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Development of an Automated Wind Turbine Using Fuzzy Logic

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The Philippines has a very large capacity of wind energy amounting up to 9GW. However, there are very serious problems that hinder the development of wind turbine technology in our country. First, strong typhoons, that visit us 9 times on the average, destroy the stand-alone turbines. Second, there are times that wind speeds are very low and not enough to produce electricity. Third, if there's enough wind, wind speeds are not constant at all times, thus creating fluctuations in electricity that damage the load.

This study aims to protect the wind turbines from strong winds, to harness as much energy from the wind and to lessen the variations in shaft speed that produces electrical fluctuations. An automated wind turbine with pitch and arm controls using fuzzy logic and microcontroller was developed to answer the aforementioned objectives.

The microcontroller used in this turbine is the Basic Stamp 2. From the input data given by the anemometer and the shaft encoder, the fuzzy set rules will be applied to determine the proper pitch angle and arm angle of the wind turbine. The microcontroller gives an output signal to any of the four solid-state relays which then activates the solenoid valves. These solenoids serve supply the hydraulic oil to the hydraulic cylinders.

The performance of the automation is evaluated through simulation and data acquisition using Solid Works and Microsoft Excel.

1.0 Introduction

This paper presents the implementation of a computer controlled wind turbine using the Basic Stamp 2 microcontroller in order to ensure its safe while maintaining the steadiness of rotor speed. The system is composed of three components: the mechanical, electronic and the software programming. The design of the mechanical set-up will be a small scale wind turbine with its rotor blades following the MINACA 4412 blade profile. The electronic component consists of the BS 2 microcontroller used for the interface of the hydraulic cylinders to the computer through its common port. The BS 2 microcontroller comes with its own software editor that allows one to do the programming. Testing will be done to determine the effectiveness of the fuzzy logic control and the microcontroller.

1.1 Wind Turbine Set-up

The wind turbine set-up is divided into three components: mechanical, electronic and software component. Figure 1 shows the diagram of the whole set-up divided into its three components. The mechanical component of the set-up is the whole turbine assembly comprising the rotor blades, the hydraulic cylinders and the test bed tower. The hydraulic cylinders are the actuators of the whole plant which are controlled by the microcontroller. The microcontroller is the main component in the electronic system which is connected in a computer through its common port. Lastly, the software component processes the input data of the anemometer and shaft encoder and then pulses are sent to the solid state relays for the control of the solenoid valves, the motor pump and eventually the hydraulic cylinders.

1.2 Mechanical Component

The mechanical component is shown in Figure 1. The test bed tower supports the entire turbine assembly. It is constructed using angular bars welded together and it was also designed in such a way that it will balance out the weight since the rotor will be extended out from the base plate and to nullify the force of the wind from creating vibrations.

1.3 Electronic Component

The electronic circuit is interfaced to the computer through the common port. The microcontroller sends signals to the circuit consisted of the solid state relays. After the input data are processed, it is converted to an equivalent output response that will now control the movement of the rotor blades or the whole rotor assembly.

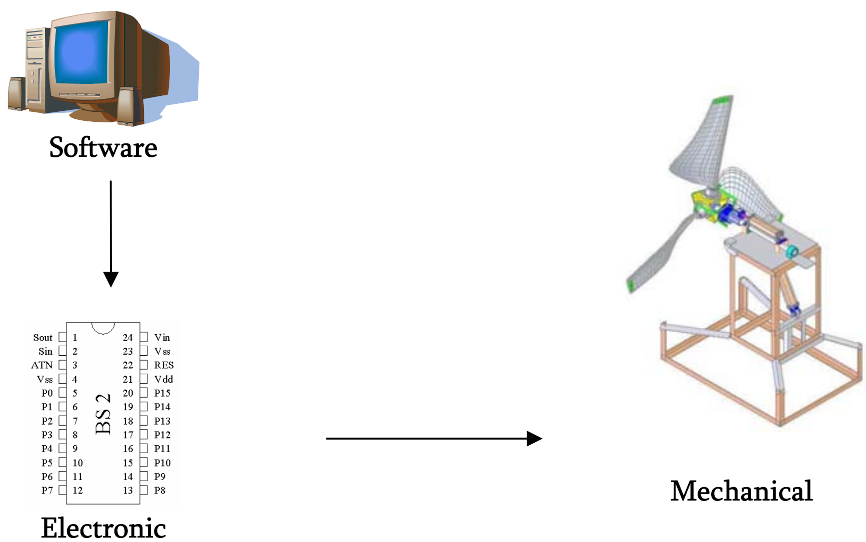


Figure 1 Wind Turbine Set-up

1.4 Software Component

The software is programmed using the Basic Stamp 2 Editor. It has its own programming language and syntax. The software component is divided into two parts: the first part is for the arm control while the second part is for the pitch control. In either case, the input will come from the DC motor. Figure 2 illustrates an overview of how the program works.

1.5 Mechatronics Component

The mechatronics component described here is the interaction between the mechanical components and the electronic components.

1.6 Arm Control

There are two programs designed and tested for the arm control. The first one is a simple 'on' and 'off' control. This means that if the maximum wind speed limit is achieved, the microcontroller will send an output signal that will cause the rotor to lower down, and raise it up if otherwise. The second program is the arm control with feedback program. For this part, the program does not only have maximum and minimum speed limits which determine when the upper nacelle assembly should be raised or lowered, we added two additional speed limits, the lower speed limit and the higher speed limit. With the additional speed limits, the arm control will not be totally lowered or raised, but the arm angle will be adjusted at small increments until the feedback tells the MCU that the desired speed is reached.

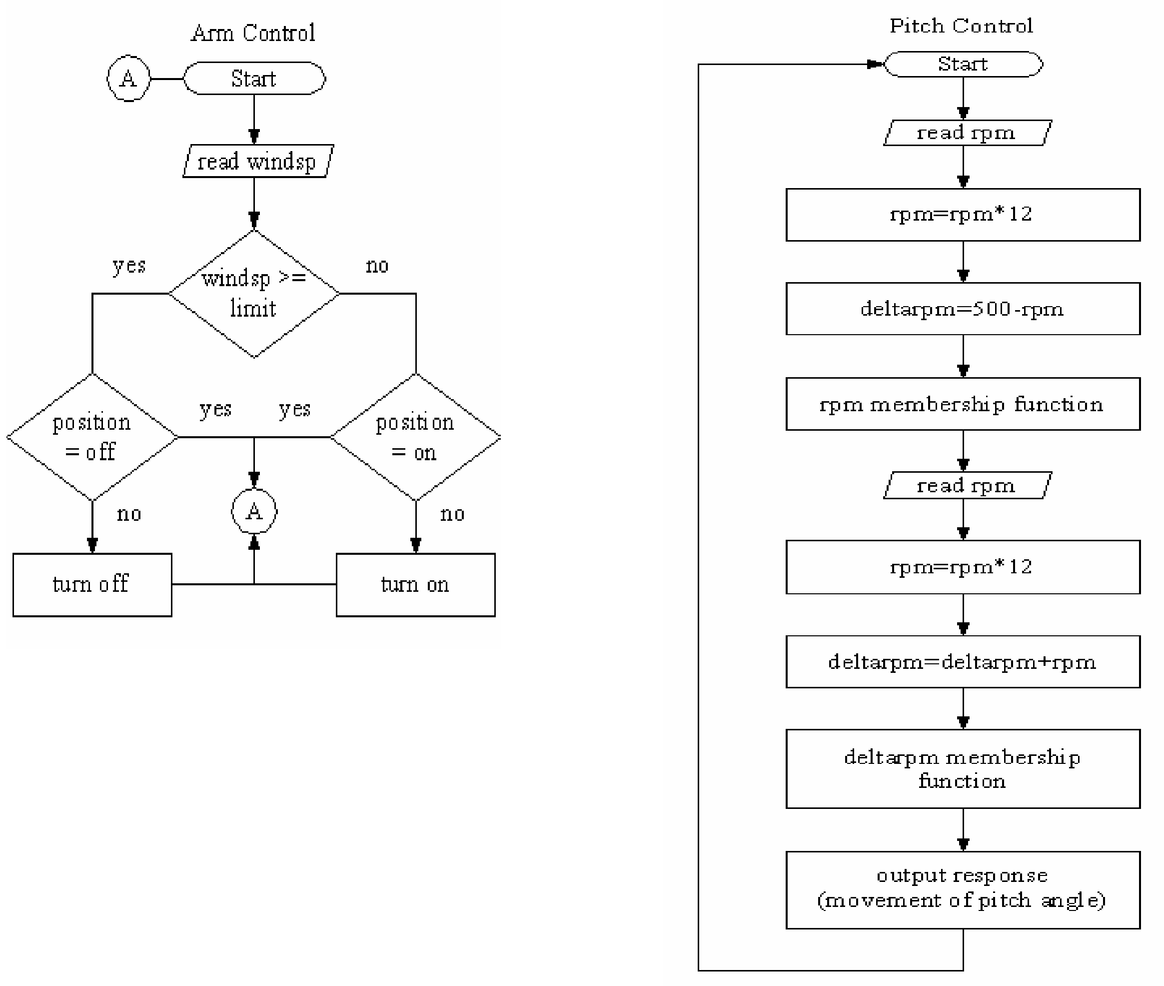
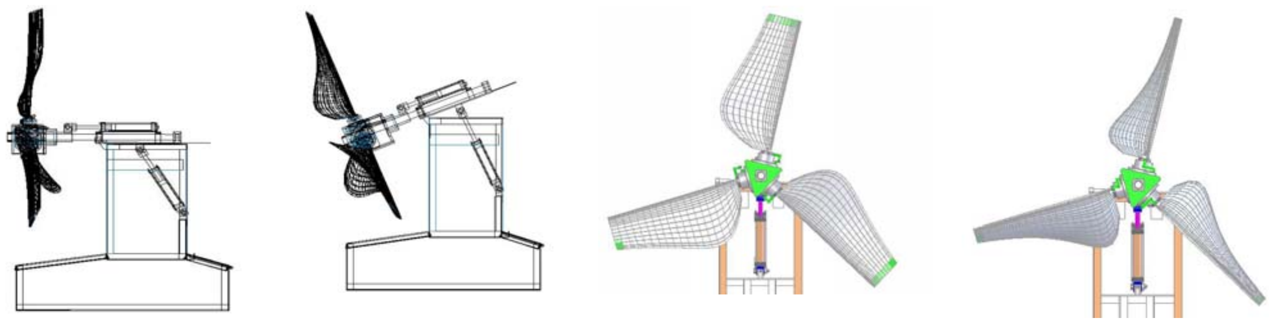


Figure 2 Program Flowchart

Limit switches are provided so that if the hydraulic cylinder has reach its maximum extension on either side, the microcontroller will turn off the motor. Figure 3a shows the turbine assembly in operation while Figure 3b shows the turbine assembly in its shutdown position.

1.7 Pitch Control

The pitch control will be programmed using fuzzy logic. The concept of Fuzzy Logic (FL) is basically a set of Boolean operation (stages) being followed and that set may have Boolean properties. FL follows the simple rule IF *A* THEN *B*. For example, IF *system is too fast* AND *system is accelerating* THEN *decelerate*. Figures 3c and 3d show the position of the rotor blades with its pitch angle unadjusted and adjusted.



a. Turbine in Operation | b. Turbine Shutdown Position | c. Unadjusted blade pitch angle | d. Adjusted blade pitch angle

Figure 3 : Mechanical Component

2.0 Experimentation and Results

Planned experimentation should be done through data acquisition and actual testing; however, due to some reasons, actual testing cannot commence. First, wind tunnel testing is not feasible in the Philippines. Moreover, there were some errors on the fabrication of the blades that they broke down early and that actual testing through very strong winds was also not possible. In this case, the proponents arrived at new ways of testing the programs for the automation of pitch and arm angles. These are the DC Motor simulation, the use of standard electric fan blades for actual testing, and testing through our self-made automation tool for pitch automation. And going back to the primary objectives of this study, we were aiming to provide the automation for the safe and optimum performance of the wind turbine.

2.1 Hydraulics Response Test and DC Motor Calibration

Prior to the testing of the Arm and Blade pitch controls, the response hydraulic system, from the input signal to the solid-state relays to the control valves and to the hydraulic cylinders, was tested given different durations for the input signals. This test is necessary for to determine if the hydraulic system gives an accurate and precise response. Furthermore, this test characterized the shortest allowable signal to the hydraulic system and based on the experiment it was 5/10 of a second.

Another important experiment that we have done to prepare the set-up for the testing of the automated wind turbine is the DC motor calibration. The DC motor was used to simulate the speed of the rotor for the following arm control and pitch control testing. From the results of the experiment, the relationship was determined between the input voltage and the number of pulses that the DC motor generates. As the voltage increases, the number of pulses that the DC motor will generate also increases. The Equivalent RPM, on the other hand, is computed by multiplying the number of pulses/second by 0.6.

2.2 Arm Control Experiments

The first experiment performed was the DC motor simulation. The experiment set-up for the Arm Control 'On/Off' function can be seen in Figure 4 while the program rules can be seen on Table 1.

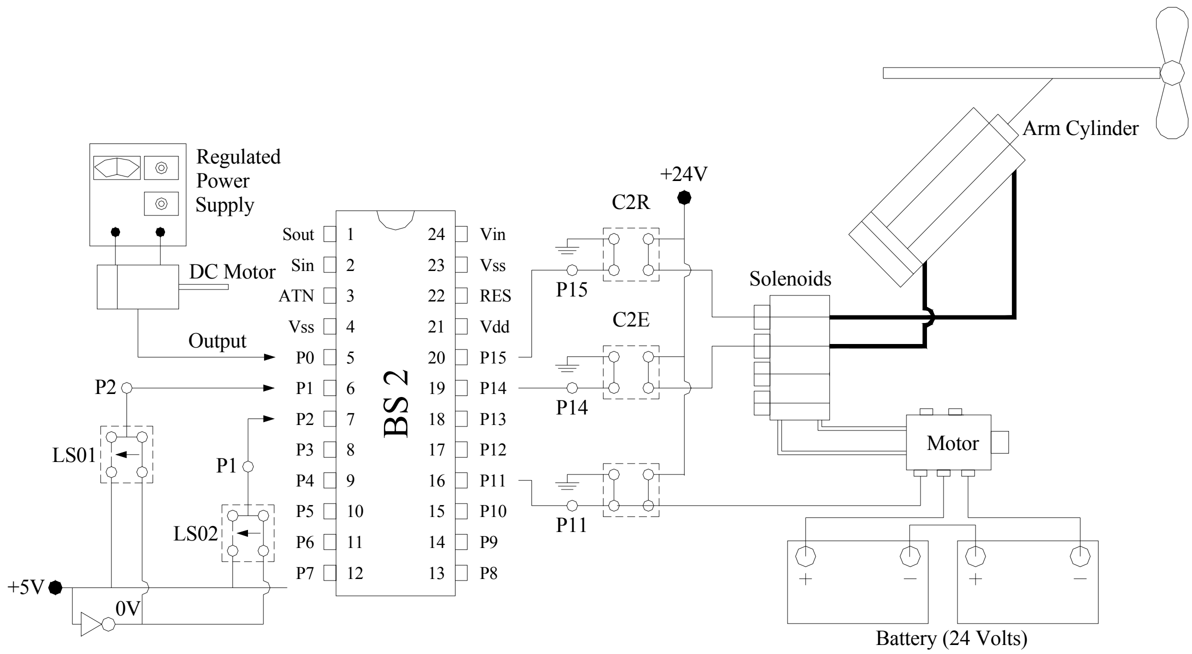


Figure 4 Arm Control using DC Motor Experiment Set-up

Table 1. Arm Control Rule using DC motor Simulation

Arm Control 'On/Off' Function		Arm Control with feedback	
Windspeed (pulses/second)	Output:	Shaft speed (RPM)	Output:
< 4000	Turbine on until arm is parallel to ground	< 480	Turbine on until arm is parallel to ground
> 4000	Turbine off until arm is perpendicular to ground	>= 480 and > 1020	Raise nacelle assembly for 0.75 seconds
		>= 1020 and <= 1620	Steady -> no response
		> 1620 and <= 2220	Lower nacelle assembly for 0.75 seconds
		> 2220	Turbine off until arm is perpendicular to ground

The results of the DC motor simulation experiments can be seen on Table 2. Based on the results, it can be seen that the MCU gave correct signals for the hydraulic system and the hydraulic system in return, gave proper adjustments to the wind turbine system.

Table 2. DC Motor Simulation for Arm Control Program Results

Arm Control 'On/Off' Function			Arm Control with feedback		
Run No.	No. of pulses/second	Turbine Action	Run No.	No. of Pulses/second	Turbine Action
1	6253	Turbine off	1	1098	no response
2	4568	no response	2	1784	Soft Turbine off
3	5412	no response	3	1506	no response
4	2563	Turbine on	4	1780	Soft Turbine off
5	1257	no response	5	1600	no response
6	2745	no response	6	695	Soft Turbine on
7	5412	Turbine off	7	780	Soft Turbine on
8	1456	Turbine on	8	853	Soft Turbine on
9	2561	no response	9	1127	no response
10	1482	no response	10	3267	Turbine off

After performing the DC motor simulation, the two arm control programs were actually tested using standard household fan blades (of 40cm rotor diameter) as the source of speed. The miniature wind turbine was placed at the left side of nacelle base (just beside the main shaft). An industrial fan with three setting for speed was used as the source of wind. The experiment set-up for this experiment can be seen on Figure 5. The input signal for the MCU are coming from the shaft encoder where the fan blades were directly inserted. Table 3 shows the program rule. The results of the experiment on Table 4 show that the MCU still gave the correct adjustments for any speed set on the industrial fan.

The arm control rule for the actual testing of the miniature wind turbine is in Figure 6.

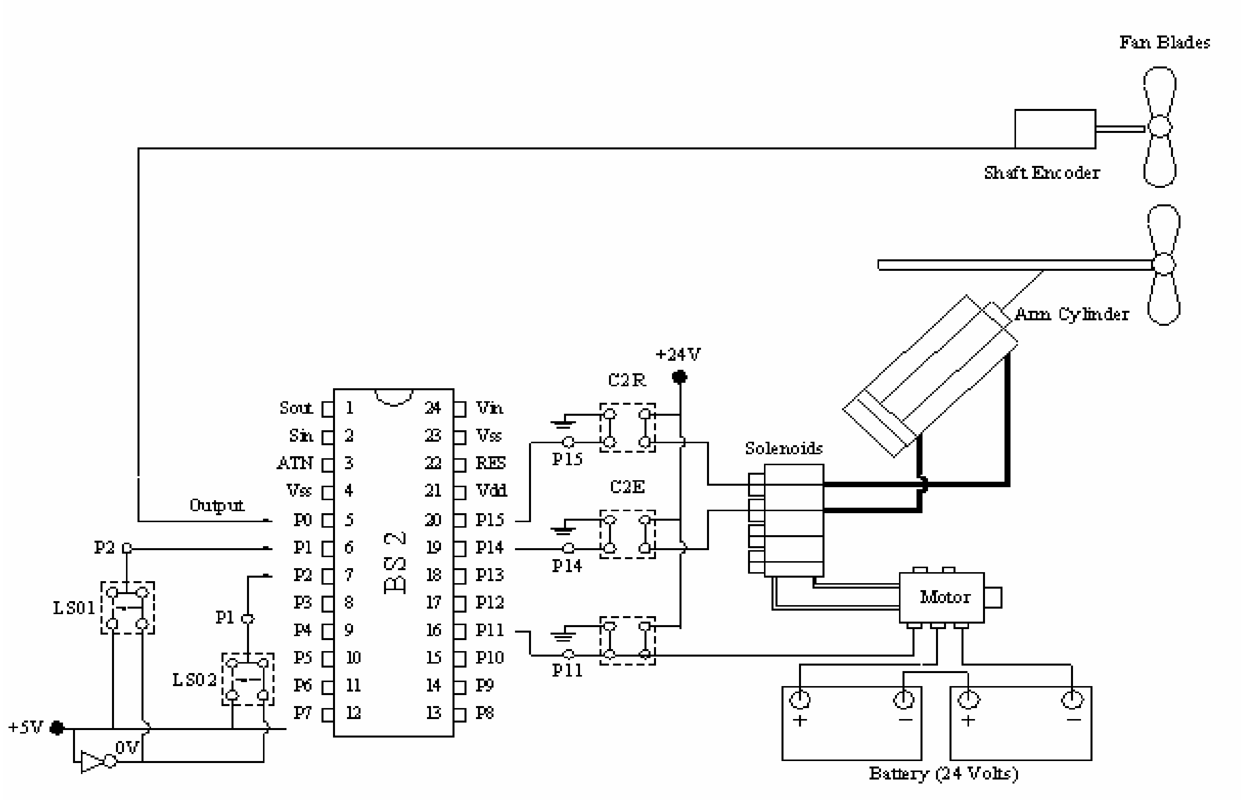


Figure 5 Arm Control using Fan Blades Experiment Set-up

Table 3. Arm Control Rule using Actual Fan Blades and Industrial Fan

Arm Control 'On/Off' Function		Arm Control with feedback	
Shaft speed (RPM)	Output:	Shaft speed (RPM)	Output:
< 400	Turbine on until arm is parallel to ground	< 480	Turbine on until arm is parallel to ground
>= 400 and <= 800	No action	>= 480 and > 1020	Raise nacelle assembly for 0.75 seconds
> 800	Turbine off until arm is perpendicular to ground	>= 1020 and <= 1620	Steady -> no response
		> 1620 and <= 2220	Lower nacelle assembly for 0.75 seconds
		> 2220	Turbine off until arm is perpendicular to ground

Table 4. Arm Control using Fan Rotor Program Results

Arm Control 'On/Off' Function			Arm Control with feedback		
Run No.	RPM	Turbine Action	Run No.	RPM	Turbine Action
1	900	Turbine off	1	150	Turbine on
2	360	Turbine on	2	1756	Soft Turbine off
3	478	no response	3	1365	no response
4	820	Turbine off	4	1868	Soft Turbine on
5	800	no response	5	2508	Turbine off
6	812	no response	6	440	Turbine on
7	846	no response	7	1080	no response
8	386	Turbine on	8	1660	Soft Turbine off
9	568	no response	9	2278	Turbine off
10	419	no response	10	260	Turbine on

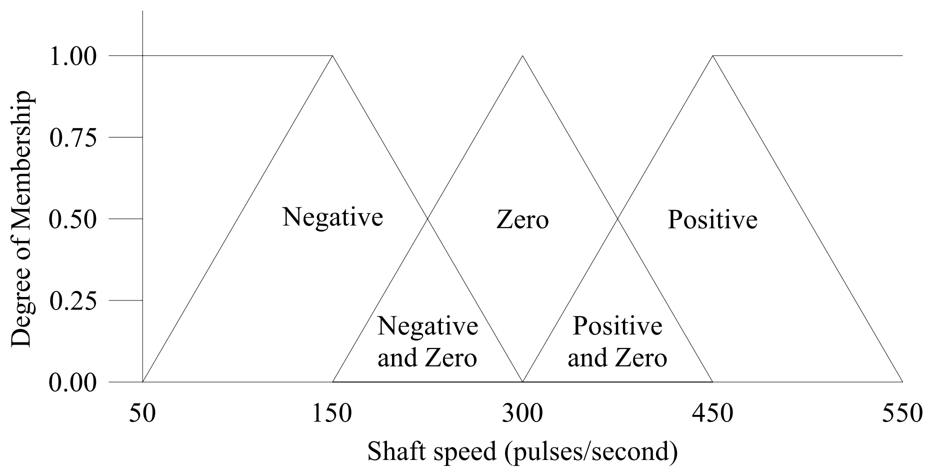


Figure 6. Shaft Speed Membership Function

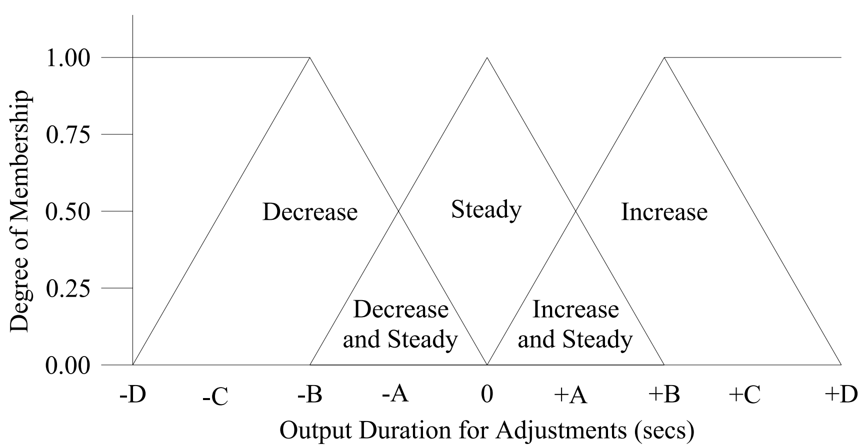


Figure 7. Percent Output Membership Function

2.3 Pitch Control Experiments

Same as the experiment done on Arm control, the blade pitch control was also tested using DC motor simulation. The experiment set-up for this testing is also the same as that of DC motor simulation for the Arm control, except that the outputs were forwarded to the control valves that control the blade pitch cylinder. Table 5 shows the result of the experiment. From there, we can see that the microcontroller unit (MCU) gives the correct adjustment for the blade pitch angle given any variation in wind speed.

Table 5. Pitch Control Program Results using DC motor Simulation Testing

Run No.	RPM1	RPM2	Result	Output Response/Pitch Action	Corresponding Angle (with respect to axial plane of the shaft)
1	493	497	1	Totally close	-45°
2	769	2098	100	Extend for 1000 ms	-23.57°
3	2101	4179	200	Totally open	45°
4	4886	4230	100	Retract for 1000 ms	23.57°
5	2798	2532	109	Extend for 500 ms	34.28°

Although the DC motor simulation testing proved that our Pitch control really works, the proponents observed that this kind of testing was not enough as basis for conclusion. So a worksheet model was created using Microsoft Excel that simulates the Fuzzy Logic program for the Pitch Control. Using the Windpro Automation tool, the proponents were able to set different membership functions for the Fuzzy Logic-based pitch control program, to see the resulting RPM after FZ applied an adjustment. The best membership function for the final Pitch control program was selected. Figures 6 and 7 show the membership function for the FZ with the time constants as variables while Figure 8 tallies the different time constraints that tells the duration for the each membership function. Figure 8 also shows the results of the test after running them through 50 different variations in rotor speed using the Windpro automation tool.

Table 6. Summary of the Results using Theoretical Fuzzy Logic Simulation

Time before reading RPM2	Result times (sec.)	Total Recovery Time (sec.)	Average Recovery Rate (sec. / hydraulic action)	Open-Close-Open Cases	Average RPM	# of Errors in the Program	Closeness to Desired RPM
1	0.5, 0.6, 0.8, 1	97.2	2.113043478	64	300.826	8	46.4109
1	0.5, 0.7, 0.9, 1.1	109.3	2.325531915	63	294.575	3	46.0960
1	0.5, 0.7, 1, 1.2	111.2	2.417391304	63	294.752	2	45.3611
1	0.5, 0.6, 0.7, 0.8	84.2	1.718367347	71	295.641	1	43.9542
1	0.5, 0.8, 1, 1.2	123.8	3.019512195	64	296.143	3	48.2525
1	0.5, 0.6, 0.9, 1.1	99.9	2.08125	63	297.331	1	45.0867
2	0.5, 0.6, 0.8, 1	97.2	2.113043478	64	302.645	4	51.5955
2	0.5, 0.7, 0.9, 1.1	109.3	2.325531915	63	295.807	5	50.0515
2	0.5, 0.7, 1, 1.2	111.2	2.417391304	63	295.739	2	49.4626
2	0.5, 0.6, 0.7, 0.8	84.2	1.718367347	71	296.812	3	47.5564
2	0.5, 0.8, 1, 1.2	123.8	3.019512195	64	297.484	2	52.1676
2	0.5, 0.6, 0.9, 1.1	99.9	2.08125	66	298.739	3	49.2157
3	0.5, 0.6, 0.8, 1	97.2	2.113043478	64	303.213	7	55.0987
3	0.5, 0.7, 0.9, 1.1	109.3	2.325531915	63	297.036	8	53.9970
3	0.5, 0.7, 1, 1.2	111.2	2.417391304	63	296.727	2	53.5615
3	0.5, 0.6, 0.7, 0.8	84.2	1.718367347	71	297.98	1	51.1473
3	0.5, 0.8, 1, 1.2	123.8	3.019512195	64	298.822	3	56.0729
3	0.5, 0.6, 0.9, 1.1	99.9	2.08125	63	300.144	1	53.3345

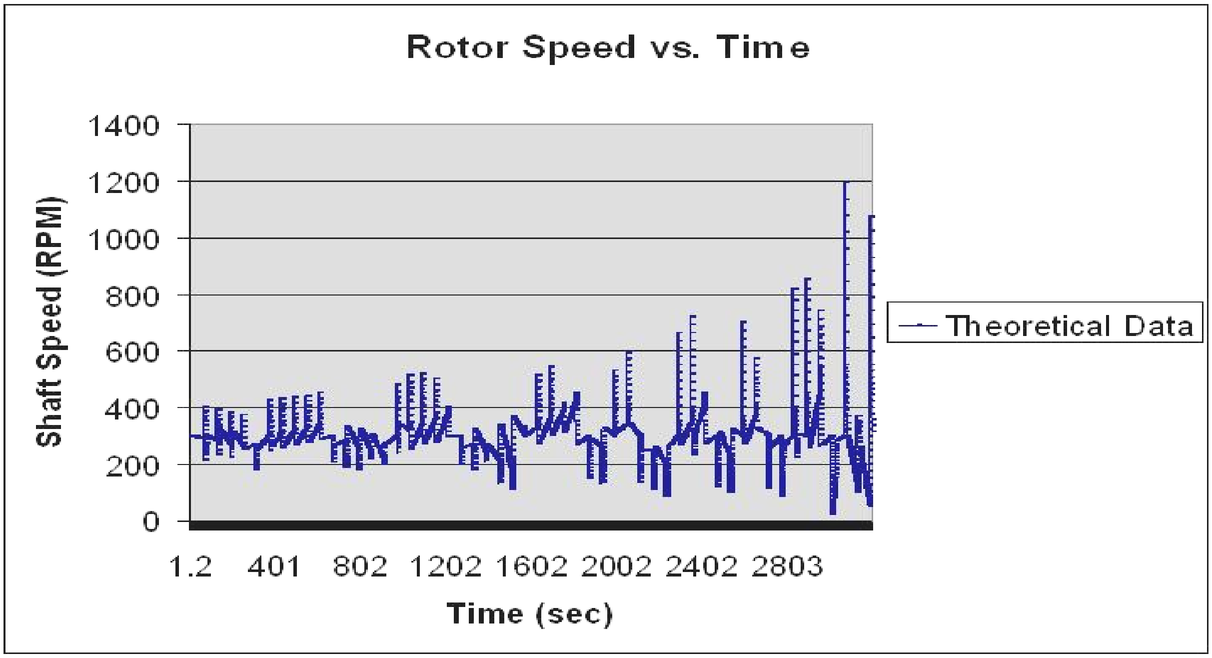


Figure 8. Result: FZ – Combination # 6

By looking at the results of the experiment using the Windpro Automation tool, it can be seen that the 6th combination gave the overall best results. The membership function set was able to maintain the rotor speed at 300RPM with average error of ±3RPM. Also, it has a good recovery rate of about 2 seconds.

The last experiment performed to test if the Pitch control really works was the Miniature wind turbine testing. Figure 9 shows the result of the experiment. Three runs were made to a turbine with fan blades and with pitch mechanism that operates in the same manner as that of the actual set-up. The source of wind was an industrial with three varying speeds. At some parts of the graph, we verified that as the distance traveled for pitch adjustment decreases, the blade pitch angle increases and the resulting rotor speed decreases because the smaller percentage of the amount of energy from the wind was captured by the blades. However, the result also appeared to have some errors because at some point in time, the resulting RPM showed an abnormal response to the changed applied in the blade pitch angle. Also, errors have caused two different graphs or results for wind speed of 6.4m/s.

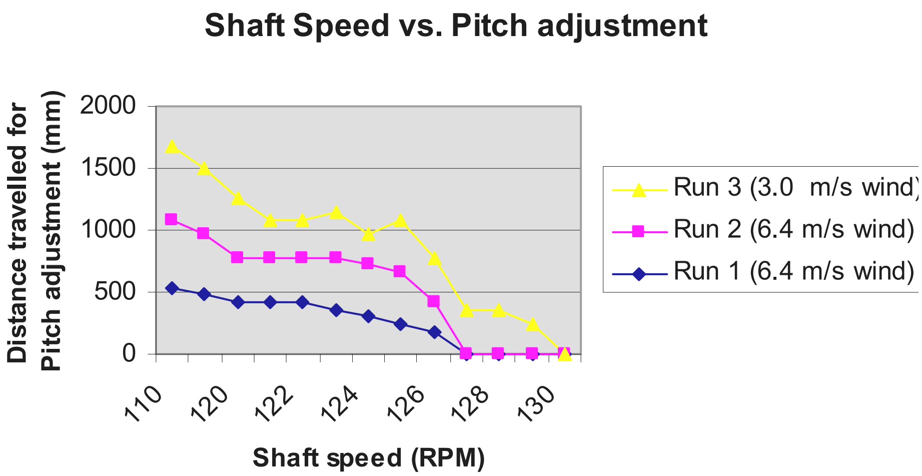


Figure 9. Fan Blade Pitch Angle Experiment

3.0 Conclusion

The effectiveness of the BS 2 microcontroller as a medium for the automation of the wind turbine was proven to be successful. Since actual testing cannot commence, two scaled-down wind turbines using standard electric fan blades were created. Further, experiments were done utilizing DC Motor simulation, the use of standard electric fan blades for actual testing, and testing through our self-made automation tool for pitch automation.

The arm control was tested using a DC motor simulation and Miniature fan blade testing. A separate experiment was also done for the limit switches and it was proven to be effective. By varying the speed of the DC motor and varying the speed level of an industrial fan, the microcontroller was effective in moving the turbine assembly to its required position without any delay. Also, it was discovered that by applying feedback to the Arm Control, the wind turbine rotor can still absorb smaller amounts of wind energy by diverting the rotor surface area to the direction of the wind. Hence, the wind turbine can harness as much wind energy while the safety function is considered. This arm control with feedback may be impractical to apply, but the results of the experiments show that this is possible for yaw control.

The experiment for the pitch control was also performed using the DC motor simulation and Theoretical Fuzzy Logic Simulation. The values for rpm and deltarpm were then evaluated by the fuzzy logic program to give one final crisp output as defined by the variable Result. The Result is then defuzzified to give the corresponding output response for the pitch mechanism. From the results in the Table 5, it can be seen that the microcontroller and the fuzzy logic program were able to give the necessary reaction for the pitch mechanism. Moreover, the microcontroller was able to move the pitch mechanism without any delay. The values for the time are computed in such a way that it is proportional to distance that the hydraulic cylinder can traverse from its center position down to its maximum/minimum position.

From the results of the experiments (both arm and pitch control), it can be concluded that the hydraulic control system designed using microcontroller was able to control the pitch and arm angles of the windmill. The hydraulic control system was done successfully and proven to be effective.

An automated windmill was also fabricated successfully. And since the dimensions were based on the actual Windpro Model C turbine, the fabricated parts for the automation can be installed to the said wind turbine.

REFERENCES

Cabebe, 2004. Cross Flow Turbine Speed Control Using Fuzzy Logic and Microcontroller. Undergraduate thesis, De La Salle University.

Cabrera, M.I. and T. Lefevre. 2002. Wind Power in Southeast Asia. Centre for Energy Environment Resources Development, Bangkok Thailand. http://www.asemgreenippnetwork.net/dsp_page.cfm?view=page&select=97

De Leon, M. D. et. al. (2004). Design, Fabrication and Testing of Automated Wind Power Dynamo Made of Composite Material. Undergraduate thesis, De La Salle University.

Golten, Jack and Andy Verwer. 1992. Control System Design and Simulation. McGraw-Hill Book Company Ltd., Singapore. pp. 1-2

Predko, Myke. 1999. Programming and Customizing the 8051 Microcontroller. McGraw-Hill Companies, Inc., USA. p. xiii, 3

Petruzzellis, Tom. 2003. Stamp 2 Communications and Control Projects. McGraw- Hill Companies, Inc., USA. p. 1

A Market Highlights and Best Prospects. October 2004. http://strategis.ic.gc.ca/epic/internet/inimr-ri.nsf/en/gr-77201e.html

Green, William. 1998. An Introduction to Fuzzy Logic Controllers in the LabView Environment. Argonne National Laboratory. http://www.ni.com/

http://www.ata.org.au/basics/basbatts.htm

http://www.suzlon.com/2_MW_Technical_description.htm#controlsys

http://www.tauernwind.com/windenergie_e/windenergie_tech_e.htm#

Introduction to Wind. http://www.mrsolar.com/Merchant2/merchant.mvc?Store_Code=MSOS&Screen=faq25

Nygaard, G. Climate an Introduction. http://www.squ1.com/index.php?http://www.squ1.com/climate/wind-speed.html

Wind Power and Windmills. http://earthsci.org/energy/wind/wind.html#Electricity%20and%20Storage%20of

Wind Turbines for Home Power. 2004. http://www.absak.com/basic/wind-power.html

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