AS #2

FOR i = 0 TO 200
   INPUT #1, dv(i)
NEXT i

outchan% = 0
inchan% = 0
vmotor# = 8!

INPUT "Enter the time between check points (minutes)"; b
b = b * 60

GOSUB sendvlts

PRINT "Hit any key to exit"

'  Is it night or day?

15  GOSUB getvolts
IF pv.out < .5 THEN
   start = TIMER
   DO
   IF INKEY$ <> "" THEN
      c = 1
      EXIT DO
   END IF
   LOOP WHILE ABS(TIMER - start) < 300!
   IF c = 1 THEN GOTO 50
   GOTO 15
END IF
PRINT "It is day"

'   Check the voltage every b minutes

10  start = TIMER
y = 0
DO
IF INKEY$ <> "" THEN
   c = 1
   EXIT DO
END IF
LOOP WHILE ABS(TIMER - start) < b
IF c = 1 THEN GOTO 50
GOSUB getvolts

'  Check to see if it is night
```

```
IF pv.out < .5 THEN   'It is night
   PRINT "It is night"
   vmotor# = 8!
   GOSUB sendvlts
   GOTO 15
END IF

PRINT "ratio="; ratio

IF INKEY$ <> "" THEN GOTO 50

20  i = round(ratio * 2!) * 100
vmotor# = vmotor# + dv(i)
IF ABS(dv(i)) < .1 THEN
   WRITE #2, ratio, vmotor#, y, pv.out, pv.in
   GOTO 10
END IF
IF vmotor# < 5.6 THEN
   vmotor# = 5.6
   GOSUB sendvlts
   WRITE #2, ratio, vmotor#, y, pv.out, pv.in
   GOTO 10
END IF
IF INKEY$ <> "" THEN GOTO 50
y = y + 1
GOSUB sendvlts
GOSUB getvolts
vm#(y) = vmotor#
r(y) = ratio

IF y > 5 THEN
   FOR i = 2 TO y
      IF ABS(r(y) - .85) < ABS(r(y - 1) - .85) THEN m = y
   NEXT i
   vmotor# = vm#(m)
   GOSUB sendvlts
   GOSUB getvolts
   WRITE #2, ratio, vmotor#, y, pv.out, pv.in
   GOTO 10
END IF

PRINT "ratio="; ratio
GOTO 20

IF INKEY$ <> "" THEN GOTO 50

50  PRINT "Goodbye!"
err.num% = Init.DA.Brds(board, brdcode%)
END
```

```
getvolts:
  inchan% = 0
  err.num% = AI.Read(board%, inchan%, 1!, value%)
  IF (err.num%) THEN
    PRINT "Error from AI.Read is "; err.num%
  END IF

  err.num% = AI.VScale(board%, channel%, 1!, 1!, 0!, value%, pv.new#)
  IF (err.num%) THEN
    PRINT "Error from AI.VScale is "; err.num%
  END IF
  pv.in = round(pv.new#)

  inchan% = 1
  err.num% = AI.Read(board%, inchan%, 1!, value%)
  IF (err.num%) THEN
    PRINT "Error from AI.Read is "; err.num%
  END IF

  err.num% = AI.VScale(board%, channel%, 1!, 1!, 0!, value%, pv.new#)
  IF (err.num%) THEN
    PRINT "Error from AI.VScale is "; err.num%
  END IF
  pv.out = round(pv.new#)
  ratio = pv.in / (pv.out + .00001)

RETURN

sendvlts:
  err.num% = AO.Configure(board%, outchan%, 1, 0, 0, 0)
  IF (err.num%) THEN
    PRINT "Error from AO.Configure is "; err.num%
  END IF

  err.num% = AO.VWrite(board%, outchan%, vmotor#)
  IF (err.num%) THEN
    PRINT "Error from AO.VWrite is "; err.num%
  END IF

  pause = TIMER
  DO
  LOOP WHILE (TIMER - pause) < 1.2
RETURN

FUNCTION round! (x#)
round = INT((x# + .005) * 100!) / 100
END FUNCTION
```

A5 Control code for the winter mode error-feedback controller

```
DECLARE FUNCTION round! (x#)
REM  $INCLUDE: 'c:\nidaqdos\basic ex\nidaq.inc'
DIM vm#(20), pv(20)

heap.size = SETMEM(-7000)
board% = 1

err.num% = Init.DA.Brds(1, brd.code%)
'    IF (err.num%) THEN
'         PRINT "Error from Init.DA.Brds is "; err.num%
'    END IF

da.dv = .4  'radians per volt
mgain = -.63 'radians per volt
test = .01
test2 = .02    'volts/radians
vmotor# = 8
outchan% = 0
noise = .02

GOSUB sendvlts

PRINT "Hit any key when blinds stop moving"
DO
LOOP WHILE INKEY$ = ""

INPUT "Enter the time between check points (min)"; b
b = b * 60
PRINT "Hit any key to exit the program"

'  Is it night or day?

15  GOSUB getvolts
l = 0
IF pv.out < .5 THEN  'it is night
  start = TIMER
  DO
  IF INKEY$ <> "" THEN
     c = 1
     EXIT DO
  END IF
  LOOP WHILE ABS(TIMER - start) < 300
  IF c = 1 THEN GOTO 50
```

```
  GOTO 15
END IF
PRINT "it is day"
vmotor# = 5.6
GOSUB sendvlts

'  Measure pv voltage and compute change in voltage
'  Keep checking if delv<test

OPEN "m1dat.dat" FOR OUTPUT AS #1

'  Is it night?

GOSUB getvolts

IF pv.out < .5 THEN  'It is night
  vmotor# = 8!
  GOSUB sendvlts
  GOTO 15
END IF

pv.old = pv.in
PRINT "the original voltage is "; pv.in
WRITE #1, pv.out, pv.in, vmotor#, 0
20 DO
  y = 0
  IF INKEY$ <> "" THEN
    c = 1
    EXIT DO
  END IF
  start = TIMER
  DO
    IF INKEY$ <> "" THEN
        c = 1
        EXIT DO
    END IF
  LOOP WHILE ABS(TIMER - start) < b
  IF c = 1 THEN EXIT DO
  GOSUB getvolts

'  Is it night?

IF pv.out < .5 THEN  'It is night
  vmotor# = 8!
  GOSUB sendvlts
  l = 1
  EXIT DO
END IF

  delv = pv.old - pv.in
```

```
'  change = delv / pv.old
'  IF delv < noise THEN change = test - .01
'  PRINT "pv.new = "; pv.in
'  IF pv.in > pv.old THEN pv.old = pv.in
'  WRITE #1, pv.out, pv.in, vmotor#, y
'LOOP WHILE change < test
'
'IF c = 1 GOTO 50
'IF l = 1 GOTO 15
'pv.check = pv.in
'pv.last = pv.check
'
''  Compute change in angle, change in motor voltage, new motor
''  voltage, and change in shade angle
'
'PRINT "delv="; delv
'
'da = delv * da.dv
'
'40  dvm.in = da / mgain
'  y = y + 1
'IF (ABS(dvm.in)) < .2 THEN dvm.in = .2 * SGN(dvm.in)
'IF (ABS(dvm.in)) > .6 THEN dvm.in = .6 * SGN(dvm.in)
'PRINT "dvm.in = "; dvm.in
'
'vmotor# = vmotor# + dvm.in
'dtheta = ABS(mgain * dvm.in)
'
''  Send the new voltage to the motor
'GOSUB sendvlts
'
''  Measure the photovoltaic output again
'GOSUB getvolts
'PRINT "pv.new = "; pv.in
'j = j + 1
'vm#(j) = vmotor#
'pv(j) = pv.in
'IF j > 5 THEN
'  y = y + 1
'  pv.max = pv(1)
'  m = 1
'  FOR k = 2 TO j
'    IF pv(k) > pv.max THEN
'      m = k
'      pv.max = pv(k)
'    END IF
'  NEXT k
'  vmotor# = vm#(m)
'
'  GOSUB sendvlts
```

```
  GOSUB getvolts
  pv.old = pv.in
  IF INKEY$ <> "" THEN GOTO 50
  j = 0
  i = 0
  PRINT "ESCAPE ROUTE!!!"
  PRINT "pv.old = "; pv.old
  WRITE #1, pv.out, pv.in, vmotor#, y
  GOTO 20
END IF
IF INKEY$ <> "" THEN GOTO 50

IF (pv.in < pv.check) THEN

  IF (pv.in > pv.last) THEN
     da = (pv.in - pv.last) * da.dv
     pv.last = pv.in
     GOTO 40
  ELSE
     PRINT "moving wrong way"
     mgain = -mgain
     da = 2 * da
     pv.last = pv.in
     GOTO 40
  END IF
ELSE
  IF INKEY$ <> "" THEN GOTO 50
  IF ((pv.in - pv.old) >= 0) THEN
     pv.old = pv.in
     j = 0
     PRINT "pv.old = "; pv.old
     WRITE #1, pv.out, pv.in, vmotor#, y
     GOTO 20
  ELSE
     da = (pv.last - pv.in) * da.dv
     pv.check = pv.in
     pv.last = pv.in
     IF INKEY$ <> "" THEN GOTO 50
     GOTO 40
  END IF
END IF

50 PRINT "Goodbye!"
err.num% = Init.DA.Brds(board, brdcode%)
END

getvolts:
  inchan% = 0
  err.num% = AI.Read(board%, inchan%, 1!, value%)
```

```
'   IF (err.num%) THEN
'      PRINT "Error from AI.Read is "; err.num%
'   END IF
'
'   err.num% = AI.VScale(board%, channel%, 1!, 1!, 0!, value%, pv.new#)
'   IF (err.num%) THEN
'      PRINT "Error from AI.VScale is "; err.num%
'   END IF
'   pv.in = round(pv.new#)
'
'   inchan% = 1
'   err.num% = AI.Read(board%, inchan%, 1!, value%)
'   IF (err.num%) THEN
'      PRINT "Error from AI.Read is "; err.num%
'   END IF
'
'   err.num% = AI.VScale(board%, channel%, 1!, 1!, 0!, value%, pv.new#)
'   IF (err.num%) THEN
'      PRINT "Error from AI.VScale is "; err.num%
'   END IF
'   pv.out = round(pv.new#)
'
'RETURN
'
'sendvlts:
''   err.num% = AO.Configure(board%, outchan%, 1, 0, 0, 0)
''   IF (err.num%) THEN
''      PRINT "Error from AO.Configure is "; err.num%
''   END IF
'
'   err.num% = AO.VWrite(board%, outchan%, vmotor#)
'   IF (err.num%) THEN
'      PRINT "Error from AO.VWrite is "; err.num%
'   END IF
'
'   pause = TIMER
'   DO
'   LOOP WHILE (TIMER - pause) < 2!
'RETURN


'FUNCTION round! (x#)
'round = INT((x# + .005) * 100!) / 100
'END FUNCTION
```

A6 Control code for the summer mode error-feedback controller

```
DECLARE FUNCTION round! (x#)
REM  $INCLUDE: 'c:\nidaqdos\basic ex\nidaq.inc'

heap.size = SETMEM(-7000)
board% = 1

err.num% = Init.DA.Brds(1, brd.code%)
'IF (err.num%) THEN
'  PRINT "Error from Init.DA.Brds is "; err.num%
'END IF

topdiff = .87
lowdiff = .8
outchan% = 0
vmotor# = 8!

OPEN "a:\m2cont.dat" FOR OUTPUT AS #1

GOSUB sendvlts
INPUT "Enter the time between checkpoints (minutes)"; b
b = b * 60

PRINT "Hit any key to exit"

'   Is it night or day?

15  GOSUB getvolts
IF pv.out < .5 THEN
   start = TIMER
   DO
   IF INKEY$ <> "" THEN
      c = 1
      EXIT DO
   END IF
   LOOP WHILE ABS(TIMER - start) < 300!
   IF c = 1 THEN GOTO 50
   GOTO 15
END IF
PRINT "It is day"

'    Check the voltage every 5 minutes

10  start = TIMER
DO
IF INKEY$ <> "" THEN
   c = 1
```

```
  EXIT DO
END IF
LOOP WHILE ABS(TIMER - start) < b
IF c = 1 THEN GOTO 50
GOSUB getvolts

'  Check to see if it is night

IF pv.out < .5 THEN   'It is night
  PRINT "It is night"
  vmotor# = 8!
  GOSUB sendvlts
  GOTO 15
END IF

PRINT "ratio="; ratio

IF INKEY$ <> "" THEN GOTO 50


20  IF ratio > topdiff THEN
  y = y + 1
  dvm.in = .2
  vmotor# = vmotor# + dvm.in
  IF vmotor# < 5.6 THEN vmotor# = 5.6
  GOSUB sendvlts
  GOSUB getvolts
  PRINT "ratio="; ratio
  IF INKEY$ <> "" THEN GOTO 50
  GOTO 20
END IF

IF INKEY$ <> "" THEN GOTO 50

IF ratio < lowdiff THEN
  dvm.in = -.2
  vmotor# = vmotor# + dvm.in
  IF vmotor# < 5.6 THEN
     vmotor# = 5.6
     GOTO 44
  END IF
  y = y + 1
  GOSUB sendvlts
  GOSUB getvolts
  PRINT "ratio="; ratio
  IF INKEY$ <> "" THEN GOTO 50
  GOTO 20
END IF

IF INKEY$ <> "" THEN GOTO 50
```

```
'44 WRITE #1, ratio, vmotor#, y, pv.out, pv.in
'y = 0
'GOTO 10
'
'50  PRINT "Goodbye!"
'err.num% = Init.DA.Brds(board, brdcode%)
'END
'
'getvolts:
'   inchan% = 0
'   err.num% = AI.Read(board%, inchan%, 1!, value%)
'   IF (err.num%) THEN
'      PRINT "Error from AI.Read is "; err.num%
'   END IF
'
'   err.num% = AI.VScale(board%, channel%, 1!, 1!, 0!, value%, pv.new#)
'   IF (err.num%) THEN
'      PRINT "Error from AI.VScale is "; err.num%
'   END IF
'   pv.in = round(pv.new#)
'
'   inchan% = 1
'   err.num% = AI.Read(board%, inchan%, 1!, value%)
'   IF (err.num%) THEN
'      PRINT "Error from AI.Read is "; err.num%
'   END IF
'
'   err.num% = AI.VScale(board%, channel%, 1!, 1!, 0!, value%, pv.new#)
'   IF (err.num%) THEN
'      PRINT "Error from AI.VScale is "; err.num%
'   END IF
'   pv.out = round(pv.new#)
'   ratio = pv.in / (pv.out + .00001)
'
'RETURN
'
'sendvlts:
''   err.num% = AO.Configure(board%, outchan%, 1, 0, 0, 0)
''   IF (err.num%) THEN
''      PRINT "Error from AO.Configure is "; err.num%
''   END IF
'
'   err.num% = AO.VWrite(board%, outchan%, vmotor#)
'   IF (err.num%) THEN
'      PRINT "Error from AO.VWrite is "; err.num%
'   END IF
'
'   pause = TIMER
'   DO
'   LOOP WHILE (TIMER - pause) < 1.2
```

```
'RETURN

'FUNCTION round! (x#)
'round = INT((x# + .005) * 100!) / 100

'END FUNCTION
```

APPENDIX B: ANGLE RELATIONSHIPS FOR SUMMER MODE

Assuming that the louvers of the Slimshade can be modeled as flat, thin slats with the width equal to the spacing between them, the geometry looks as shown in Figure B1. The solar altitude angle is defined by α_S. The sun projects a shadow onto a vertical surface creating a triangle as shown in Figure B1. From standard geometry practices the width of the shadow, denoted by x, can be determined from the relationship:

$$x = w\left[\frac{\sin(\alpha_s + \beta)}{\sin(90 - \alpha_s)}\right]$$

If the louvers are just barely blocking all direct beam radiation, then x is equal to w. Using this fact gives a simple relationship between α_S and β as follows:

$$\beta = 90 - 2\alpha_s$$

This relationship assumes the louver angle as defined is positive with horizontal being zero. As the angles were defined in section 3.1, this relationship would give the absolute value of the louver angle.

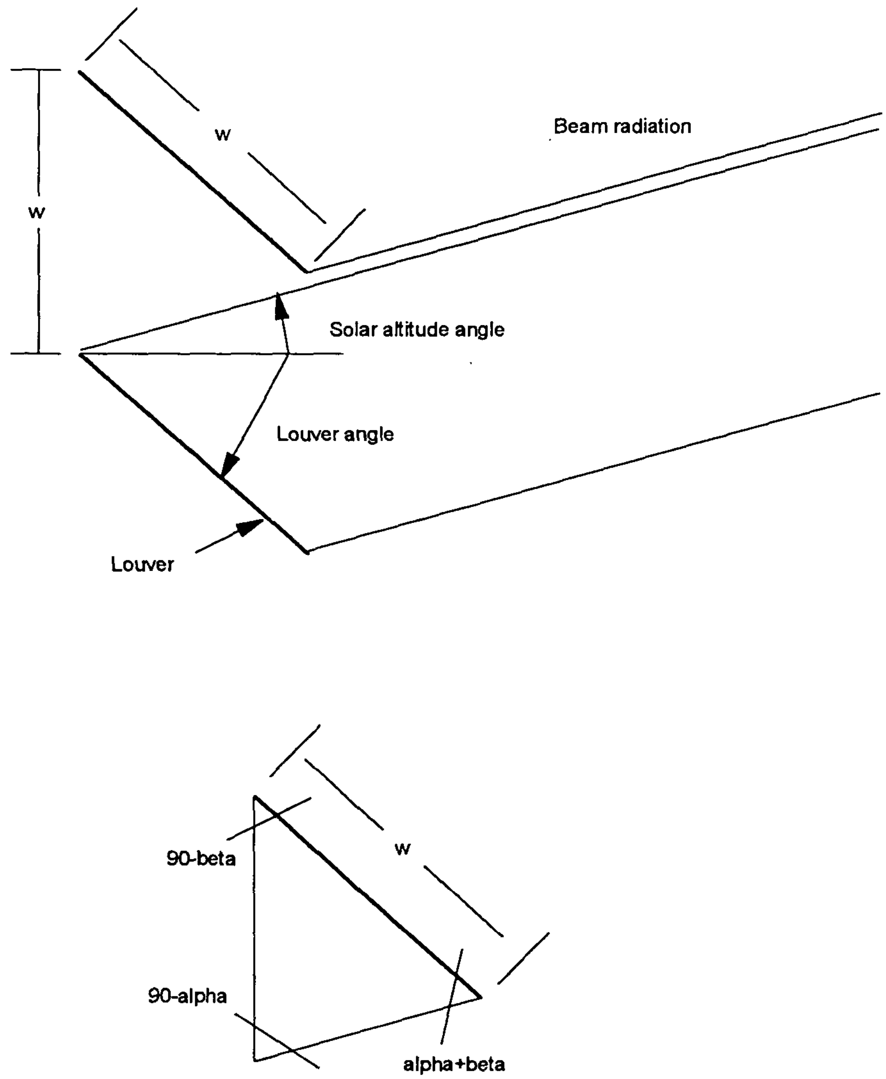

Figure B1: Angle definitions

APPENDIX C: THEORETICAL CALCULATIONS OF MOTOR POSITION VOLTAGES

To perform a theoretical estimation of the motor voltages over a day many equations which describe the relative position between the window and sun are needed. These equations have been taken from Duffie and Beckman [3] and are numbered as in the text. The solar zenith angle is given by:

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \qquad [1.6.6]$$

Where:

φ=latitude=42°N at Ames, Iowa

$$\delta = 23.45\sin\left(360\frac{284+n}{365}\right) \qquad [1.6.1]$$

n=day of year (1-365)

ω=hour angle as defined in Duffie and Beckman [3, page 13]

The window in which the tests were performed faces southeast which corresponds to an approximate surface azimuth angle of -45 degrees [3]. No direct solar radiation hits the surface of the window when the solar azimuth angle is at an angle greater than 90 degrees with the surface azimuth angle. The solar azimuth angle can be calculated using equations (1.6.6a - 1.6.6g) [3, page 16]. With this information, the correct louver angle can be calculated for any time. Assuming that the louver position varies linearly between 3 and 8 volts with 3 volts corresponding to +90 degrees and 8 volts to -90 degrees as defined in section 3.1, the motor voltage equation is a straight line equation.

motor voltage =-(5/180)(louver angle-90)+3

Using the above information and May 25 as the day of the year, the theoretical motor voltages were calculated for the winter mode of the controller. In this mode the louver angle is equal to the solar altitude angle. The results of this simulation are shown in Figure 5.1. Using May 1 as the day of the year and the information in Appendix B, the motor voltages were estimated. The results of this simulation can be seen in Figure 5.6.