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YURIKÓ OZAKI
DESIGN OF THE ROBOTIC SELF-TRAVELLING SPRINKLER SYSTEM
M.S.c BY RESEARCH THESIS
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THESES
1999

DEPARTMENT: PRECISION FARMING
SUPERVISOR: SIMON BLACKMORE

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Abstract

A conventional rain gun system is adversely affected by windy conditions. Therefore, the robotic self-travelling sprinkler (STS) system that controls the head and the water supply with relation to instant windy conditions.

The robotic STS head has two degrees of freedom; sector and trajectory angles, driven by stepper motors to follow the control model, which are found by applying prediction models of water distribution, Centre of volume and Semi-empirical models. As a result, it was shown that the control for the sector angle compensated for the horizontal water distortion from wind, however, the trajectory angle was found to need more data to model the optimum trajectory angle.

To control the water supply, a cut-off solenoid valve was installed and shut when wind was over 6 m/s upwind and 7 m/s downwind. This indicated that the trajectory angle was less than 10 degrees above horizontal. Under such windy conditions, water can not be distributed as far from the STS as required or becomes spray, which cannot reach to the ground. As the experimental results showed, the system enabled to minimize the commercially ineffective water distribution.

A chemigation system was added, which can injects chemicals into the main water flow. The system enables farmers to save the cost for extra chemigation equipment.

The process of the system while working can be checked by the interactive communication system between the embedded computer and the user's computer. Therefore, this system made the robotic STS system more reliable, furthermore, it enabled the user's computer to read and save the data sent from the field controller unit.

This robotic STS system can distribute water or chemicals to the required area, even if up to the irregular boundaries,(fence lines, corners of fields), with the minimum water supply. Also, the system is ready to incorporate treatment maps and DGPS. In other words, it is possible to feed the adequate amount of water or chemicals which varies depending on the different regions of fields, species of plants, and seasons.

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I also would like to thank to P.h.D students for their help with my experiments.

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Table of Contents

Abstract	I
Acknowledgement	II
Table of Contents	III
Table of Figures	IV
Table of Tables	V
List of Test and Control programs on the CD	VI
1. Introduction	1
1.1 Background	1
1.2 Introduction to the robotic STS system	4
1.2.1 <i>Advantages of the robotic STS system</i>	4
1.2.2 <i>The outline of the robotic STS system</i>	4
1.3 Hypothesis	8
1.4 Aim	8
1.5 Objectives	8
2. Design of the Robotic STS Head	9
2.1 Introduction to the robotic STS head design	9
2.2 Design	11
2.2.1 <i>Specifications</i>	11
2.2.2 <i>Material</i>	14
2.2.3 <i>Rotating joints</i>	15
3. Development of Hardware	16
3.1 Motors and Gearboxes	16
3.1.1 <i>Motors</i>	16
3.1.2 <i>Driver Board</i>	17
3.1.3 <i>Gearbox</i>	20
3.2 Field controller unit	20
3.2.1 <i>Introduction to the embedded computer</i>	20
3.2.2 <i>TB486 PC/104 Target card PC compatible computer</i>	21
3.2.3 <i>TP406 PC/104 Digital I/O Counter/Timer board</i>	22
3.2.4 <i>TPO24 PC/104 OPT-Isolated Digital I/O board</i>	25
3.3 Sensors	27
3.3.1 <i>Wind vane</i>	27
3.3.2 <i>Anemometer</i>	29
3.3.3 <i>Pressure Transducer</i>	30
3.3.4 <i>Motor position micro-switches</i>	32

3.3.5	<i>Cut-off Valve</i>	32
3.3.6	<i>Chemigation pump</i>	33
3.3.7	<i>Environmental protection</i>	34
3.4	Position	39
3.4.1	<i>Dead reckoning</i>	39
3.4.2	<i>DGPS</i>	40
4.	Development of Software	41
4.1	Introduction to Software	41
4.2	Main modules of control programs	42
4.2.1	<i>Motor control program</i>	42
4.2.2	<i>Reading data function</i>	45
4.2.3	<i>Calculation of the optimum angles</i>	46
4.2.4	<i>COM1 communication between the embedded computer and the user's PC</i>	47
4.3	The structures of main control programs	49
4.3.1	<i>MAINSTIL.C</i>	49
4.3.2	<i>MAIN50X.C</i>	51
4.3.3	<i>MAINGPS.C</i>	55
5.	Prediction and Control models	57
5.1	Introduction to models	57
5.1.1	<i>Centre of volume model – C.V. & Semi-empirical model</i>	57
5.1.2	<i>Multi phase model</i>	59
5.1.3	<i>Introduction of the prediction and control models</i>	59
5.2	Experiment for prediction models	60
5.2.1	<i>Experimental design</i>	60
5.2.2	<i>Results –Uncontrolled</i>	61
5.3	Sector angle	62
5.3.1	<i>Prediction model of the sector angle</i>	62
5.3.2	<i>Equation of the optimum sector angle</i>	63
5.4	Trajectory angle	65
5.4.1	<i>Prediction model of trajectory angle</i>	65
5.4.2	<i>Equations of the optimum trajectory angle</i>	66
6.	Results of the controlled operations and Discussion	68
6.1	Data of the first set	68
6.2	Data of the second experiment	73

7. Conclusion and Recommendation	78
7.1 Conclusion	78
7.2 Recommendation	79
7.2.1 <i>The structure</i>	79
7.2.2 <i>System</i>	79
Appendix I	81
Design of the robotic STS by CAD	82
Assembly	89
Appendix II	91
Data_uncontrolled_02-05	92
Data_controlled_02-05	96
Data_controlled_12-15	100
Appendix III	104
How to use the main control programs	105
Appendix IV	106
References	107

List of Figures

Fig.1-1: The prototype of the robotic STS system	2
Fig.1-2: The flow chart of the prototype control system	3
Fig.1-3: The robotic STS	5
Fig.1-4: The structure of the robotic STS system.	6
Fig.2-1: The picture of the robotic STS system	10
Fig.2-2: All parts of the robotic STS system	11
Fig.2-3: A shaft bolt	12
Fig.2-4: Micro switch pin on Main Part 4	13
Fig.2-5: The hysteresis of the motor position micro switch.	13
Fig.3-1: The configurations of motors.	16
Fig.3-2: Unipolar stepper motor drive board connections.	18
Fig.3-3: The electric circuit of motors, motor drivers, power supply.	19
Fig.3-4: The connection of the wind vane between the sensor and the sensor board	28
Fig.3-5: The connection of the wind vane between the sensor board and the main board.	28
Fig.3-6: The connection between the anemometer and the main board.	29
Fig.3-7: The connection between the pressure transducer and the controller box.	30
Fig.3-8: The electric connection in the controller box.	31
Fig.3-9: The calibration of the output frequency to the output voltage from the pressure transducer.	31
Fig.3-10: Motor rotate position micro switch.	32
Fig.3-11: The system of the solenoid valve.	33
Fig.3-12: The connection between the valve and the Main board.	33
Fig.3-13: The connection between the pump and the Main board.	33
Fig.3-15: Control box	34
Fig.3-15: The electric circuit of the Main board.	35
Fig.3-16: The electric circuit of the sensor board.	36
Fig.3-17: The electric circuit of the PC connector board.	37
Fig.3-18: Driver board	38
Fig.3-19: The electric circuit of the regulator board.	38
Fig.3-20: Heat sinks for regulators (right) and motor resistors (left).	39

Fig.3-21: Wheel micro switch	39
Fig.4-1: The structure of MIANSTIL.C	50
Fig.4-2: The structure of MAIN50X.	53
Fig.4-3: The structure of MAINGPS.C.	56
Fig.5-1: The format of the water distribution.	57
Fig.5-2: Maximum radius of throw of 3.4mm drop as function of trajectory angle.	58
Fig.5-3: Optimum trajectory for maximum upwind distance of throw.	59
Fig.5-4: The scene of the field experiment.	61
Fig.5-5: The wind condition and water distribution of Data_Uncontrolled_01.	62
Fig.5-6: The horizontal shift of Center of volume to horizontal wind speed.	63
Fig.5-7: Geometric model of the shift of a center of volume.	64
Fig.5-8: The real Y value of Center of volume to the average wind speed.	65
Fig.5-9: The optimum trajectory angle (degrees) to wind speed (m/s) at downwind.	67
Fig.6-1: The water distribution and the cumulative wind data.	69
Fig.6-2: The rate of water distribution and the value at X=0.	69
Fig.6-3: The water distribution and the cumulative wind data of Data_Controlled_11.	74
Fig.6-4: The rate of water distribution and the value at X=0 of Data_Controlled_11.	74
Fig.6-5: The relationship between total amount of water and the rate of data number which indicate over 6 m/s upwind, 7 m/s downwind.	77
Fig.I-1: Main part 1	82
Fig.I-2: Main part 2,5	83
Fig.I-3: Main part 3	84
Fig.I-4: Main part 4	85
Fig.I-5: Main part 6	86
Fig.I-6: Nozzle	87
Fig.I-7: Gearbox plates	88
Fig.I-8: Step 1	89
Fig.I-9: Step 2	89
Fig.I-10: Step 3	90
Fig.I-11: Step 4	90
Fig.I-12: Step 5	90
Fig.II-1: Data_uncontrolled_02	92
Fig.II-2: Data_uncontrolled_03	93
Fig.II-3: Data_uncontrolled_04	94

Fig.II-4: Data_uncontrolled_05	95
Fig.II-5: Data_controlled_02	96
Fig.II-6: Data_controlled_02	97
Fig.II-7: Data_controlled_02	98
Fig.II-8: Data_controlled_02	99
Fig.II-9: Data_controlled_12	100
Fig.II-1: Data_controlled_13	101
Fig.II-1: Data_controlled_14	102
Fig.II-1: Data_controlled_15	103

List of Tables

Table 2-1: Comparison among four available materials	15
Table 3-1: Main features of motors	16
Table 3-2: Technical specifications of unipolar motor driver.	17
Table 3-3: The adequate value of R	18
Table 3-4: The main features of the gearbox	20
Table 3-5: TP406 address map for parallel I/O	23
Table 3-6: Pin assignments of Digital I/O on TP406.	23
Table 3-7: Register assignment of Counters/Timers on TP406.	24
Table 3-8: Pin assignments of Counters/Timers on TPO24.	25
Table 3-9: Offset addresses of registers on TPO24.	26
Table 3-10: Pin assignment of Digital I/O on TPO24.	27
Table 3-11: Main specifications of Wind Vane.	28
Table 3-12: Main specifications of the anemometer.	29
Table 3-13: The features of the pressure transducer, MODEL DA 100PSIA.	30
Table 4-1: The list of main modules in control programs.	41
Table 4-2: A list of functions in 2m_vp12.C	42
Table 4-3: Set numbers for timer interrupt.	43
Table 4-4: The output number for the frequency of the interval timer.	43
Table 4-5: Output numbers for controlling peripheral devices.	45
Table 4-6: A list of functions in Cnt_avg.C	45
Table 4-7: A list of functions in Calc_posX.C	47
Table 4-8: The list of functions in com1wrrd.c	48
Table 4-9: The list of functions in Read1.C.	48
Table 4-10: The list of modules in readgps.c.	55
Table 5-1: The results under the uncontrolled operation.	61
Table 5-2: $X_{predicted}$ and X_{real} of C.V. under the uncontrolled operations.	63
Table 6-1: The average wind data and the rate of water distribution at $X=0$, X of the maximum water distribution.	68
Table 6-2: The values of controlled and predicted C.V. in the first experiment.	68
Table 6-3: The data of Data_controlled_01.	69

Table 6-4: ANOVA between the mean of $X_{0\text{ predicted}}$ and the mean of $X_{0\text{ controlled}}$.	70
Table 6-5: The values of the compensated C.V. for motor position micro switch.	71
Table 6-6: ANOVA between the mean of $X_{0\text{ compensated}}$ and the mean of $X_{0\text{ predicted}}$.	71
Table 6-7: ANOVA of $Y_{0\text{ predicted}}$ and $Y_{0\text{ controlled}}$.	72
Table 6-8: The average wind data and the rate of water distribution at $X=0$, X of the maximum water distribution.	73
Table 6-9: The values of controlled and predicted C.V. from the second experiment.	73
Table 6-10: The data of Data_controlled_11.	74
Table 6-11: The average of $X_{1\text{ controlled}}$ and $X_{1\text{ predicted}}$.	75
Table 6-12: ANOVA of the mean of $X_{1\text{ controlled}}$ and that of $X_{1\text{ predicted}}$.	75
Table 6-13: The data of $Y_{1\text{ controlled}}$ and $Y_{1\text{ predicted}}$ and their averages from the second experiment.	75
Table 6-14: ANOVA between the mean of $Y_{1\text{ controlled}}$ and that of $Y_{1\text{ predicted}}$ from the second experiment.	76
Table 6-15: Total amount of the collected water in the uncontrolled experiment.	76
Table 6-16: Total amount of the collected water in catch cans in the second experiment.	76

List of Test and Control programs on the CD

Directory	File name	Contents
Main:\	2m_vp12.c 2m_vp1.h	Control motors
	cal_pos1.c cal_pos2.c cal_pos3.c cal_pos4.c cal_pos5.c	Calculate the optimum trajectory and sector angles. Confirm the position, 27 degrees for trajectory, 90 degrees for sector.
	Cnt_avg.c Cnt_tavg.c	Read the data, pressure, wind speed, wind direction.
	Ini.c Ini.h	Initialize ports on the Tp406 and Tpo24.
	Ini_p12.c Ini_pos1.c	Initialize the positions of trajectory and sector angles.
	Main.h Main503.c Main504.c Main505.c Main503.exe Main504.exe Main505.exe	Main programs.
	Micros.h Micros.c	Read the signals from microswitches.
	Opt_24.h	Header file for ports on Tpo24.
	Set_pres.c	Set water pressure.
	Tpo406io.h	Header file for ports on Tp406.

Mainstil:\	2m_vp.c 2m_vp1.h	Control motors.
	Cnt_avg.c Cnt_tavg.c	Read the data, pressure, wind speed, wind direction.
	Ini.c Ini.h	Initialize ports on the Tp406 and Tpo24.
	Ini_p12.c Ini_pos1.c	Initialize the positions of trajectory and sector angles.
	Main.h Mainstil.c Mainstil.exe	Main programs.
	Micros.h Micros.c	Read the signals from micro switches.
	Opt_24.h	Header file for ports on Tpo24.
	Set_pres.c	Set water pressure.
	Tpo406io.h	Header file for ports on Tp406.

Maingps:\	2m_vp1.c 2m_vp1.h	Control motors.
	Bstring.h Bstring.lib	Header and library for
	Clr_io.c	Clear I/O ports
	Calc.c	Calculate the position in meter.
	Cnt_avg1.c Cnt_tavg.c	Read the data , pressure, wind direction, wind speed.
	Com1wrrd.c	Communicate with external computers.
	Commes.c Commes.h Commes.exe	Set up a com port.
	Extract.c Extract.h	Extract the numerical data from strings.
	Gps.c Gps.h	Read the strings from the aerial.
	Ini.c Ini.h	Initialize ports on Tp406 and Tpo24.
	Ini_posi.c	Initialize the positions of the STS head.
	Litecomm.h Litecomm.c Litecomm.fns	Set up com ports.
	Main.h Mf.h Main-gps.c Main-gps.prj	Main programs.
	Micros.h Micro.c	Read signals from micro switches.
	Opt24.h	Header file for Tpo24.
	Readgps.c	Main file for reading GPS.
	Set_pres.c	Set water pressure.
	Tccomms.lib	Library for com ports
	Tpo406io.h	Header file for Tp406.

Program:\Test:\	Test_24inp.c	Test program for input ports on TPO24.
	Test_406.c	Test program for I/O ports on TP406.
	Testr_lpt.c	Test program for LPT port.
	Test_m1.c	Test program for motor 1.
	Test_m2.c	Test program for motor 2.
	Test_ms.c	Test program for micro switches.
	Test_pum.c	Test program for pump.
	Test_rti.c	Test program for a Real Time Clock on TB486
	Test_val.c	Test program for valve.
	Test_24op.c	Test program for output port on TPO24.
	Test_save.c	Test program for saving data.

Program:\Interact:\	com1rd.c com1rd1.c	Test program for reading data from external computer.
	com1rdwr.c	Test program for communication between two computers, read and write.
	com1wrrd.c	Test program for communication between two computers, write and read.
	Read1.c Read2.c	Program for reading string data from the embedded computer.
	Ini_p232.c	Test program for communication between the user's and embedded computers with a control program for initializing the rotate position.
	Freecomm.c Freecomm.h Freecomm.exe	An example program for Rs232 communication
	Rs232.c Rs232.h	An example program for RS232 communication in Assmenbler.

Program:\Control:\	2m_spd_c.c 2m_v_p.c Ini_posi.c	Test programs for checking motors.
--------------------	--------------------------------------	------------------------------------

Program:\Gps:\	Bstring.h Bstring.lib	Header and library file for dealing with strings.
	Calc.c Calc.h	Calculate the position in meter <i>meters</i>
	Calctest.c	Test program for calculating the position in meter. <i>meters</i>
	Commes.c Commes.h Commes.exe	Open and close a com port.
	Extract.c Extract.h	Extract the numerical data from strings.
	Gps.c Gps.h	Read the strings from the aerial.
	Ini.c Ini.h	Initialize ports on Tp406 and Tpo24.
	Ini_posi.c	Initialize the positions of the STS head.
	Litecomm.h Litecomm.c Litecomm.fns	Set up com ports.
	Main_ini.c Main_ini1.c Main_ini.prj	Main programs for reading Gps and controlling the steering of the vehicle.
	Mf.h Main Mf_19.c Mf_19.prj	Main program for GPS.

	Save.c Save.h	Save the position data
	Screen.c Screen.h	Display the data
	Test_adc.c Test_dir.c Test_dri.exe Test_gps.c Test_gps.prj Test_gps.exe	Test program for A/D converter on TB486. Test program for controlling the steering. Test program for reading GPS.
	Tccomms.lib	Library file

1. Introduction

There is an increasing demand on agriculture to minimize the amount of input resources, which has encouraged for the development of a new field of agriculture called Precision farming. Precision farming is distinct from the existing farming techniques in that it applies the state-of-the-art technology to compensate for both natural and human variability.

The effectiveness of a conventional rain-gun system is reduced by wind, which distorts the wetted area. The water distribution pattern under windy conditions is a well-researched area and many models exist (Center of volume model, Semi-empirical model, etc). Therefore, this study used some of the models to help design a new head of a self-travelling sprinkler (STS), which is called the robotic STS head. This head was controlled with two degrees of freedom to compensate for wind-induced water distortions by applying mechatronics.

STS was chosen as the object of this research owing to the popularity in Europe. However, the size of STS in commercial culture, is much larger than the one used in this study.

Finally, this study has a conjunction to the Ph.D thesis of Turker (1997). It sometimes needs to refer to the thesis.

1.1 Background

A self-travelling sprinkler is an irrigation machine that can move by itself while distributing water. Turker (1997) built a sprinkler head system to compensate for the water distortion from wind. The system succeeded to reduce the distortion under windy conditions. The self-travelling sprinkler used for this study was the same as the one used by Turker. It was composed of a sprinkler head on a wheeled carriage. A cable is anchored in the end of the field, which is drawn by a hydraulic motor. The prototype figure is shown in Fig. 1-1 and also the control system in Fig.1-2.

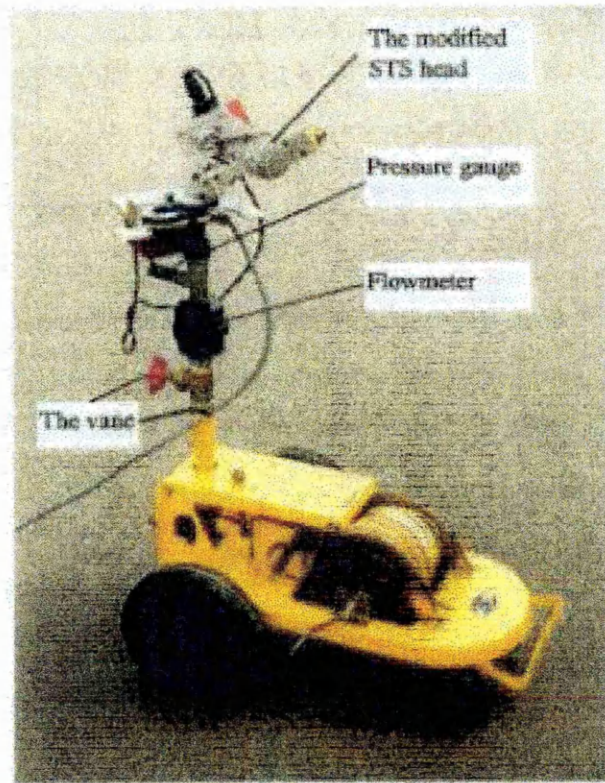


Fig.1-1: The prototype of the robotic STS system
Turker (1997); Precision irrigation using self-travelling sprinkler.

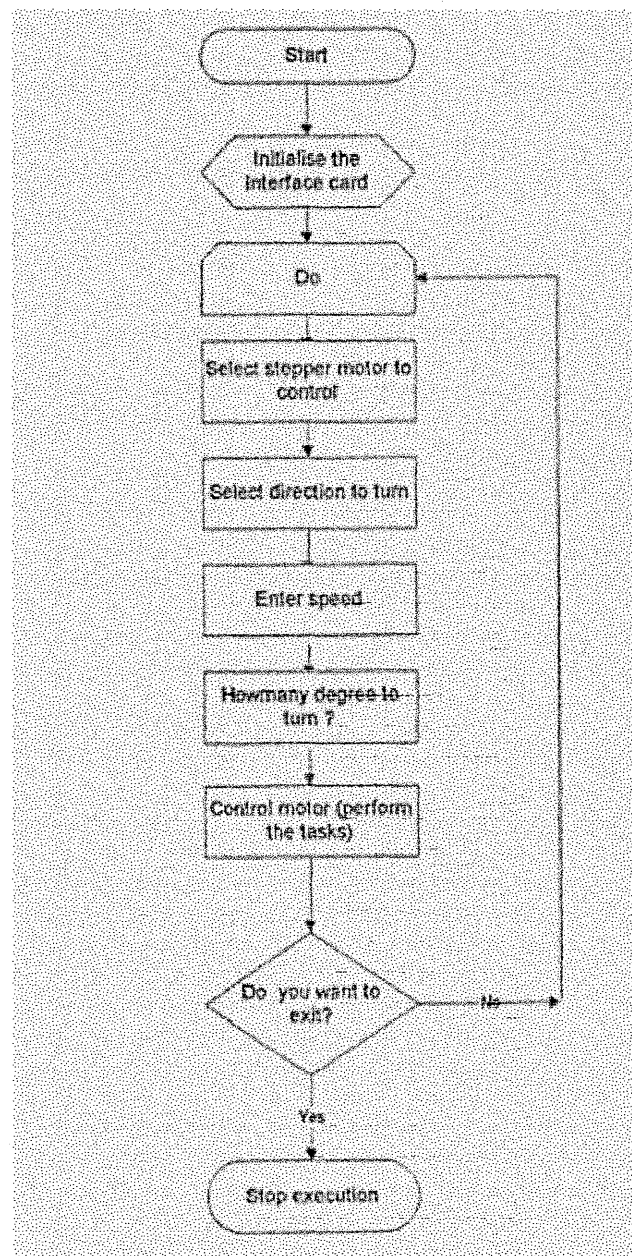


Fig.1-2: The flow chart of the prototype control system
Turker (1997); Precision irrigation using self-travelling sprinkler.

As the result showed, the system made it possible to decrease the distortion of water distribution by 40% with the control system as compared to the uncontrolled system. However, several points in hardware and software were improved. This made the system run more accurately and it was also better to catch up with recent devices used in precision farming, for example, vegetation

maps, GPS, etc. Therefore, the prototype sprinkler was redesigned to be the new robotic STS system introduced in Section 1.2 and 1.3.

1.2 Introduction to the robotic STS system

1.2.1 Advantages of the robotic STS system

This robotic STS system has several advantages:

- 1) The STS head is controlled instantaneously to correct the water distortion from the wind with relation to the wind speed and direction. In addition, the water supply is shut down when the wind becomes too strong to let this system run commercially efficiently.
- 2) Using the experimental and mathematical models of water behavior out of a sprinkler, the system enables water to be distributed to the required area, even if up to irregular boundaries, for example, fence lines, corners of fields, virtual field boundaries.
- 3) This system is able to feed liquid fertilizers and chemicals into the field without any other additional equipment. This enables farmers to save costs and work.
- 4) The data of treatment maps can be introduced to the models of the STS head controlled by reckoning the position with both a DGPS or dead reckoning system. In other words, it is possible to feed adequate amount of water or chemicals, which vary in the regions of the field, species of plants, seasons.

1.2.2 The outline of the robotic STS system

This system has two motors which are controlled by an embedded computer to compensate for water drift from wind. The feature of the robotic STS system is shown in Fig.1-3. In reference to the structure of the system described in Fig.1-4, the labels are explained.

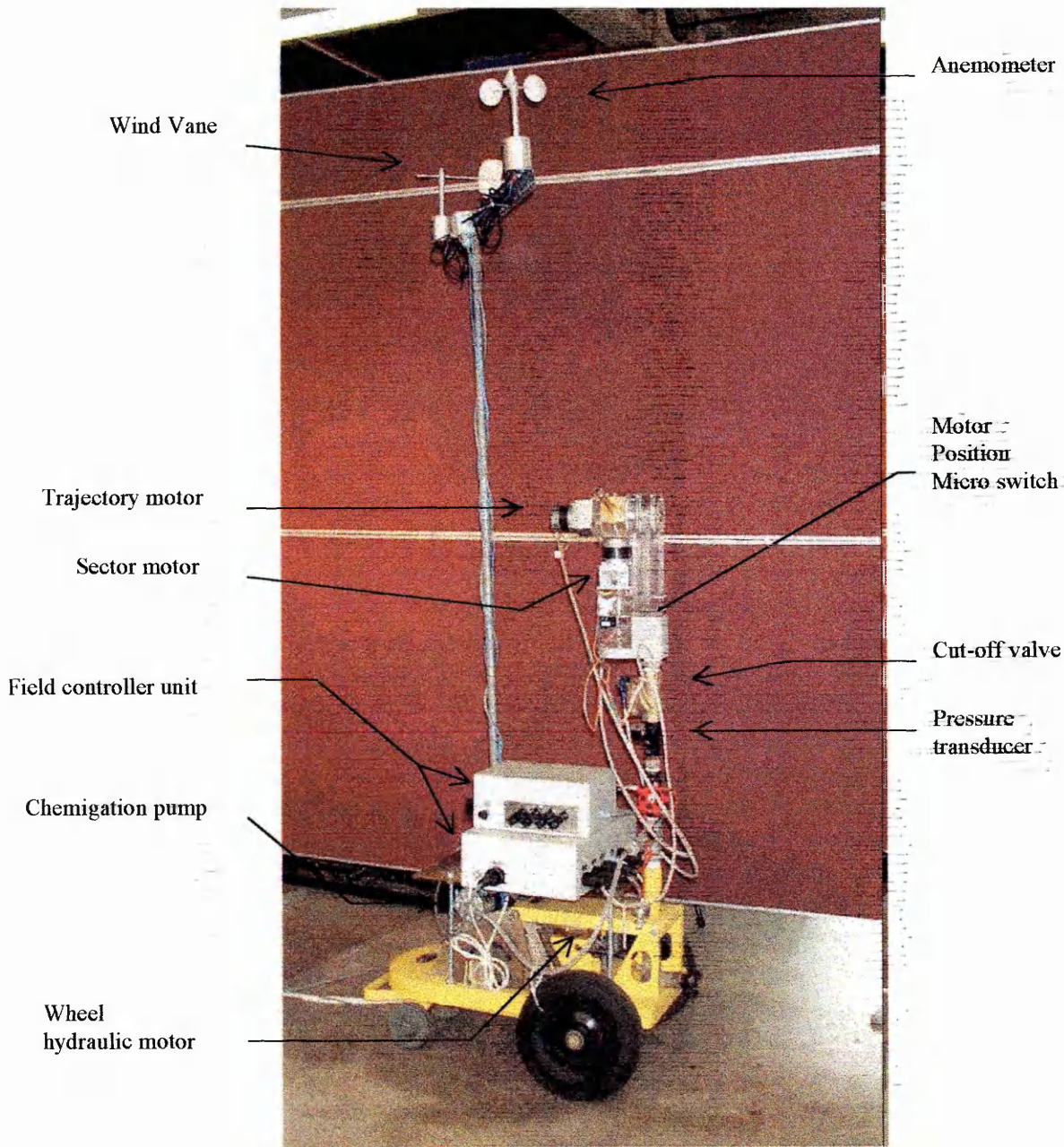


Fig.1-3: The robotic STS

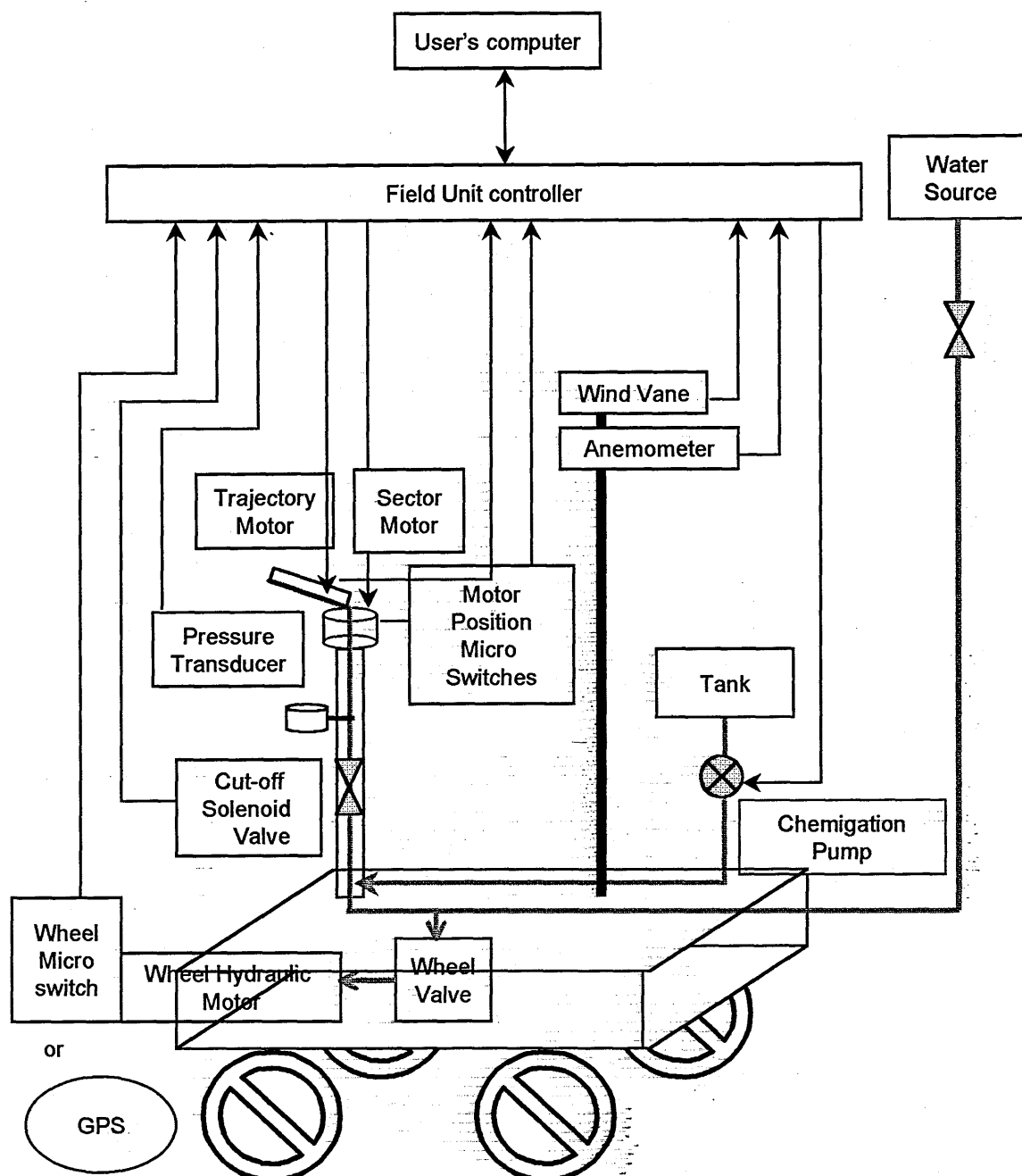


Fig.1-4: The structure of the robotic STS system.

- User's computer

Connected to the field controller unit by an RS232, the user's computer functions to display the data, strings from the field unit and saves it for later assessment.

- Field controller unit

Runs the executed files sent from user's computer. It controls the whole system. The unit contains three PC/104 format cards and a few electric circuit boards to connect all peripheral

devices.

- Trajectory motor

Following the result of calculation from the field controller unit, it rotates the trajectory angle of the sprinkler head to compensate for the water drift from wind.

- Sector motor

Following the results of calculation from the controller unit, it rotates the sector angle of the sprinkler head to compensate for the water drift from wind.

- Motor position micro-switches

One is for the trajectory motor and the other is for the sector motor. Both of them are used to confirm each motor angle.

- Pressure transducer

The pressure data is used to calculate jet characteristics.

- Wind vane

The wind direction data from the wind vane is used to adjust the direction of the sprinkler head.

- Anemometer

The wind speed data from the anemometer is used to adjust the direction of the sprinkler head.

- Cut off solenoid valve

When the wind gets strong, the cut-off valve is closed to make this system more effective in economical terms.

- Chemigation pump

It is used to feed chemicals into this system.

- Wheel hydraulic motor

Taking water from the main flow, the motor moves in a vertical direction and a plate is pushed up and down, which turns the wheel by two bars attaching to the wheel tooth.

- Wheel micro-switch

It is switched on when the wheel hydraulic motor makes a cycle.

- Wheel valve

The speed of this sprinkler depends on how wide the valve is opened.

The arrows in Fig.1-4 describe the directions of signals, therefore, an arrow which has signs at both sides means that signals go through in both directions.

1.3 Hypothesis

The effectiveness of the STS system can be improved by redesigning the prototype in both hardware and software aspects with new technology. Furthermore, incorporating an application of chemicals, the system can be more economical.

1.4 Aim

The aim is to show that the robotic STS system can be controlled accurately and precisely enough to distribute water so as to concentrate on the center uniformly under any windy conditions.

1.5 Objectives

To achieve the aim, a numbers of objectives have to be met:

- 1) To redesign the structure of the STS head, so it can be controlled simply and efficiently.
- 2) To control the STS head in order to compensate for wind drift.
- 3) To incorporate the application of chemicals, (fertilizer, herbicide, pesticide) into this irrigation system.
- 4) To close down the STS when the wind becomes strong in order to reduce the amount of wasted water.

2. Design of the Robotic STS Head

2.1 Introduction to STS design

The new structure of the robotic STS head made the control system easier and more accurate. It was the same as the previous one in that the head has two degrees of freedom, each of which was taken charge of by a stepper motor. However, this was designed to be suitable to be driven directly by motors, which led to need no gear belts.

While considering the simplest and easiest design, some of them were come across only to be unable to satisfy two basic conditions, one of which is to make small torque motors available and the other is to be easy to be fabricated.

Finally, by refusing to use metals in order to realize both less torque and easier fabrication, acrylic was chosen and the design turns as shown in Fig.2-1. The details of acrylic are written in Section 2.2.2.

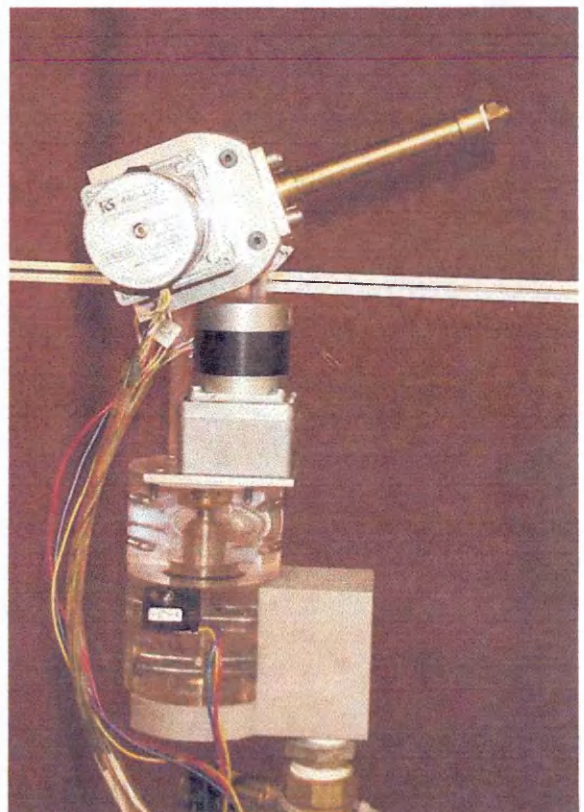
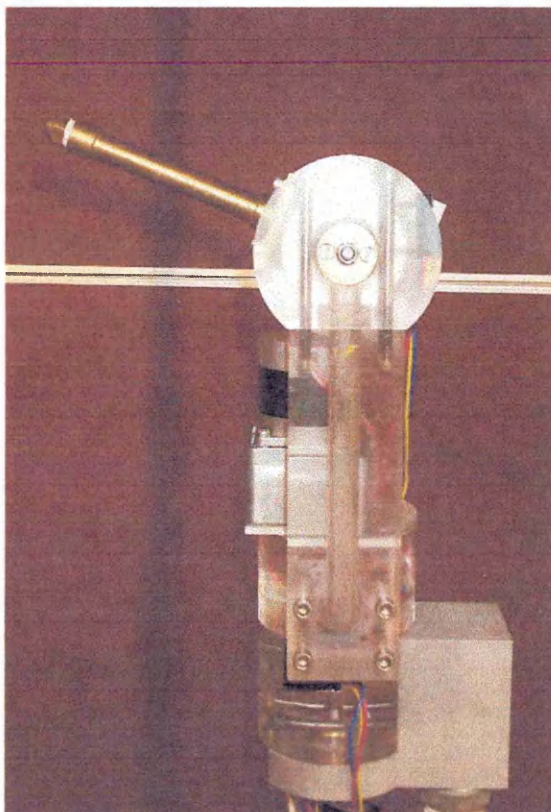
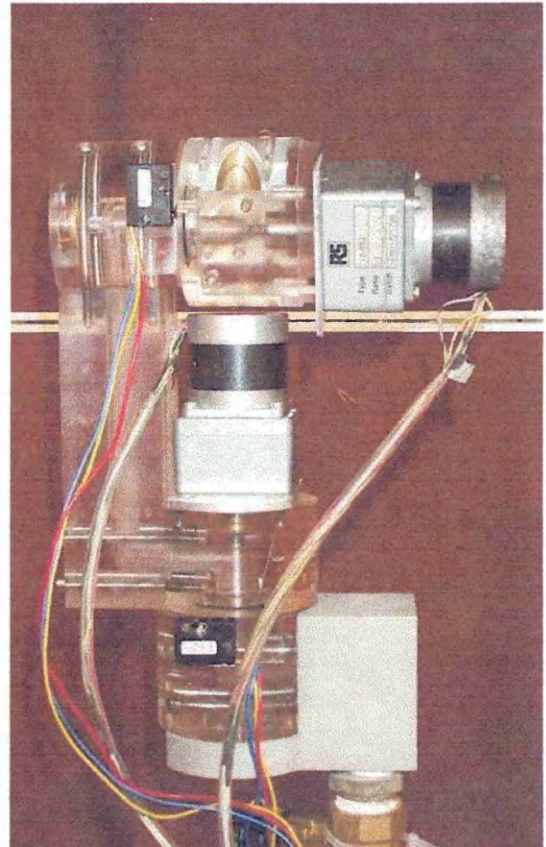
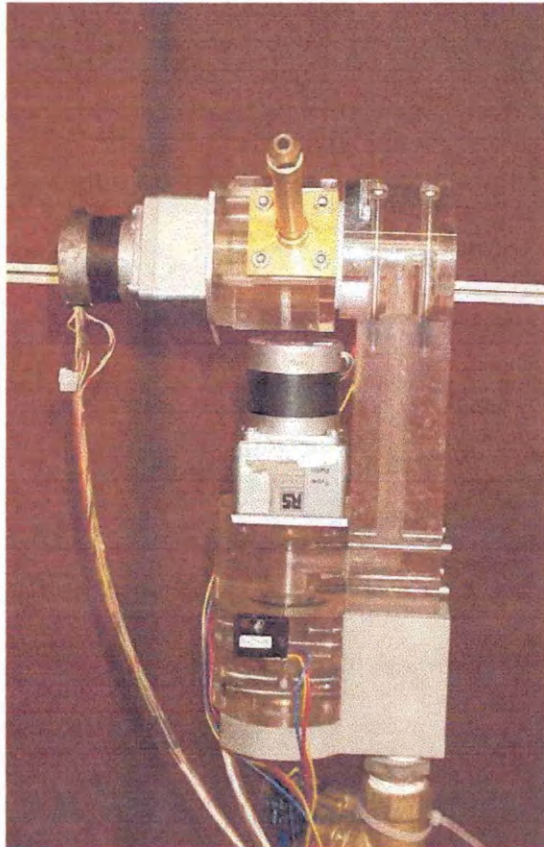


Fig.2-1: The picture of the robotic STS head

2.2 Design

2.2.1 Specifications

All of the parts that comprise the sprinkler head are shown in Fig.2-2. The parts were designed by AutoCAD. The drawings are shown in Appendix I. The main features of the parts are described as follows.

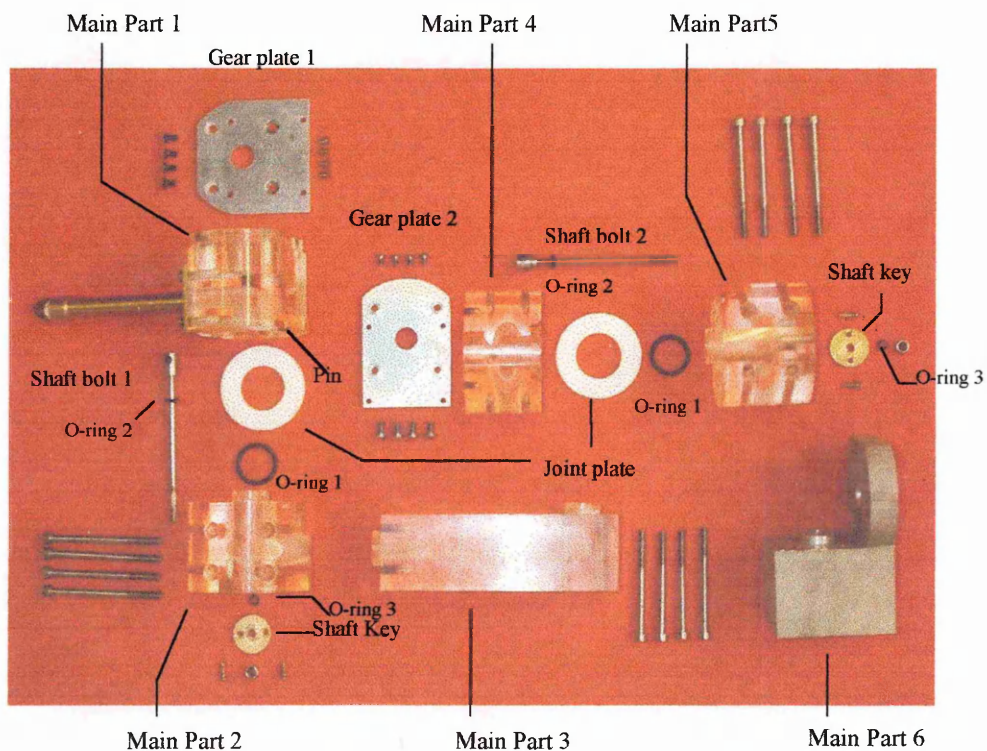


Fig.2-2: All parts of the robotic STS head

- Main parts

Material : Acrylic (which is explained in next section.)

- Main Part6 -Base

Material : Aluminum alloy

Function :

To connect the base of the sprinkler to the head and support all the other parts.

- Nozzle

Material : Brass.

- Gear plates

Material : Aluminum alloy

Function:

To connect the gearboxes to the main parts (Main Part 1, Main Part 4).

- Shaft bolts

Material : A allen bolt, a coupler, hexagon socket screw. (Fig.2-3)

Function :

It has two functions, one of which is to extend the motor shaft to the end of the main part and the other is to hold two main parts, Main Part 1, 2 and Main Part 4, 5.

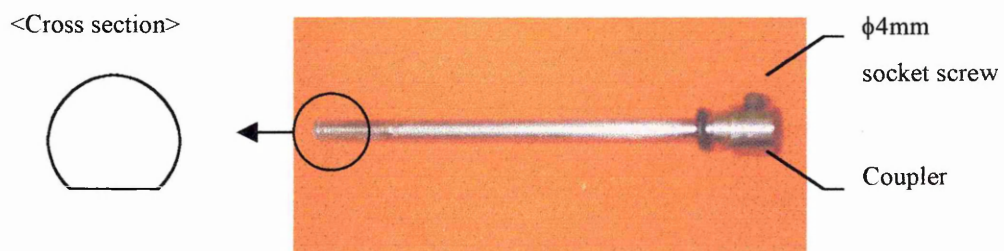


Fig.2-3: A shaft bolt

- Shaft keys for the shaft bolts

Material : Brass

Function :

To hold the shaft bolts to stop the rotation of the motor shafts, which are fixed at the other end of the shaft bolts.

- Joint plates

Material : P.T.F.E. (Polytetrafluoroethylene)

Function:

To hold the rotating joint parallel and make it less friction.

- O-rings (Fig.2-15)

Material : O-ring 1) Size I.D. 24mm, O.D. 31mm
 O-ring 2) Size I.D. 6mm, O.D. 11.4mm
 O-ring 3) Size I.D. 5mm, O.D. 8.6mm

Function :

O-ring 1) To seal the rotating junctions (between Part I and II, Part IV and V).
O-ring 2) To seal the gap between the shaft keys and the shaft bolts.
O-ring 3) To seal the gap between the heads of the shaft bolts and the bolts themselves.

- Micro switch pin

Material : Brass & M2 screw.

Function :

To confirm the certain positions for trajectory and sector angles. (27 degrees from the horizontal on Main Part 1, 90 degrees from the travelling direction on Main Part 4).

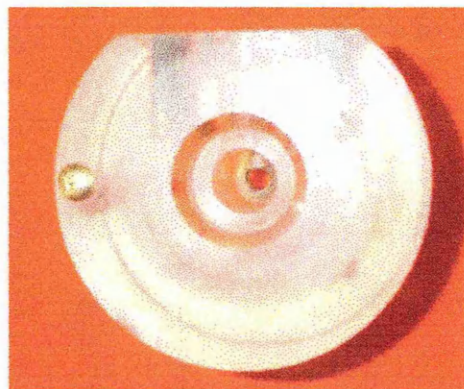


Fig.2-4: Micro switch pin on Main Part 4.

The size of this pin is shown below.

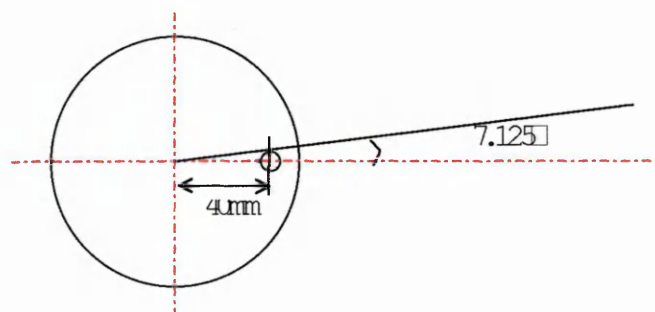


Fig.2-5: The hysteresis of the motor position micro switch.

2.2.2 Material

Acrylic was chosen in this study owing to the following characteristics of it.

a) Mechanical

- High strength/weight ratio.
- The stiffness: 1,000 lb. per. sq. in. is for a safe design.
- Low water absorption.
- Ease of fabrication and machining.
- Notch sensitive.

b) Chemical

- Resistance to dilute acids (except hydrofluoric and hydrocyanic) and dilute and concentrated alkali solutions
- Resistance to many organic solvents, fats, mineral oils, aqueous solution of inorganic salts, and most common gasses
- Weakness to chlorinated aliphatic hydrocarbons (e.g. chloroform, trichloroethylene), aromatic hydrocarbons (e.g. benzene, toluene, petrol), ketones (e.g. acetone), alcohol, ethers and esters. They causes to swell, craze, weaken the material, dissolve it completely.

c) Thermal

- Stable up to 90°C although its thermal expansion is high being about seven times that of steel.

d) Optical

- Extreme clarity: the overall light transmission for normally incident light is about 92%.

From the mechanical points of view, acrylic is weak compared to metals like brass which was used for the prototype. However, considering that it is easy to fabricate and this study is such a small model that water pressure is lower than 3 bar, acrylic is strong enough according to the above specifications. Furthermore, it is suitable to experiments because its clarity makes it possible to see what is happening inside the sprinkler head, say, the water turbulence, the shaft connectors, the rotate junctions. Concerning about the friction at the rotate junction, the rotate speed is set lower than 1 rpm for a stable drive, so that the friction will not make the junction

higher temperature than 90°C, which means that acrylic is stable.

As a summary, a comparison among a few materials thought to be available is shown in Table 2-1. The larger number among 1 to 5 indicates the more suitable to this study in each category.

	Acrylic	Polypropylene	Brass	Aluminum alloy
Specific gravity	5	5	1	1
Stiffness	1	1	5	5
Strength/weight	5	5	1	1
Resistance to chemicals	2	5	5	3
Easiness of fabrication	5	1	5	1
Appearance	5	1	2	2
Cost	2	5	1	2
Total	26	23	19	15

Table 2-1: Comparison among four available materials.

The result shows that acrylic is most suitable to this project.

2.2.3 Rotating joints

A friction torque that occurs to the rotating joints, which are between Main part 1 and 2, Main part 4 and 5, depends on the tightness of the nut. To stop leaking at the rotating joints, the friction torque is 750 mNm when water is not let in but no more than 250 mNm when water is supplied. While the holding torque of the motor is 500 mNm, the gearbox multiplies that by five. Therefore, there is enough torque to rotate the joints.

3. Development of Hardware

3.1 Motors and Gearboxes

3.1.1 Motors

Two motors are used to drive the sprinkler head trajectory and sector angle. One of them (RS stock No.440-442) takes charge of trajectory and the other (No.332-082) of sector.

These are 4-phase hybrid motors and their main specifications are shown in Table.3-1. The further details can be referred to RS data sheet No.232-5745.

RS Stock No.	440-442	332-082
Step angle	1.8	1.8
Nominal phase parameters and rating: Voltage	5.1	5
Resistance at 20°C	5	5
Current (A)	1	1
Holding torque (mNm)	500	460

Table 3-1: Main features of motors

The configurations of the motors are shown in Fig.3-1.

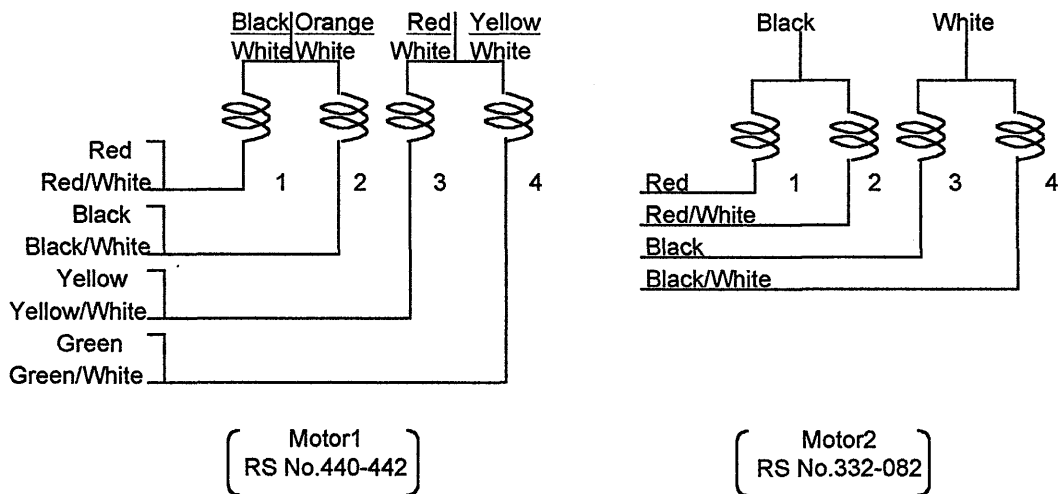


Fig.3-1: The configurations of motors.

Furthermore, Fig.3-3 in next section shows the electric circuit of the motor connections to the motor driver boards and the power supply.

3.1.2 Driver Board

Unipolar stepper motor drive board (RS stock No.332-098) was used. The technical specifications are written in Table.3-2.

a) Technical specifications

Size	standard Euro card 168 × 100 × 15	
Mating edge connector	standard 32-way DIN41612 socket	
Supply (board and motor)	15-30V	15V(Current setting)
Current consumption board only motor windings	60 mA Max. 2A	
On-board auxiliary output	12V d.c. 50mA max regulated	
Switching logic control	Level '0' 0V Level '1' 12V	
Inputs 1. full/half step 2. direction 3. clock 4. preset	0: half 1: full 0: anti-clockwise 1: clockwise 0: low pulse 1: high pulse	(Current setting) Level '0' fixed Level '0' fixed.

Table 3-2: Technical specifications of unipolar motor driver.

Fig. 3-2 tells the details of the connections.

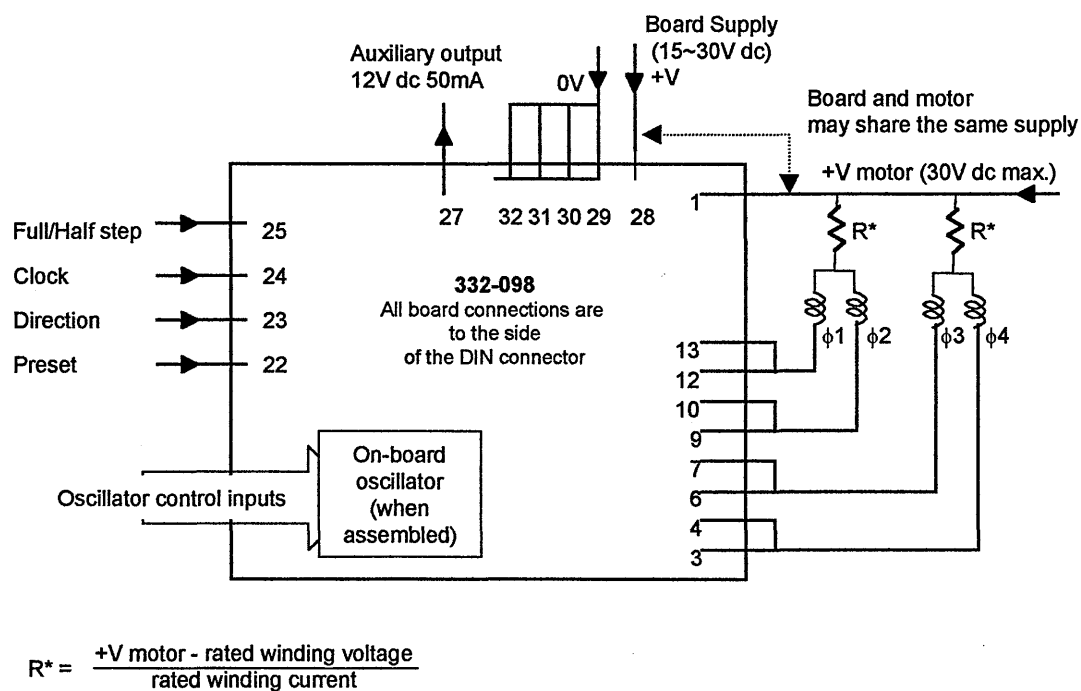


Fig.3-2: Unipolar stepper motor drive board connections.

If the power supply voltage is set to 24Vdc then R value for use with the RS motors are given in Table 3-3.

Motor	Rated current (A)	Rated winding voltage (V)	R (Ω)	Power dissipation through R (W)
332-082 440-442	1	5	19	19

Table 3-3: The adequate value of R

b) Electric connection to the peripheral devices

The wiring of motors, motor drivers, and main board is shown in Fig.3-3.

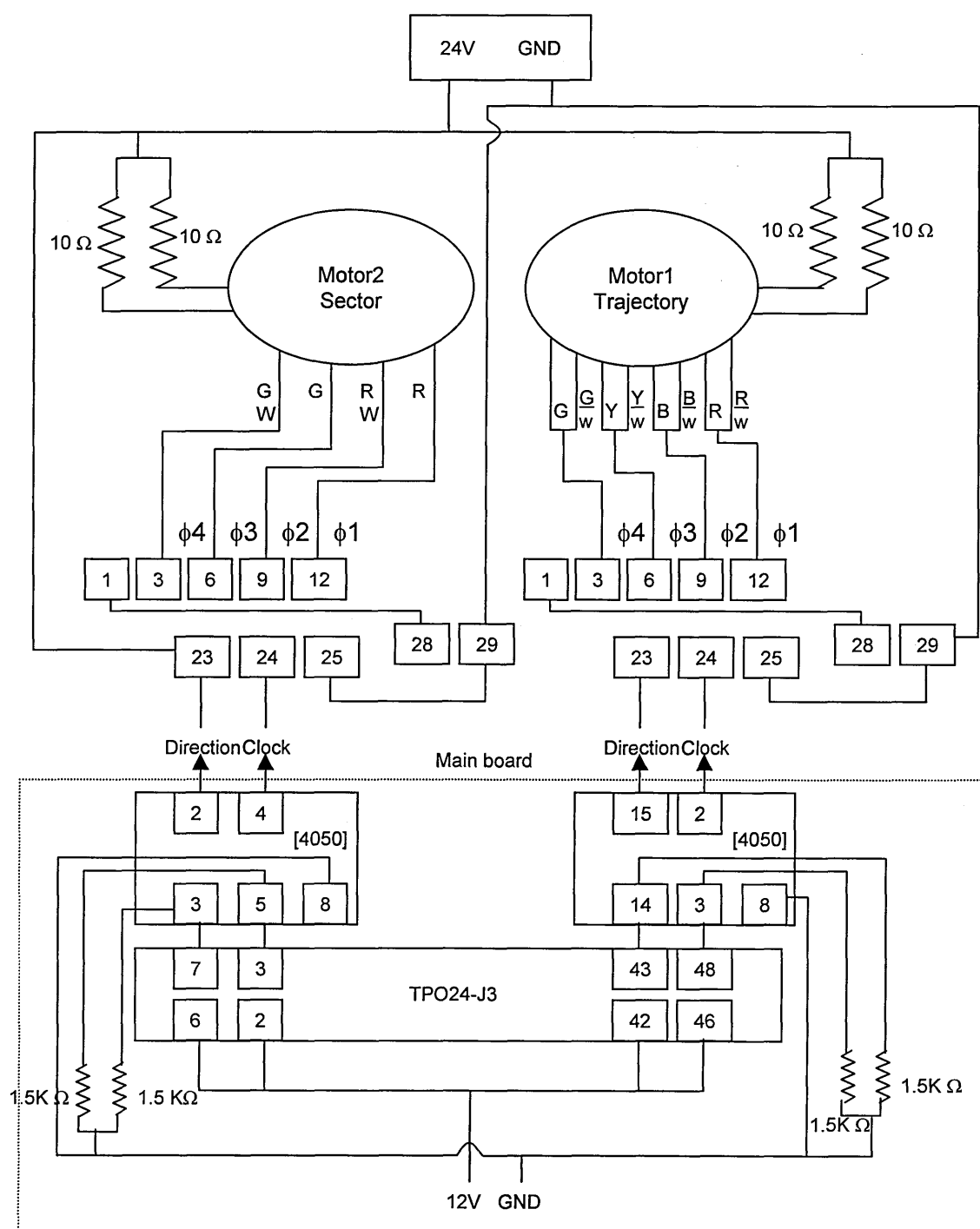


Fig.3-3: The electric circuit of motors, motor drivers, power supply.

c) Current settings

- Power supply : 15V
- Full/half step : Half (by connecting pin 25 to pin 29 (GND).)
- Preset : Not using

3.1.3 Gearbox

The motors have the smallest step angle of all the others that have been found so far. However, it is not accurate enough to drive the sprinkler head and near the limit of their holding torque. to take into account of the speed, the smallest gearbox, Multipurpose Gearbox (4Nm)-Ratio 5:1 (RS stock No.718-852) was chosen. The features are shown in Table.3-4.

Gear ratio	Output speed using 250 rpm synchronous motor	Number of steps/rev	Rotate direction with respect to input	Max. output Torque
5:1	50rpm	1000	Opposite	1.5Nm

Table 3-4: The main features of the gearbox

3.2 *Field controller unit*

3.2.1 Introduction to the embedded computer

In this study, a PC/104 computer and two PC/104 I/O boards that are provided by DSP design were used. PC/104 cards are much smaller than ISA-bus cards found in PC's and stack together, which eliminates the need for a motherboard, backplane, and/or card cage. Power requirements and signal drive are reduced to meet the needs of an embedded system because PC/104 is essentially a PC with a different form factor, most of the program development tools used for a DOS PC can be used for a PC/104 system.

The three following sections show what features each part of the controller has and what their functions are for this sprinkler system.

3.2.2 TB486 PC/104 Target card PC compatible computer

The TB486 is a single board PC/104 compatible computer that can operate as a stand-alone module or can be used in a system consisting of a number of other PC/104 modules that runs ms DOS.

a) Features

- High integration processor: a 66MHz AMD Elan SC410 is fitted.
- PC/104 V2.3 16-bit bus interface for wide compatibility.
- Floppy and IDE disk controllers.
- Three RS232 serial ports – COM2 is user-configurable as RS-485.
- Up to 64M bytes of DRAM is supported.
- A 512 byte size serial EEPROM is provided to retain set-up parameter in the absence of an external battery.

b) Stand alone operation

- Power supply

+5V is required by using the power connector J4.

- Reset

By issuing a low going pulse on the /RESET line of J3.

c) Current settings

- Memory

A 4 M bytes DRAM is attached to the socket on this card.

- Clock

The CPU runs at 33MHz, which can be set higher up to 100MHz.

d) Current consumption

4 M bytes DRAM = 657 mA.

Mode 33MHz = 208 mA. (when Graphics and Ethernet are off.)

Serial ports = 4 mA.

Total Power Consumption = 869 (mA)

3.2.3 TP406 PC/104 Digital I/O Counter/Timer board

The TP406 provides a range of parallel I/O and counter/timer functions for use with PC/104 bus based systems.

The parallel I/O functions are provided by two uPD71055 chips which are equivalent to the Intel 8255 chips.

The counters/timers functions are provided by uPD71054 chips. These are equivalent to the Intel 8254 chip. The CLK, GATE, and OUT pins are all made available to the user. Further information should be referred to Technical reference manual of TP406 from DSP Design.

a) Features

- 40 lines of parallel I/O.
- 24mA current source/sink capability.
- Pull-up resistor on most I/O pins.
- Six counter/timers channels with flexible connection options.
- I/O mapped – address jumper selectable.
- Option to interrupt processor.
- Single +5V power supply. Very low power operation possible.

b) Current settings

- Base Address – Jumper Area E5

Base Address is 0x210, which gives a binary number 00100001 (corresponding to A11 to A4).

So Jumper Area E5 is set as shown below:

[A1-B1 C1], [A2 B2-C2], [A3 B3-C3], [A4 B4-C4]

[A5 B5-C5], [A6-B6 C6], [A7 B7-C7], [A8 B8-C8]

c) Parallel I/O

Individual addresses are described in Table 3-5.

Offset	Chip	Register
0	71055 No.1	Port A Data register
1	71055 No.1	Port B Data register
2	71055 No.1	Port C Data register
3	71055 No.1	Command register
4	71055 No.2	Port A Data register
5	71055 No.2	Port B Data register
6	71055 No.2	Port C Data register
7	71055 No.2	Command register

Table 3-5: TP406 address map for parallel I/O

Three micro switches are connected to this parallel port with such a pin assignment as shown in Table 3-6.

PIN	Signal	Usage	PIN	Signal	Usage
1	0V		2	0V	
3	PA0	NC	4	PA1	Motor position micro switch 1
5	PA2	NC	6	PA2	Motor position micro switch 2
7	PA4	NC	8	PA	NC
9	PA6	NC	10	PA	NC
11	0v	NC	12	PE3	NC
13	PB0	NC	14	PB1	Wheel micro switch
15	PB2	NC	16	PB3	NC
17	PB4	NC	18	PB5	NC
19	PB6	NC	20	PB7	NC
21	0v	NC	22	PE2	NC
23	PC0	NC	24	PC1	NC
25	PC2	NC	26	PC3	NC
27	PC4	NC	28	PC5	NC
29	PC6	NC	30	PC7	NC
31	0v	NC	32	PE1	NC
33	PD0	NC	34	PD1	NC
35	PD2	NC	36	PD3	NC
37	PD4	NC	38	PD5	NC
39	PD6	NC	40	PD7	NC
41	0v	NC	42	PD0	NC
43	PE4	NC	44	PE7	NC
45	PE5	NC	46	PE6	NC
47	-12V	NC	48	+12V	NC
49	+5V	NC	50	+5V	NC

Table 3-6: Pin assignments of Digital I/O on TP406.

- Current Setting

[Buffer command word] = 0x0F.

[Port A, Port B, Port C, Port D, Port E] = [IN, IN, OUT, OUT, OUT]

So,

[Command word] = 0x00.

- Operation

When the micro switch is on, input signal turns to be 1.

A test program of the parallel I/O is given as TP406.c in the attached CD.

d) Counters/Timers

26-ways Counter/Timer connector is J5 whose register assignments are shown in Table 3-7.

Further, the next table gives the current connection to peripheral devices.

Assignment	Offset	Chip	Register
Timer for reading data	8	71054 No.1	Counter 0 register
Anemometer(Wind speed)	C	71054 No.2	Counter 0 register
Wind vane(Wind Direction)	D	71054 No.2	Counter 1 register
Pressure Transducer	E	71054 No.2	Counter 2 register
Set control word in chip No.1	B	71054 No.1	Control word register
Set control word in chip No.2	F	71054 No.2	Control word register

Table 3-7: Register assignment of Counters/Timers on TP406.

- Current settings

[Jumper Area E1]

This jumper area allows a buffered version of the PC/104 clock signals (called BCLK) to drive the CLK inputs of the uPD71054 counter/timer chip No.1.

Set [A1-B1], [A2-B2], [A3-B3] for the function as a timer in programs.

[Jumper Area E4] - No shorts.

[Operating Mode]

Chip No.1 : Mode 4

Chip No.2 : Mode 0

[Pin assignment]

PIN	SIGNAL	USAGE	PIN	SIGNAL	USAGE	CHIP/ CHANNEL
1	GND		2	CLK0	Timer for reading data	No.1 Chan.0
3	GATE0		4	OUT0		
5	GND		6	CLK1		No.1 Chan.1
7	GATE1		8	OUT1		
9	GND		10	CLK2		No.1 Chan.0
11	GATE2		12	OUT2		
13	GND		14	CLK0		No.2 Chan.0
15	GATE0	5V	16	OUT0	Wind speed	
17	GND		18	CLK1		No.2 Chan.1
19	GATE1	5V	20	OUT1	Wind Vane	
21	GND		22	CLK2		No.2 Chan.2
23	GATE2	5V	24	OUT2	Pressure	
25	BCLK		26	Vcc	Input to GATE	

Table 3-8: Pin assignments of Counters/Timers on TPO24.

3.2.4 TPO24 PC/104 OPT-Isolated Digital I/O board

The TPO24 provides 12 lines each of opto-isolated digital inputs and outputs for use with PC/104 bus based systems. TPO24 is intended to provide a level of opto-isolations in low voltage systems.

The parallel I/O functions are provided by a uPD71055 chip which is equivalent to the Intel 8255 chip. 12 of the pins of the uPD71055 are buffered and drive the opto-isolated outputs, and other 12 pins receive inputs from the opto-isolated inputs.

a) Features

- 12 lines of opto-isolated outputs.
- 160mA current source/sink capability on each output.
- 12 lines of opto-isolated inputs.
- All inputs and outputs are isolated from each other.
- I/O mapped – address jumper selectable.
- Single +5V power supply. Very low power operation possible.

[Register assignment]

OFFSET	REGISTER
0	Port A Data register
1	Port B Data register
2	Port C Data register
3	Command register

Table 3-9: Offset addresses of registers on TPO24.

b) Current settings

- Base Address – Jumper Area E1

Base Address is 0x220, which gives a binary number 01001000 (corresponding to A9 to A2).

So Jumper Area E1 is set as shown below:

[A1 B1-C1], [A2 B2-C2], [A3 B3-C3], [A4-B4 C4]

[A5 B5-C5], [A6 B6-C6], [A7-B7 C7], [A8-B8 C8]

- Operating Mode, Control Word

‘Mode0’ is set.

Port A, higher half of Port C are set as output and the other ports as input.

Since,

[Control Word] = 0x03

[Pin assignment]

PIN	SIGNAL	USAGE	PIN	SIGNAL	USAGE
1	PPA0		2	PPA0	12V
3	PA0	Motor1 clock signal	4	PA0	
5	PPA1		6	PPA1	12V
7	PA1	Motor1 rotate direction	8	PA1	
9	PPA2		10	PPA2	
11	PA2		12	PA2	
13	PPA3		14	PPA3	
15	PA3		16	PA3	
17	PPA4		18	PPA4	
19	PA4		20	PA4	
21	PPA5		22	PPA5	12V
23	PA5	Chemigation pump	24	PA5	
25	PPA6		26	PPA6	12V
27	PA6	Solenoid valve	28	PA6	
29	PPA7		30	PPA7	
31	PA7		32	PA7	
33	PPC4		34	PPC4	
35	PC4		36	PC4	
37	PPC5		38	PPC5	
39	PC5		40	PC5	
41	PPC6		42	PPC6	12V
43	PC6	Motor2 clock signal	44	PC6	
45	PPC7		46	PPC7	12V
47	PC7	Motor2 rotate direction	48	PC7	
49	N/C		50	N/C	

Table 3-10: Pin assignment of Digital I/O on TPO24.

c) Current consumption

[Max. Power Consumption] = 55 mA

when all output Opto-isolators on.

You can test I/O port by test24op.c and the board called TEST BOARD-OPT24.

3.3 Sensors

3.3.1 Wind vane

To know the wind direction applied for the control models , a precision potentiometer wind vane with corrosion resistance case provided by Vector Instruments Inc. was used. The main specifications of the wind vane is described as Table 3-11.

[Performance]	
Maximum wind speed	over 75 m/s (150 Kts, 170 mpf).
Threshold	0.6 m/s
Response	Distance constant: 2.3 m
	Damping ratio: 0.2
Range	360 mechanical angle, full circle continuous rotation allowed.
[Electrical]	
Wiper current	20mA max.
Supply voltage	20V max.
Electrical variation angle	$356.5^{\circ} \pm 1.5^{\circ}$ (3.5° deadband).
Resolution	$\pm 0.2^{\circ}$

Table 3-11: Main specifications of Wind Vane.

The output is analog. So, a FVC654 was used to convert the analog voltage into frequency to be able to be fed into a counter channel.

The electric circuit to connect the wind vane to the computer is designed as Fig.3-4, and Fig.3-5.

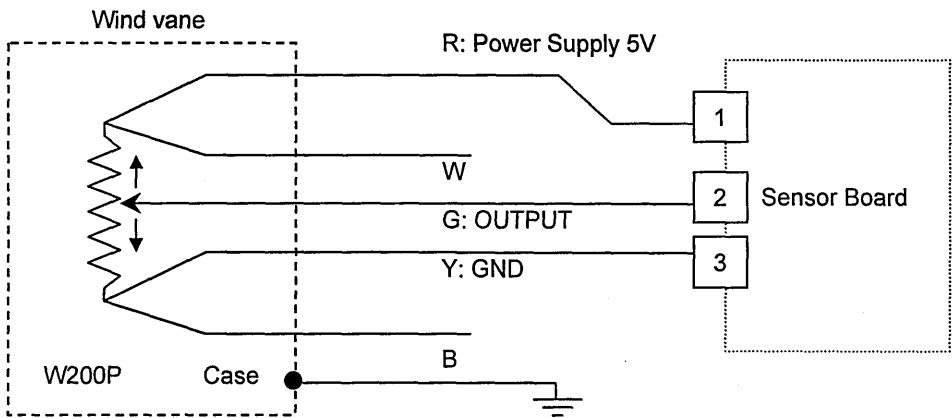


Fig.3-4: The connection of the wind vane between the sensor and the sensor board.

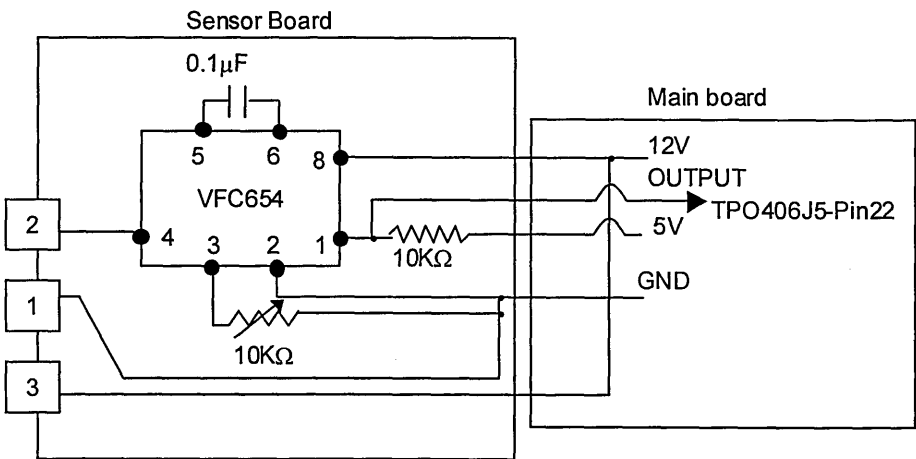


Fig.3-5: The connection of the wind vane between the sensor board and the main board.

The equation to show the real value is sought as below.

The output frequency of FVC654 is 500 at 358.25 degrees and the potentiometer is linear.

Since,

$$[Wind\ Direction] = 360 - (356.5 \times Frequency / 500 + 1.75) \quad (3.1)$$

3.3.2 Anemometer

To decide the orientation of the sprinkler nozzle, wind speed should be known. PULSE OUTPUT ANEMOMETER A101M provided by Vector Instruments Inc. was used. The main specifications are described as the following Table 3-12.

Performance]	
Non-linearity	0.7% (10-55m/s speed range).
Distance constant	5m (R30 rotor).
Calibration	10Hz per m/s 2%
Resolution	10cm
[Electrical]	
Operating conditions:	
LED:	
Forward current	10mA min.
Opto-Schmitt photo sensor IC:	
Supply Voltage, Vcc	4.5V min., 16V max.
Output voltage, Vo	0.4V max, output 'low' Vcc, output 'high'
Schmitt hysteresis	30% max., 10% min.
Total Current (LED + IC)	18mA typ., 30mA max.
Cable	6core, 7/0.2mm, 3 meters long.

Table 3-12: Main specifications of the anemometer.

Then, the electric circuit to connect wind vane to the computer is designed as Fig.3-6.

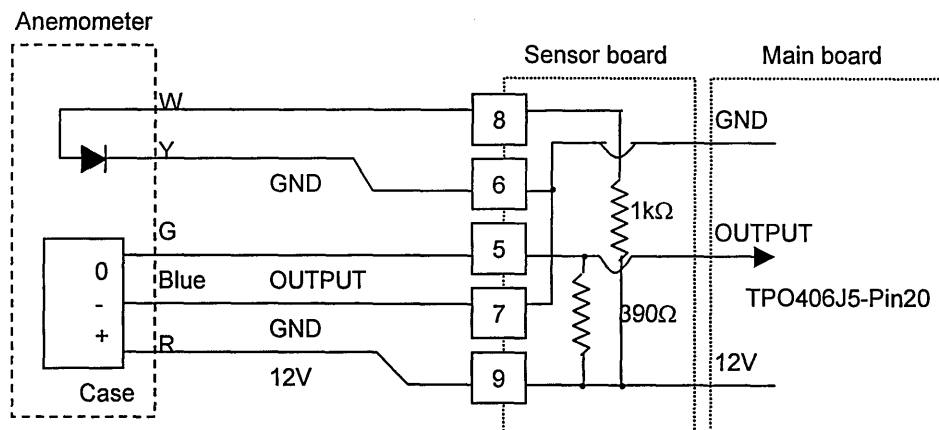


Fig.3-6: The connection between the anemometer and the main board.

The equation to describe the real value is shown as below.

From the above data sheet,

$$[Wind\ Speed\ (m/s)] = 0.1 \times [Output\ Frequency] \quad (3.2)$$

3.3.3 Pressure Transducer

A pressure transducer, MODEL SA 100PSIA from Data Instruments Inc., was installed in order to know the characteristics of the water distribution. The detail features are described as the following table.

[Range]	0-13.8 bar, 0-100psi
[Electrical]	
Span	5±0.1 Vdc at 77°F (25°C)
Excitation Voltage	9 to 20 Vdc
Null Offset	1.0±0.20 Vdc at 77°F (25°C)
Output Current	15mA

Table 3-13: the features of the pressure transducer, MODEL DA 100PSIA.

Electric circuit:

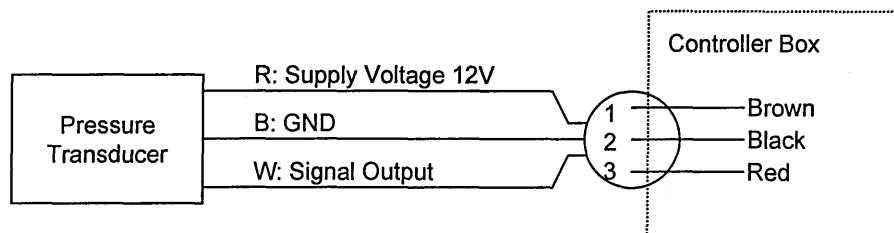


Fig.3-7: The connection between the pressure transducer and the controller box.

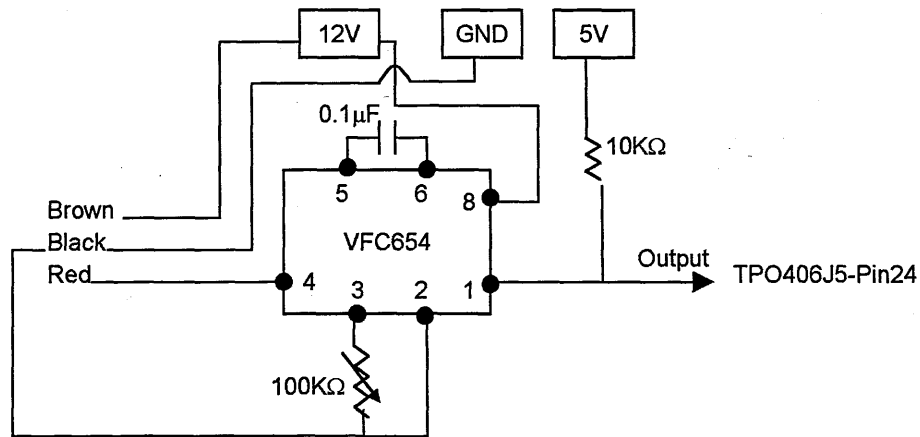


Fig.3-8: The electric connection in the controller box.

The equation to give the real value is found as below.

Using a pressure meter, the relationship of frequency output to input pressure is found as shown in Fig.3-9.

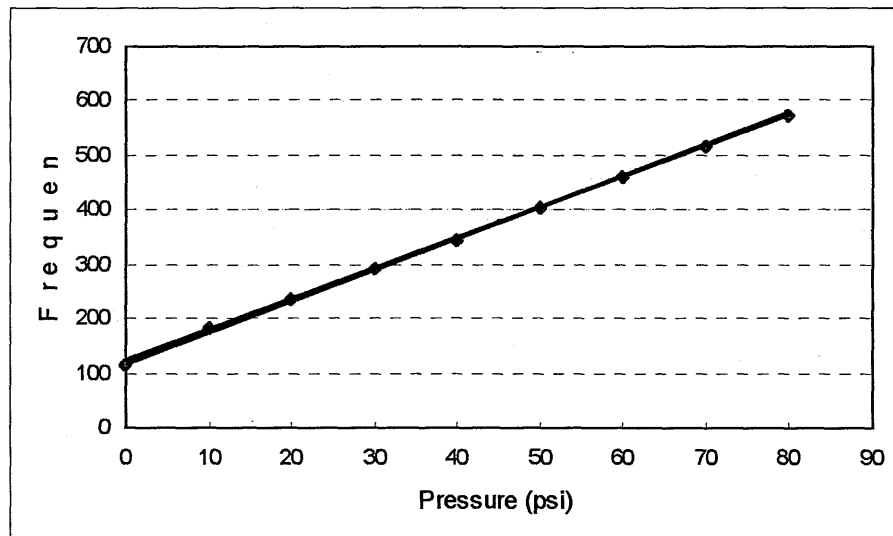


Fig.3-9: The calibration of the output frequency to the output voltage from the pressure transducer.

The regression line is;

$$\text{Frequency (Hz)} = 5.7373 \times \text{Pressure (psi)} + 117 \quad R^2 = 0.9994 \quad (3.3)$$

Since, the equation to show the actual pressure value is

$$\text{Pressure (psi)} = (\text{Frequency} - 117) / 5.7373 \quad (3.4)$$

3.1.1 Motor position micro-switches

A rotational position of a stepping motor is known by counting the clock signals which a computer outputs to the motor. However, to know the initial position and to consider a possibility that slipping might occur, it needs to confirm the positions of motors sometimes. Single sealed miniature micro switches V3S Series, from Burgess, were used. As shown in Fig.3-10, there is a pin which is set to press the micro-switches at the definite point, 90° from the travelling direction for the sector angle, 27° from the ground for the trajectory angle. The mechanism of this micro-switch is totally enclosed to IP67.

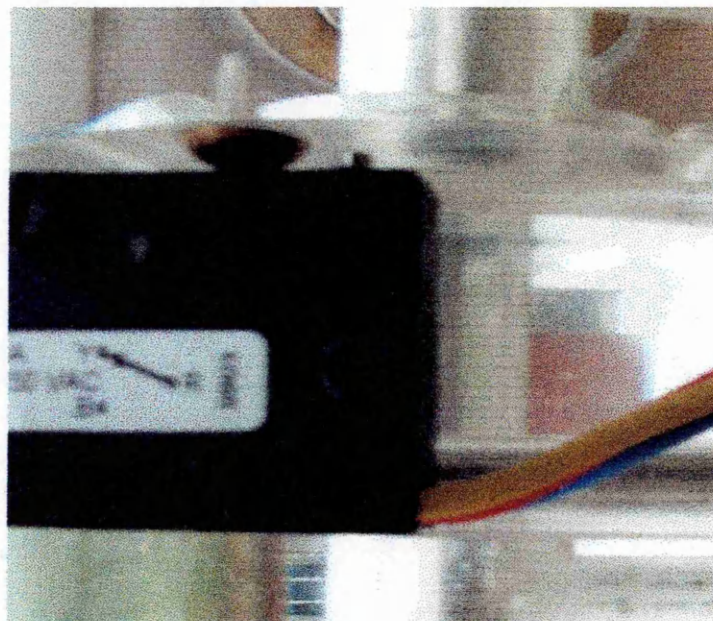


Fig.3-10: Motor rotate position micro switch.

3.1.2 Cut-off Valve

When wind becomes strong, water should not be distributed efficiently. Therefore, the water supply is stopped with dependent on the calculation results of the control model for the trajectory angle. If the resulted angle is below 9 degrees, the valve will be closed. This solenoid valve provided by SIRAI is normally opened as shown in Fig.3-11 and rated by 12V, 0.5A. The electric circuit for it is described in Fig. 3-12.

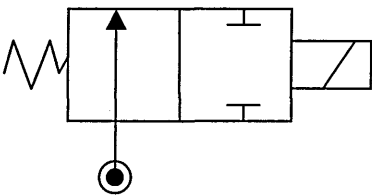


Fig.3-11: The system of the solenoid valve.

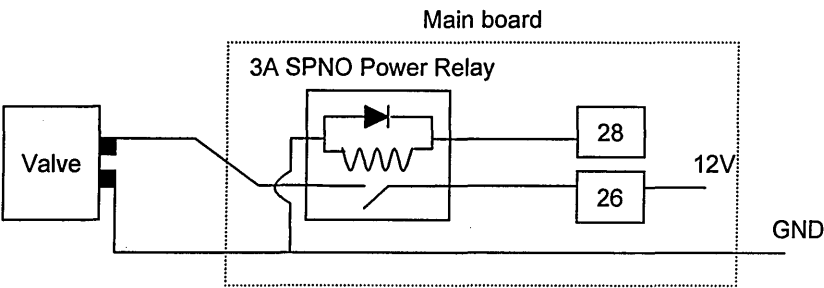


Fig.3-12: The connection between the valve and the Main board.

3.3.6 Chemigation pump

It will be economical and environmentally gentle that a chemigation system is added to the prototype irrigation system because it can eliminate another equipment for chemicals and the chemicals are distributed precisely. A diaphragm pump rated by 12 V, 0.55A is used to inject chemicals into the main flow. However, the back pressure of the main flow is bigger than that of the pump. A suitable pump is recommended in Section 7.2.

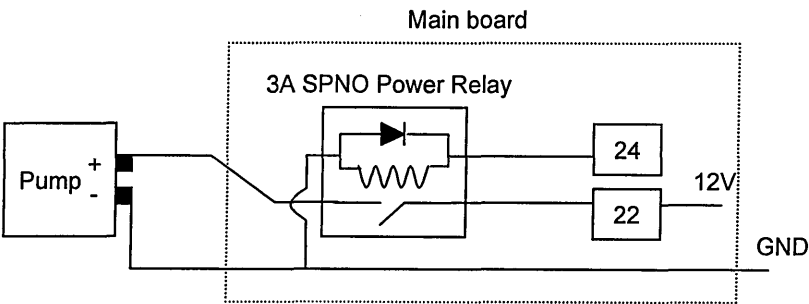


Fig.3-13: The connection between the pump and the Main board.

3.3.7 Environmental protection

There are two boxes, control box and motor driver box as a field unit controller. The boxes are rated IP66.

a) Control box

It includes a main board, a sensor board, PC/104 cards, and a PC connector board.

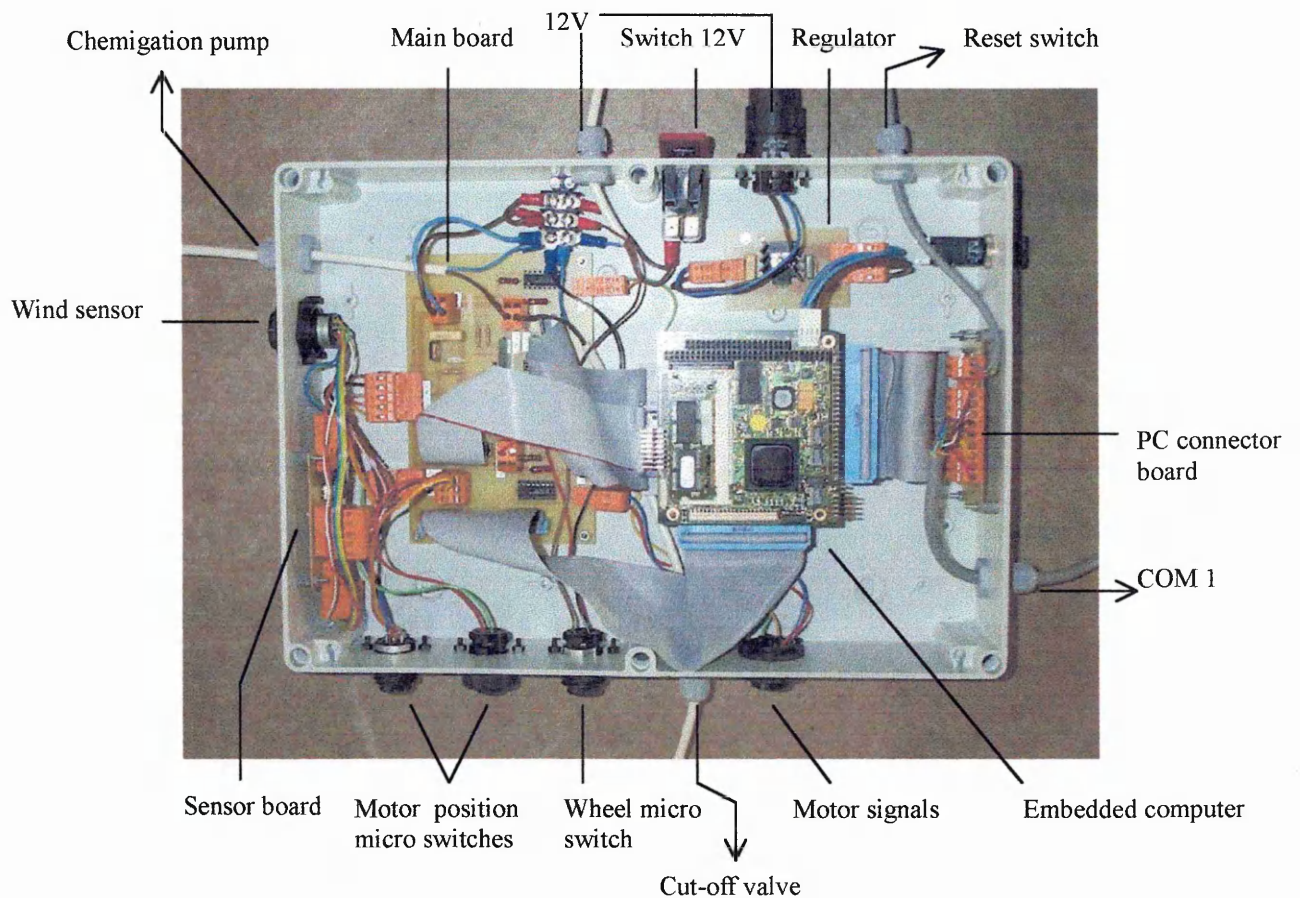


Fig.3-15: Control box

<Main board>

Function:

- Regulate 12V to 5V.
- A connection between the sensor board and J5 (counters/timers) on TP406.
- A connection and buffer between the driver boards in the motor driver box and J3 on TPO24.

- Two relays for the sprinkler valve and the pump which are driven by the signals from J3 on TPO24.
- A connection between micro switches and J3 (parallel I/O) on TP406.

Electric circuit:

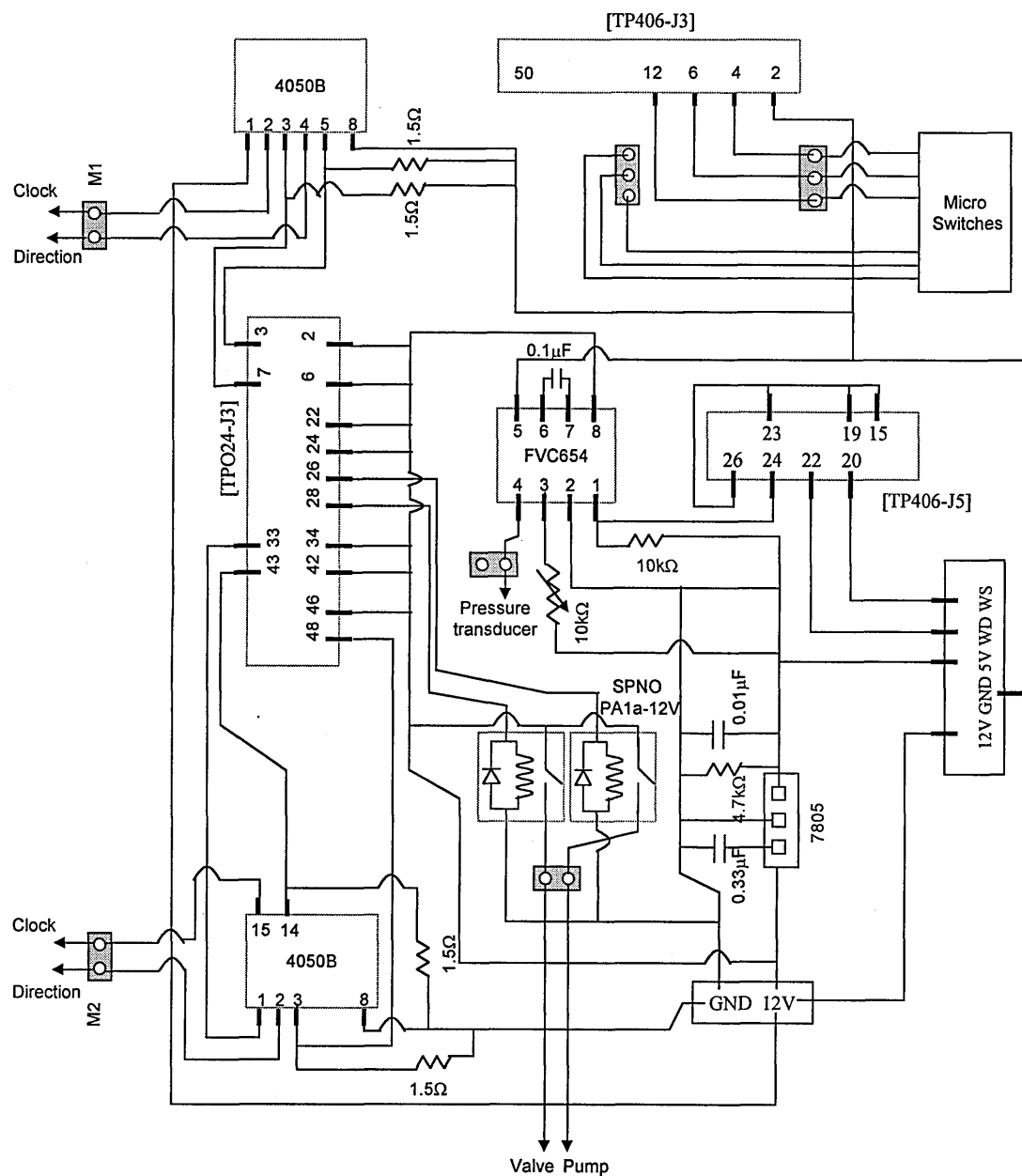


Fig.3-15: The electric circuit of the Main board.

<Sensor board>

Functions:

- A connection between the anemometer, the wind vane and the main board.
- Convert the output voltage from the wind vane into frequency by VFC654

Electric circuit:

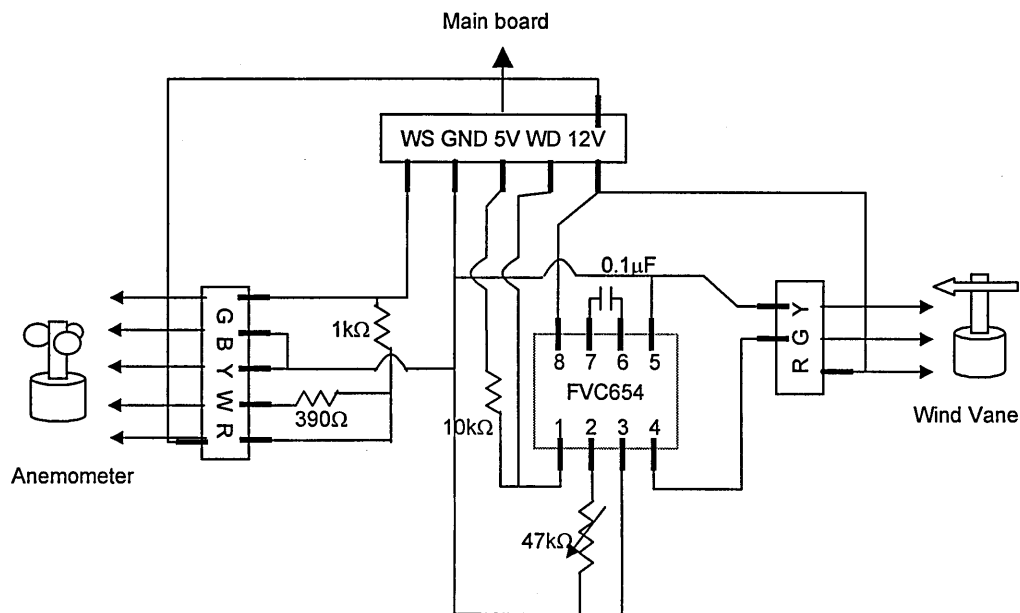


Fig.3-16: The electric circuit of the sensor board.

<PC connector board>

To transfer the data, Wind Speed, Wind Direction, Pressure, Travelling Distance, Trajectory and Sector angle, COM1 is connected to an external computer to save them.

Function:

- To adjust the connector of PC/104 to PC as shown below.

Electric circuit:

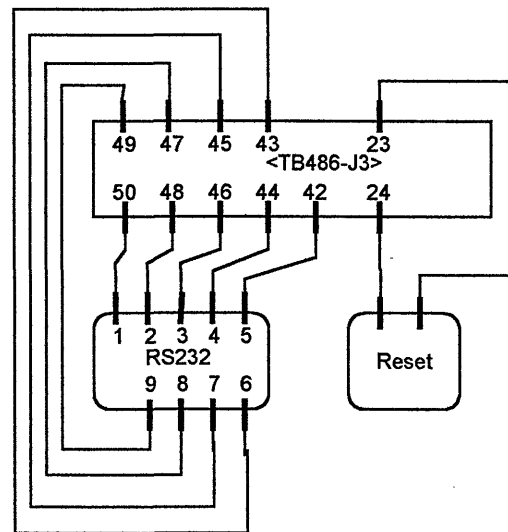


Fig.3-17: The electric circuit of the PC connector board.

b) Motor driver box

It includes two motor driver boards, 4-Phase Unipolar Stepper Motor Drive Board 332-098 (from RS) whose details are described in 3.1.2 and a regulator board which converts 24V to 15V.

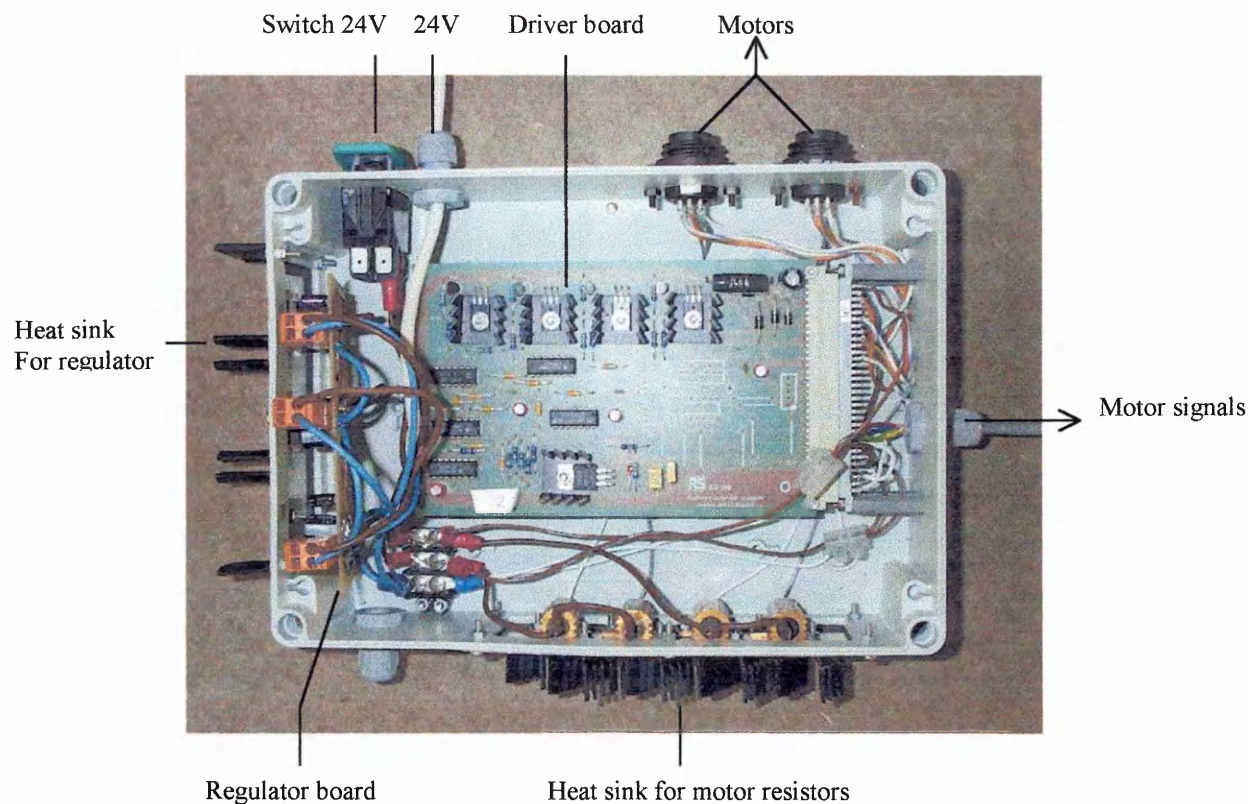


Fig.3-18: Driver board

<Motor drivers>

All of the details are referred to Section 3.2.1.

<Regulator board>

Function:

- The input voltage 24V is regulated to be 15V fed into motor drivers and motors.

Electric circuit:

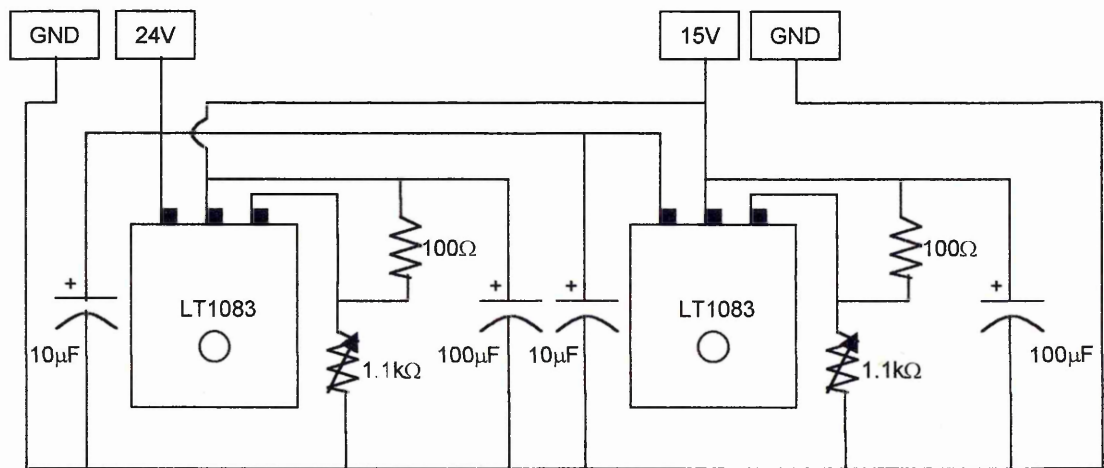


Fig.3-19: The electric circuit of the regulator board.

- Heat sink:

Three heat sinks are set on the opposite of the regulators between which an aluminum plate is installed instead of the plastic one. Fig. 3-19 shows the features.

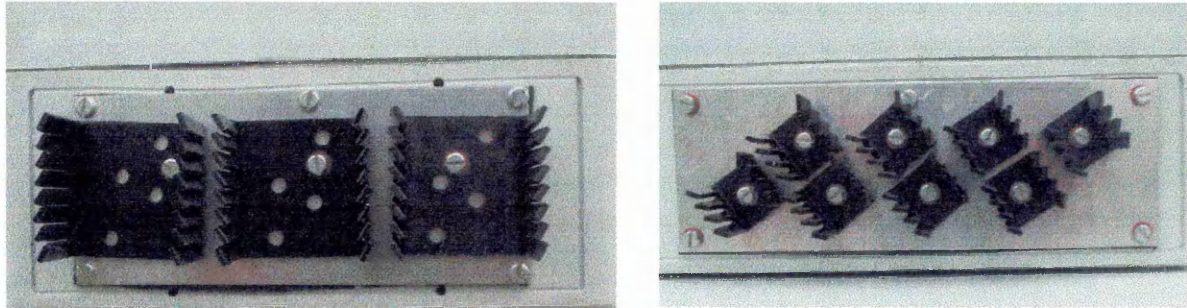


Fig.3-20: Heat sinks for regulators (right) and motor resistors (left).

3.4 Position

3.4.1 Dead reckoning

To count the pumping cycles of the hydraulic motor in order to know the position of the sprinkler, a micro switch is set to attach to the lever of the sprinkler wheel as shown in Fig.3-30. This micro switch is Single sealed miniature micro switch V3SYR Series from Burgess. The mechanism of this micro-switch is totally enclosed to IP67. The equation of travelling distance is,

$$[Travelling\ distance] = [Counted\ value] * 0.07\ (m) \quad (3.4)$$

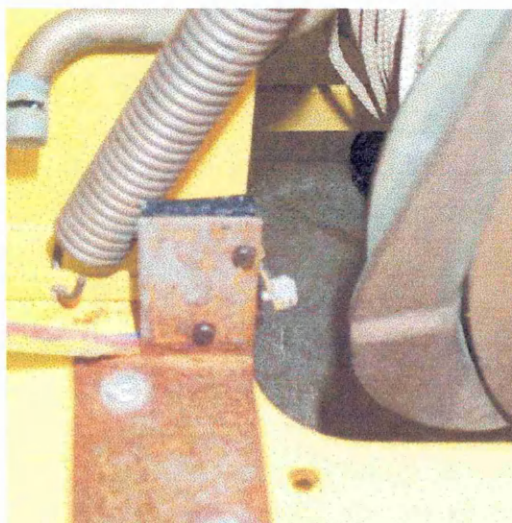


Fig.3-21: Wheel micro switch

3.4.2 DGPS

DGPS stands for Differential GPS which allows users to obtain increased accuracy from the GPS system. In some projects, DGPS has already been tried applying to Agricultural machinery to develop treatment maps which can show the requirement that varies in different regions of a field, different species of plants, or different seasons.

In this study, treatment maps of water and fertilizer requirements can be developed with DGPS. Further, by comparing the dead reckoning data with that of DGPS, this positioning system will become more reliable.

The structure of the system flow with DGPS and treatment maps is shown in Section 4.3.3.

4. Development of Software

4.1 Introduction to Software

The software was designed to operate this system to compensate the water drift from the wind more instantaneously and more accurately. There are three control programs that are named MAINSTIL.C, MAIN50X.C, and MAINGPS.C. The programs are composed of a few modules, which are shown as Table 4-1. Section 4.2 explains the main of the modules in more detail.

Name	Contents
ini.c	Initialize I/O ports and counters/timers.
ini_p12.c	Initialize the rotate position of motors.
set_pres.c	Select normal irrigation or chemigation. Confirm the pressure value.
micros.c	Read the input data from micro switches.
cal_pos4.c	Calculate the compensated angles.
Cnt_avg.c	Reading the data (Pressure, wind direction, wind speed) by using Real Time Clock.
2m_vp12.c	Drive motors.
Com1wrrd.c	Send strings to the external computer and read strings from it.
2m_vp1.h	Header file for 2m_vp12.c
ini.h	Header file for ini.c
main.h	Header file for control programs.
Opt24.h	Header file for parallel I/O on TPO24
Tpo406io.h	Header file for parallel I/O on TP406
Cnt_tavg.h	Header file for Cnt_avg.c

Table 4-1: The list of main modules in control programs.

Other programs used for checking the devices, sensors, micro switches, motors, GPS, are on the CD in Appendix IV. MainGPS.c has not been tried yet but is written about due to the usefulness for the next improvement.

4.2 Main modules of control programs

4.2.1 Motor control program

It is named 2m_vp12.c.

A list of functions in 2m_vp12.c is shown below.

Name	Contents	Variable
interrupt Motor()	Output motor clock signals	current_sAngle current_tAngle
CHANGE_TIMER()	Timer for interrupt	new count
Set_speed()	Set motor speed	speed1, speed2
Set_vp()	Set valve and pump	ctr_v, ctr_p
start_stop()	Set commands for motors to stop or start	SS[0], SS[1]
set_command()	Set commands for motors	dir[0], dir[1]
set_position()	Set the variables of commands according to calculation results.	d_sAngle, d_tAngle

Table 4-2: A list of functions in 2m_vp12.C

To drive two motors simultaneously and control the rotational direction, speed instantaneously, a timer interrupt was applied for the motor drive module as described in the next page. The current interval time is fixed to be 50Hz, however, the timing of the output of the control command can be changed from 18Hz to 1000Hz as shown in Table 4-4. This means that the rotational directions, speeds of the two motors can be set respectively to follow the calculation results. The speed of both the trajectory and sector motor is set 2, where is highest. Therefore, actual motor rotate speed is 1.5 rpm, which turns the gearbox's output at 0.3 rpm.

The equations below are used to calculate the rotational speed.

$$[Rotate\ speed\ of\ motor] = \frac{0.9 \times \frac{1000}{(IntervalTime(ms)) \times 2} \times 60}{360} \quad (4.1)$$

$$[Rotate\ speed\ of\ gear] = [Rotate\ speed\ of\ motor] / 5 \quad (4.2)$$

It should be warned that a higher frequency than 100HZ causes the motors to move unstably because of the conflict between the motor drive clocks and the data transfer by a RS232.

To know the current positions of motors, which are named `current_sAngle` for the sector angle, `current_tAngle` for the trajectory angle in the control programs, the output pulses are counted depending on the rotational directions. If the rotational directions are in the anti clockwise, the current positions are added 1, otherwise, subtracted 1. A part of the program is shown below to make it understandable.

```
void interrupt motor(void)
{
    unsigned char command1;
    unsigned char command2;
    unsigned char drv_command1;
    unsigned char drv_command2;

    command1 = set_command(0);
    command2 = set_command(1);
    drv_command1 = command1 + start_stop(0);
    drv_command2 = command2 + start_stop(1);

    if((count % speed1) == 0){
        outportb(IO_TPO24+TPO24IO_PA, drv_command1);
        if((dir[0]==1) && (SS[0]==1)) current_tAngle++;
        else if((dir[0]==0) && (SS[0]==1)) current_tAngle--;
        else current_tAngle = current_tAngle;}
    if((count % speed2) == 0){
        outportb(IO_TPO24+TPO24IO_PC, drv_command2);
        if((dir[1]==1) && (SS[1]==1)) current_sAngle++;
        else if((dir[1]==0) && (SS[1]==1)) current_sAngle--;
        else current_sAngle=current_sAngle;}
    if((count % speed1) == (speed1/2)) {
        outportb(IO_TPO24+TPO24IO_PA, command1);
    }
    if((count % speed2) == (speed2/2)) {
        outportb(IO_TPO24+TPO24IO_PC, command2);
    }
    count++;
}
```

The interrupt timer is driven by Counter 0 channel of a chip 8254 on TB486. The setting of the timer interrupt is shown in the below Table 4-3.

SITUATIONS	Variables	COMMAND (MOTOR1)	COMMAND (MOTOR2)
MOTOR CLOCK SIGNAL High Low		0x02 0x00	0x02 << 6 0x00 << 6
ROTATE DIRECTION Clockwise Anti clockwise	dir [] = 1 dir [] = 0	0x01 0x00	0x01 << 6 0x00 << 6
OPEN VALVE CLOSE VALVE	ctr_v[0] = 1 ctr_v[0] = 0	0x00 0x20	
DRIVE PUMP STOP PUMP	ctr_p[0] = 1 ctr_p[0] = 0	0x10 0x00	

Table 4-5: Output numbers for controlling peripheral devices.

4.2.2 Reading data function

The function is called Cnt_avg.C.

A list of functions is shown below.

Name	Contents	Varilable
Data_read0()	Read first data	CH
Data_read1()	Read second data after 250ms interval	CH
conversion()	Converse numerical data to a string called laptop[]	
Timing()	Wait for 250 ms	
time_avg()	Data correction for 250ms	
time_avg_pres()	Data correction for 250ms	

Table 4-6: A list of functions in Cnt_avg.C

To read the data every 250 ms, a counter/timer Chip No2 Channel 0 on TP406 is used. The function is shown below.

The timer is divided by two, which means that $m = 0$ when the count value is over 0x7FFF, otherwise $m = 1$ as shown in the part of the program. This counter frequency is 8.33 MHz.

Since, t_count , the number of times when $m = 1$,

$$[t_count \text{ per second}] = 8.33 \times 1000 / \text{xFFFF} \quad (4.3)$$

$$= 127.1$$

So, when $t_count = 32$, the interval is 250ms.

```

*****
void Timing(void)
{
    char m=0;
    unsigned t_low, t_high;
    unsigned t;
    unsigned char t_count=0;

    outportb(TP406+CntREG1, 0x34);          /*Mode 4*/
    outportb(TP406+Cnt1, 0xFF);
    outportb(TP406+Cnt1, 0xFF);

    do{
        t_low = inportb(TP406+Cnt1);
        t_high = (inportb(TP406+Cnt1) << 8);
        t = t_low + t_high;

        if((t < 0x7fff) && (m==0)) {
            t_count++;
            m=1;
        } else if((t >= 0x7fff) && (m==1)) m=0;
    }while(t_count<32);    /* 127.1 = 8.33/0xffff */
}
*****

```

The subtraction between the first counter value and the second one after 250 ms is kept into an array until 1 second passes, which means that the process is repeated 4 times. The four values are summed up to get the average value every second which is calibrated to show them in each unit as described below.

The details of the calibrations are written in section 3.3.1, 3.3.2, 3.3.3.

$$[Wind\ Direction] = 360 - (The\ summed\ value) \times 356.5 / 500 + 1.75 \quad (4.4)$$

$$[Wind\ Speed] = (The\ summed\ value) \times 0.1 \quad (4.5)$$

$$[Pressure] = (The\ summed\ value \times 4 - 116) / 5.5 \quad (4.6)$$

4.2.3 Calculation of the optimum angles

It is named Calc_pos3.C, or Calc_pos4.C.

A list of functions is shown below.

Name	Contents	Return value
opt_sector ()	Calculate the optimum sector angle	p_sAngle (=rotated sector angle)
opt_trajectory ()	Calculate the optimum trajectory angle	p_tAngle (=rotated trajectory angle)
confirm ()	Confirm the rotate positions	TRUE or FALSE

Table 4-7: A list of functions in Calc_posX.C

The parameter of the equation on the sector angle in Calc_pos3.C is constant, C'_{sec} , whereas it is a variable in Calc_pos4.C as shown below. The details of the equations are described in Section 5.3.2.

$$[Optimum\ sector\ angle] = 90 - Arc\ tan\left(\frac{C'_{sec} \times (WindSpeed) \times \cos(\theta)}{d}\right) \quad (4.7)$$

$$C'_{sec} = 0.7$$

$$[Optimum\ sector\ angle] = 90 - Arc\ tan\left(\frac{C_{sec} \times \frac{1}{2}(1 + K) \times (WindSpeed) \times \cos(\theta)}{d}\right) \quad (4.8)$$

The value of d is changed depending on wind direction:

$$\begin{aligned} d &= 8.5 && \text{when wind direction is less than } 180^\circ. \\ d &= 9.5 && \text{otherwise.} \end{aligned}$$

Calculating the optimum angles for the spot wind direction and speed, the programs return the values of the difference between the current angle and the aimed angle to the 2m_vp12.C. This program is executed every 250 ms soon after reading wind data.

4.2.4 COM1 communication between the embedded computer and the user's PC

The programs are named Com1wrrd.C in the side of the embedded computer and Read1.C in the user's computer. The two programs enable the embedded computer to communicate with the user's computer.

The lists of functions in Com1wrrd.C and in Read1.C are shown in the following tables.

Name	Contents
interrupt COM1INT()	Read data when it gets to COM1
com1_rd_fw()	Read a user's input F(fertilizer) or W(water).
com1_rd()	Wait till Enter key on user's computer is pressed.
com1_op_wr()	Open COM1 to write strings
com1_wr()	Output strings to COM1

Table 4-8: The list of functions in com1wrrd.c

Name	Contents
interrupt oldcom1isr()	Read data when it gets to COM1
open_file()	Open file "Data.txt".
com1_rd()	Read and Save data or message from the embedded computer.
com1_wr()	Open COM1 to write strings

Table 4-9: The list of functions in Read1.C.

The field controller unit does not have a display to see the inside of the embedded computer nor a keyboard to command to it. Furthermore, the embedded computer does not have enough memory to run a few programs with Turbo C and save data. Therefore, it needed to make the communication between the embedded computer and the user's interactively.

Com1wrrd.C can send the data, Wind Direction, Wind Speed, Pressure, Distance, Trajectory Angle, Sector Angle, which are outputted into COM1 port from the embedded computer. Read1.C can read the data or messages shown below and save them.

"Enter for start"	when the system starts.
"Choose 'F' or 'W'"	when user chooses fertilizer or water to be fed.
"Done"	when the pressure is ready with Set_pres.C.
"Initialized"	when the positions are initialized.
"Complete"	when all operation is finished.

Whereas, 'ENTER' key on user's computer is pressed when every thing is ready to start the system, the main program starts running.

4.3 The structures of main control programs

There are three main programs, MAINSTIL.C, MAIN50X.C, and MAINGPS.C. The programs are composed of small modules.

4.3.1 MAINSTIL.C

This program is used to know the specifications of this robotic STS, which are the water distribution patterns at no wind and in windy conditions when the head is uncontrolled. The result of the execution enables to make the prediction and control models of the trajectory angle and sector. The flow chart of this program is shown in Fig.4-1.

First, after the pressure becomes high enough to operate the STS system, the positions of motors are initialized, 90° from the travelling direction in sector angle and 27° from the horizontal in trajectory angle. Second, it collects data of wind direction, wind speed, pressure and does not drive motors. The data is sent through RS232 from the embedded computer to the user's computer, displayed, and saved on it. The time interval of sending data is 1 second.

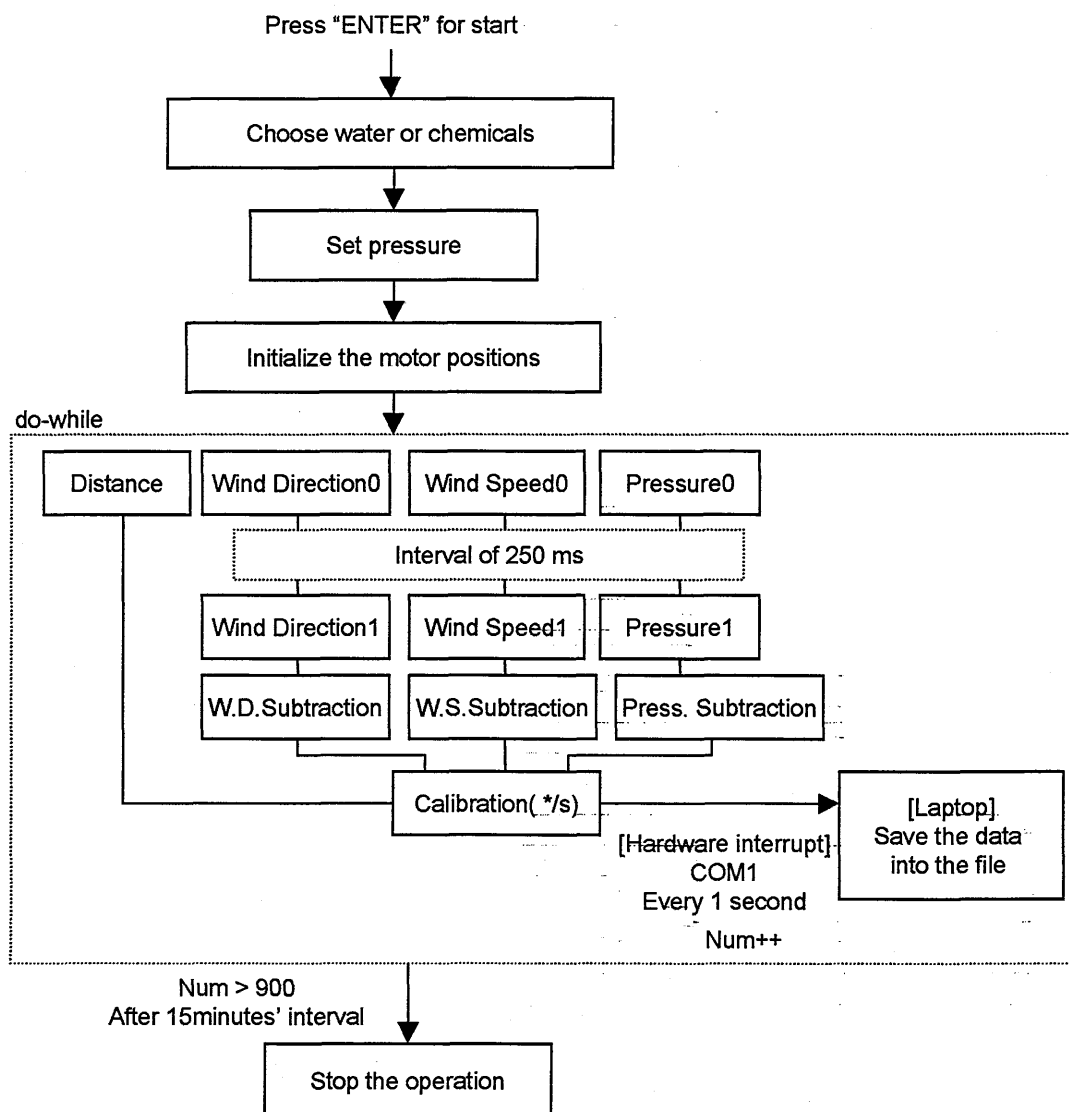


Fig.4-1: The structure of MAINSTIL.C

Following the flow chart, the main program of MAINSTIL.C was composed as below.

```

*****
#include <dos.h>
#include <stdio.h>
#include <conio.h>
#include <math.h>
#include <stdlib.h>
#include <string.h>
#include <time.h>

#include "main.h"
  
```

```

#include "ini.c"
#include "com1wrrd.c"
#include "cnt_avg.c"
#include "set_pres.c"
#include "micros.c"      /*don't change this order!!*/
#include "2m_vp12.c"
#include "ini_p12.c"

char *str1="Press 'Enter' key for start:";
char *str5="Complete:";

void main(void)
{

    clrscr();
    initialize();

    com1_op_wr();
    com1_wr(str1);
    com1_rd();

    com1_op_wr();

    set_pres();

    ini_position();

    do{
        time_avg();

    }while(num<900);      /* Stop in 15 mins */

    clr_IO();
    com1_wr(str5);
}
*****

```

The result of the execution of MAINSTIL.C is shown in Section 5.2.

4.3.2 MAIN50X.C

MAIN50X.C is different from MAINSTIL.C in that it drives the motors at the same time as collecting data. There are two different ways to read the data. One is that when the wheel micro-switch is pressed, the timer interrupt for motors is set disable and read the data which is sent to user's computer by a RS232. The other is to send the data every 15 seconds when the motor interrupt is set disable. The latter way was used for the experiments. After the program finishes dealing with the data, the motor interrupt is set enable again. In this program, the data includes Distance, Wind Direction, Wind Speed, Pressure, Trajectory angle, Sector angle. This process is repeated until the sprinkler reaches the destination which is calculated by using the wheel micro

switch, in case of experiment, until 15 minutes passes.

The calculation of the travelling distance by the wheel micro switch is described as below.

When the switch is ON, the sprinkler has advanced 7cm.

Since, the travelling distance:

$$Distance = [The\ number\ of\ ON] \times 0.07\ (m) \quad (4.9)$$

The structure of MAIN50X is shown in Fig.4-2.

MAIN50X includes MAIN504 and MAIN503. There is a difference between the two in that MAIN504.C applies Calc_pos4.C while MAIN503.C uses Calc_pos3.C.

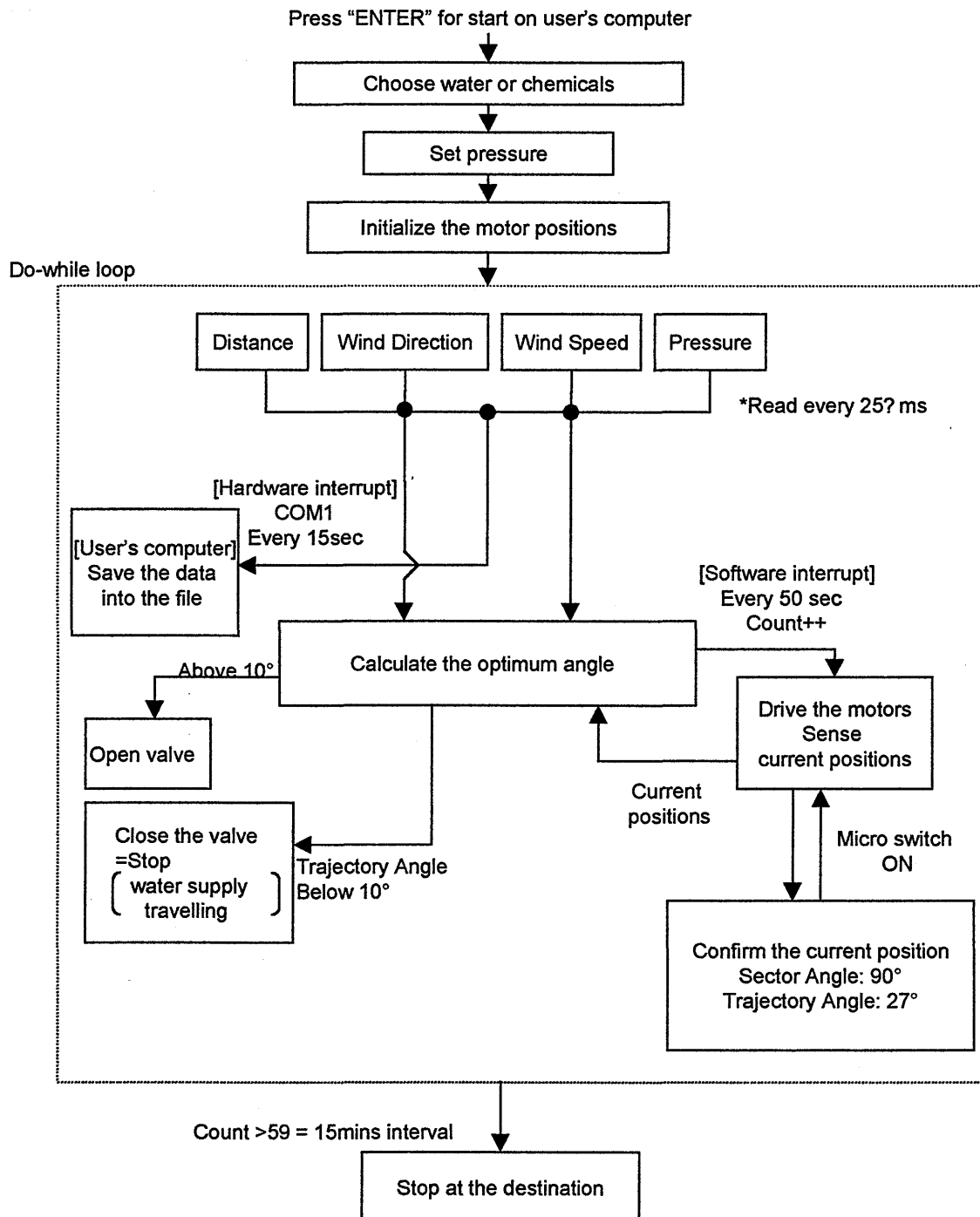


Fig.4-2: The structure of MAIN50X.

The main program of MAIN50X is shown below.

```
#include <dos.h>
#include <stdio.h>
#include <conio.h>
#include <math.h>
#include <stdlib.h>
#include <string.h>

#include "main.h"
#include "ini.c"
#include "com1wrrd.c"
#include "cnt_avg.c"
#include "set_pres.c"
#include "micros.c"      /*don't change this order!!*/
#include "cal_pos4.c"
#include "2m_vp12.c"
#include "ini_p12.c"

char *str1="Press 'Enter' key for start.";
char *str5="Complete.";

void main(void)
{
    char s;
    int calc_num=0;
    char i;

    clrscr();
    initialize();

    com1_op_wr();
    com1_wr(str1);
    com1_rd();
    com1_op_wr();

    set_pres();

    ini_position();

    for(s=0; s<60; s++){

        enable();
        Old_Time_Isr = getvect(TIME_KEEPER_INT);
        setvect(TIME_KEEPER_INT, motor);

        set_speed();

        n=5;

        do{
            time_avg();
            if(k==1) set_position(opt_sector(), opt_trajectory());
            calc_num ++;
        }while((calc_num%60)!=0);      /* Stop at 10m from the starting point */

        setvect(TIME_KEEPER_INT, Old_Time_Isr);
```

```
disable();

conversion();
com1_wr(laptop);

}
clr_IO();

com1_wr(str5);
}
*****
```

The results of the executions are shown in Section 6.2 and 6.3.

4.3.3 MAINGPS.C

This program is for using DGPS as the next improvement.

When GPS is incorporated with this system, PC connector board should be redesigned to make COM port 2 available because COM1 has been occupied for transferring data. It can be suggested that there is a high possibility that the conflict among two com ports and an interrupt for motors becomes more severe. Therefore, the programs should be constructed with more attention to the timing for all the operation.

A module named “readgps.c” is only added to the MAIN50X.C. The GPS module includes smaller modules as shown below and the structure of MIANGPS.C is shown in Fig. 4-3.

Name	Contents
comms.c	Open or close com ports.
calc.c	Calculate the real position in meter from the latitude and the longitude.
extract.c	Convert the string data into numerical data.
gps.c	Read the strings including the position data from the aerial.
mf.h	Header file for readgps.c
litecomm.h	Header file for comms.c

Table 4-10: The list of modules in readgps.c.

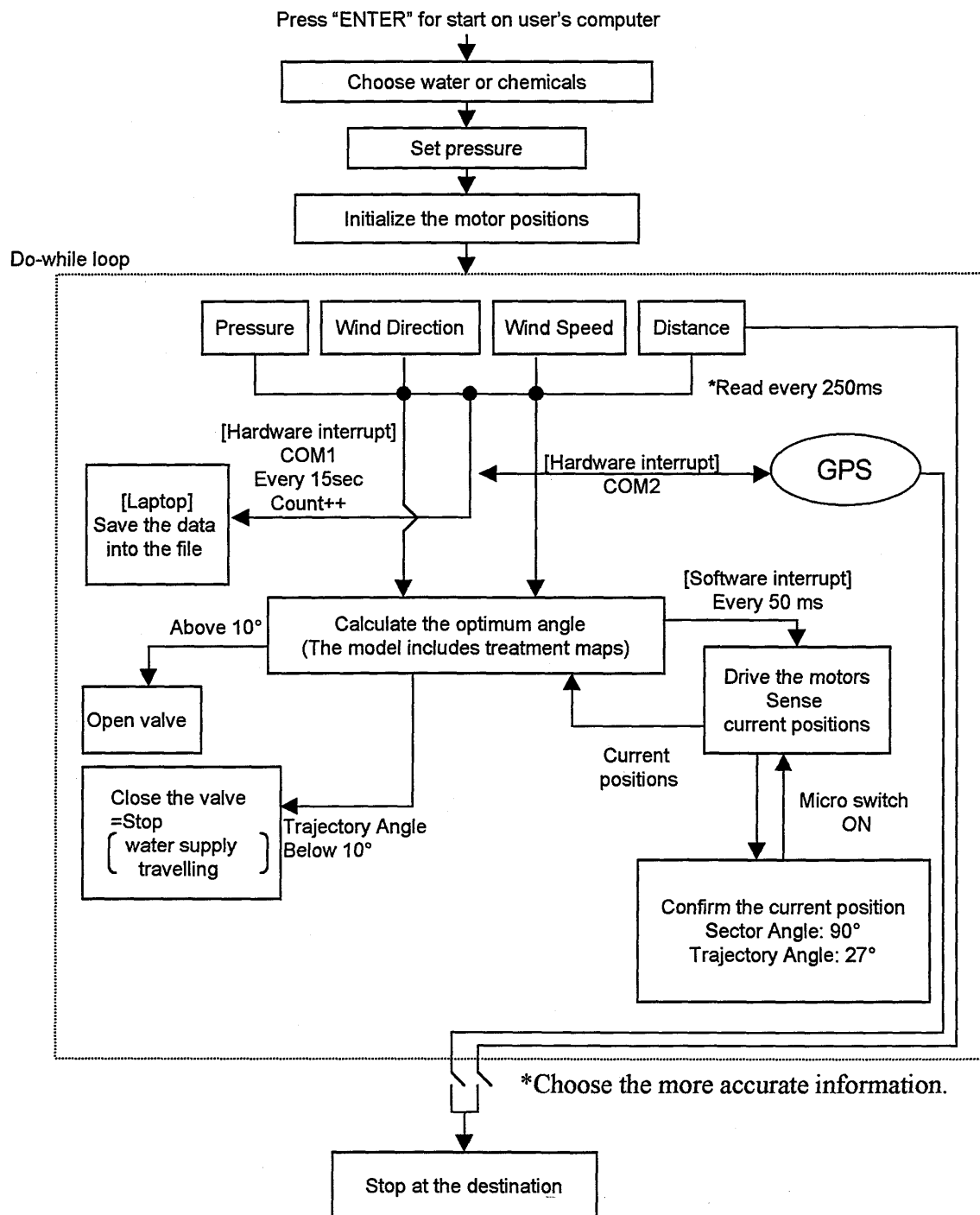


Fig.4-3: The structure of MAINGPS.C.

5. Prediction and Control models

5.1 Introduction to models

5.1.1 Centre of volume model – C.V. & Semi-empirical model

Center of volume and semi-empirical model can predict the water distribution of STS. The former can predict the shift of the center of volume (C.V.) taking into account wind speed and direction, while the latter can indicate the edge of the wetted area according to crosswind, upwind, downwind. In this study, the center of volume model was mainly applied except for to seek the optimum trajectory angle.

In the center of volume model, X , Y , axes are defined as Fig.5-1 to calculate a center of volume as follows.

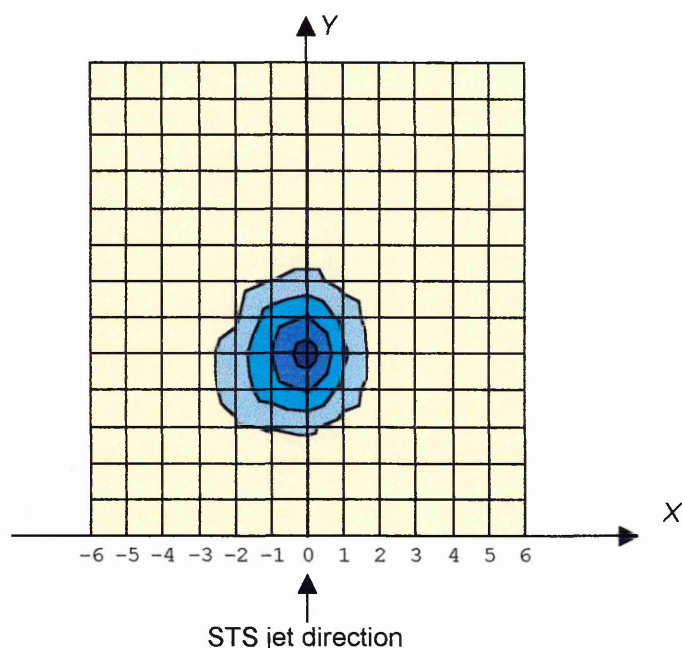


Fig.5-1: The format of the water distribution.

When $W(X,Y)$ is the amount of water in a catch can placed on a point (X, Y) ,

$$X_{C.V.} = \frac{\sum_{X=-6}^{X=6} X \times \sum_{Y=0}^{Y=14} W(X,Y)}{\sum W(X,Y)} \quad (5.1)$$

$$Y_{C.V.} = \frac{\sum_{X=0}^{Y=14} Y \times \sum_{X=-6}^{X=6} W(X,Y)}{\sum W(X,Y)} \quad (5.2)$$

Although the model can be applied to simulate the horizontal shift of the center of volume, it cannot indicate the optimum angles.

Therefore, a semi-empirical model is employed for the optimum trajectory angle. This indicates such an angle to maximize the edge of the wetted area. The results of the semi empirical model (von Bernuth R.D. (1989)) are shown below.

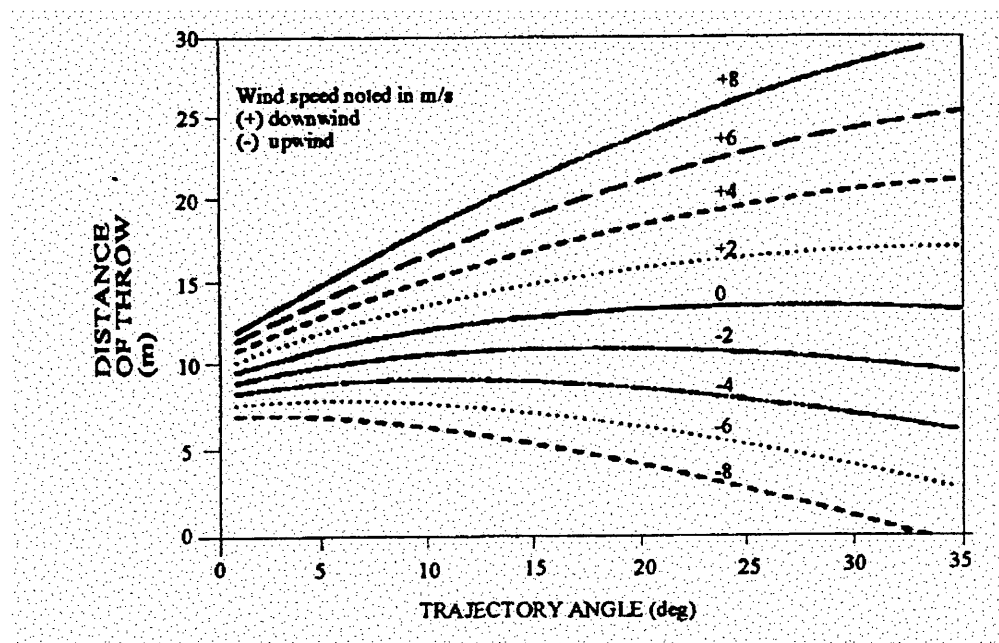


Fig.5-2: Maximum radius of throw of 3.4mm drop as function of trajectory angle.

? Water pressure

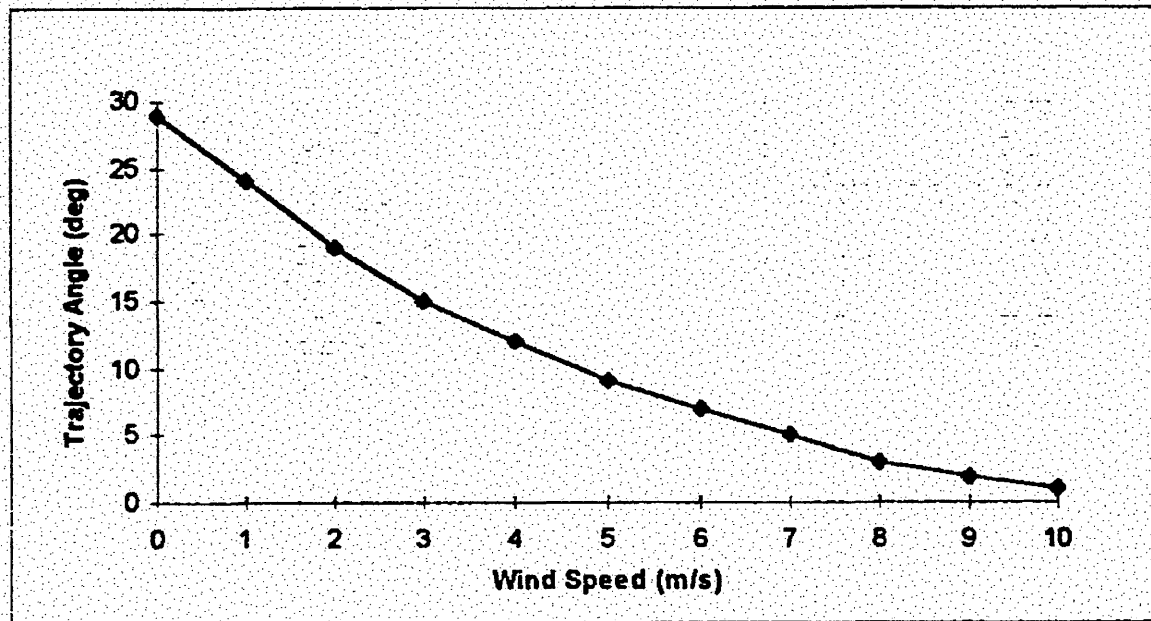


Fig.5-3: Optimum trajectory for maximum upwind distance of throw.

5.1.2 Multi phase model

A multi phase model for agricultural applications (Gross D.J., Parkin C.S., Weatherhead E.K.), is a more sophisticated model, which can simulate the wetted area of a sprinkler by investigating the behavior of a droplet. The averaged values of velocity and droplets radius are applied to the model. The results showed that the model is accurate enough to be useful for this prediction model.

Therefore, it will be applied to predict the water distribution from the spot jet direction more accurately and to develop more precise control models. Furthermore, it can be also applied to create a treatment while the STS is operated.

5.1.3 Introduction of the prediction and control models

To predict and analyze the water distribution pattern, a center of volume model is applied except for to seek the optimum trajectory angle for which a semi-empirical model is used (Section 5.4.2).

First, an experiment was carried out under static operation to make prediction models (Section 5.3.1, 5.4.1). Next, the equations that express the optimum sector angle were found by using the results (Section 5.3.2). It was assumed that the sector angle was only concerned with the

horizontal wind speed, while the trajectory angle was related with the wind speed.

5.2 Experiment for prediction models

5.2.1 Experimental design

The scene of the experiment is shown in Fig.5-4.

A total number, 168, of the catch cans were arranged on the flat grass field in 13 columns and 14 rows every 1 m. However, there were only 7 catch cans at the both sided columns, 1 and 13. The first column was 1.5 m far from the jet of the STS. The amount of water in a catch can was measured with 500ml measuring cylinders. To run this system outside, at least two 12V batteries were required.

The interval time of an experiment was 15 minutes for which wind data was read and saved in the user's computer every second.

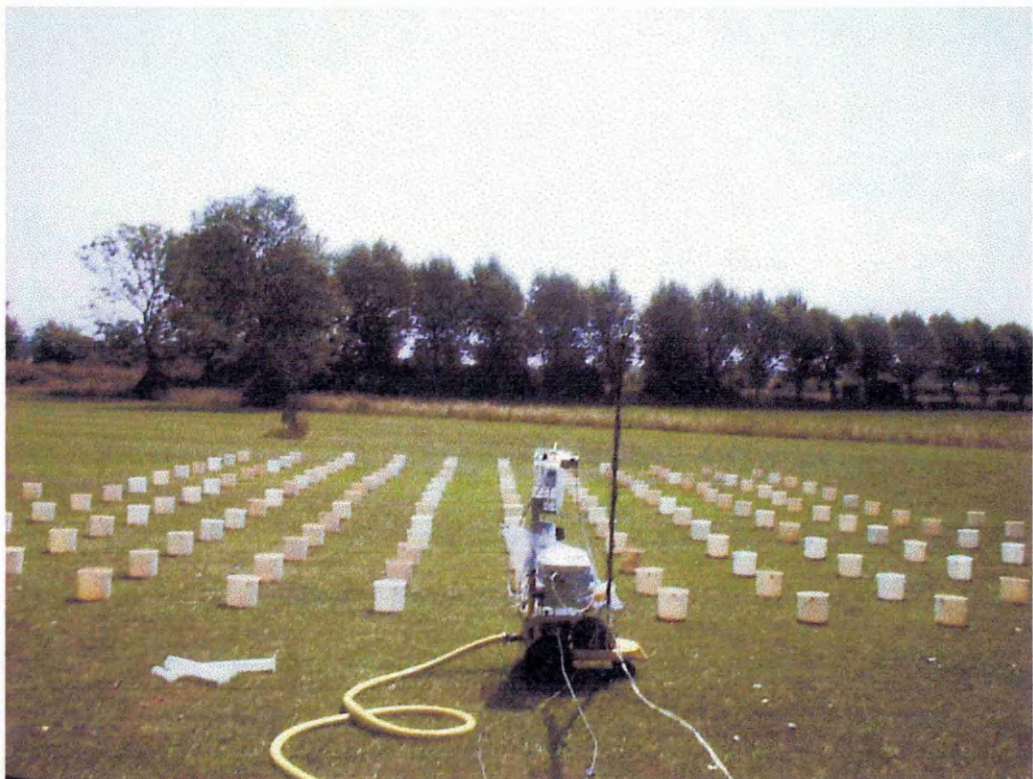


Fig.5-4: The scene of the field experiment. (Silsoe college, Cranfield Uni., U.K.,13/07/99)

5.2.2 Results –Uncontrolled

Five experiment were performed on 11/07/99 when the weather was fine. The data is described in Table 5-1.

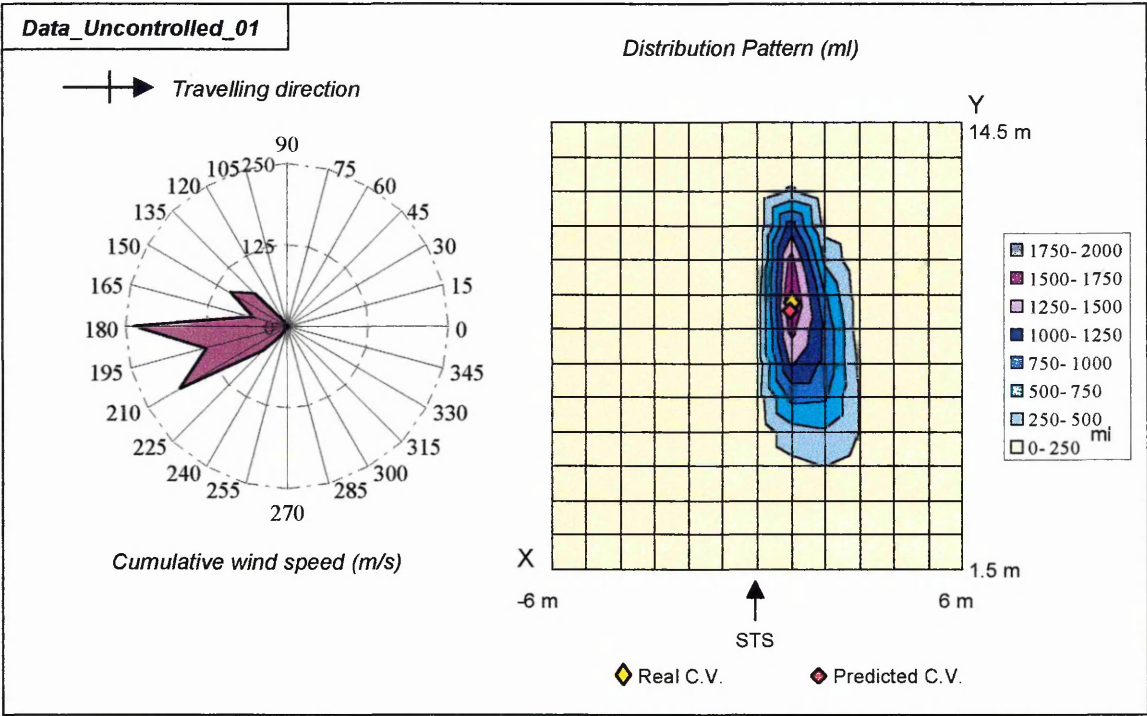
All of the data was collected under 38 psi.

? How do you justify 4-figure precision in these (and other) tables

Data No.	Average wind speed (m/s)	Average wind direction (°)	X of C.V. (m)	Y of C.V. (m)
Uncontrolled_01	1.406	198.4	1.456	8.34
Uncontrolled_02	2.515	174.5	2.437	6.63
Uncontrolled_03	2.208	185.2	2.318	6.727
Uncontrolled_04	1.99	200	1.763	7.225
Uncontrolled_05	1.59	208	1.66	7.62

Table 5-1: The results under the uncontrolled operation.

The cumulative wind speed and water distribution of the first data, Uncontrolled_01, is shown in Fig. 5-2. Other four data are in Appendix II.



Pressure (psi)	Real C.V. (X,Y)	Predicted C.V. (X,Y)	Average wind Speed (m/s)	Average wind direction (°)
38	(1.456, 8.34)	(1.34, 8.105)	1.406	98.4

Fig.5-5: The wind condition and water distribution of Data_Uncontrolled_01.

The prediction models are written in Section 5.3.1 for the horizontal shift of C.V. X , Section 5.4.1 for the vertical shift of C.V., Y .

5.3 Sector angle

5.3.1 Prediction model of the sector angle

Only the horizontal shift is taken into account for the prediction model of sector angle. The data written in Table 5-1 is plotted to find an adequate regression between the horizontal shift and horizontal wind speed.

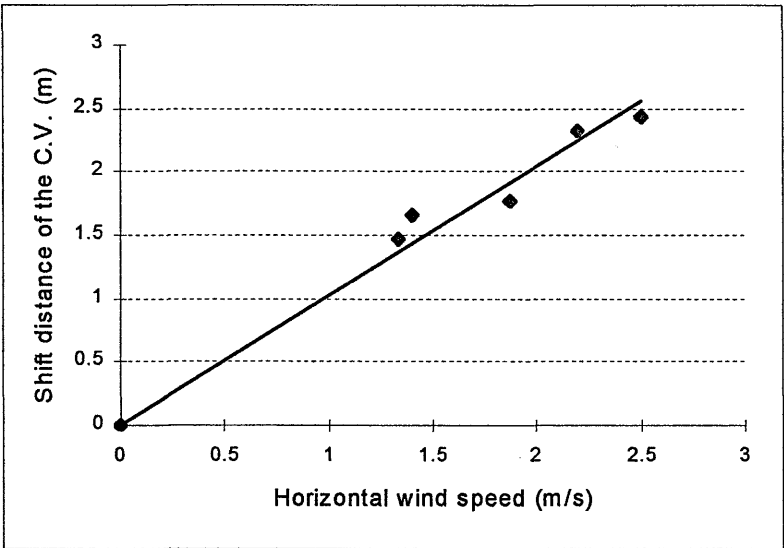


Fig.5-6: The horizontal shift of Center of volume to horizontal wind speed.

The regression line is:

$$X = 1.023 \times (Wind\ Speed) \times \cos(Wind\ Direction) \quad R_2 = 0.973 \tag{5.3}$$

X is the horizontal shift distance. The constant 1.023 is defined as C_{sec} .

Since,

$$X_{predicted} = C_{sec} \times (Wind\ Speed) \times \cos(Wind\ Direction) \tag{5.4}$$

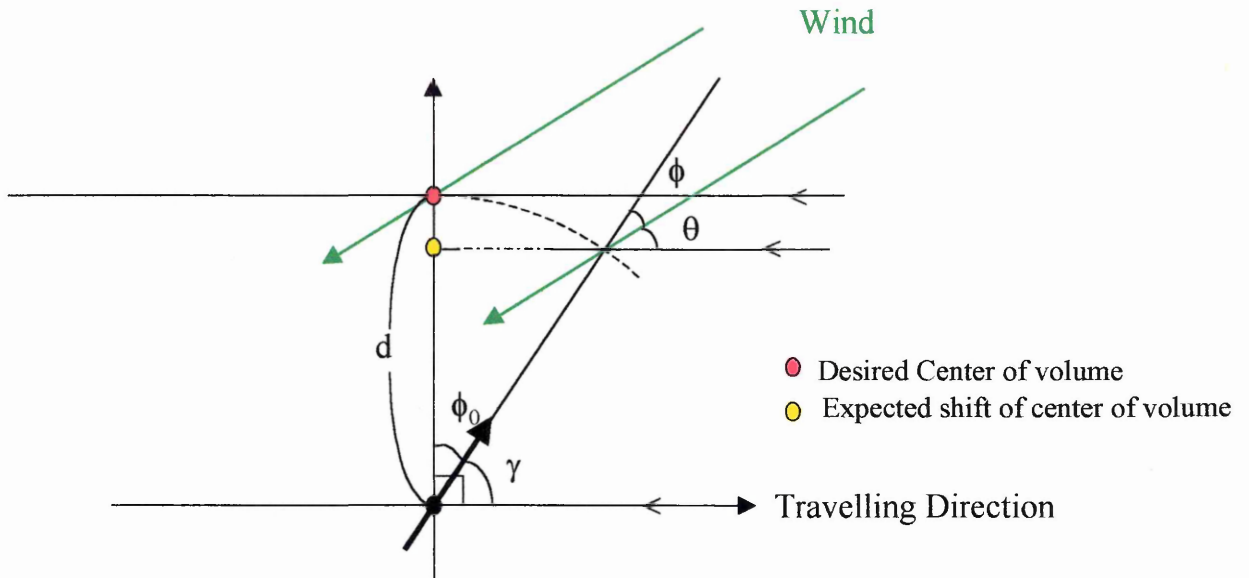
From the equation, the predicted points are sought as shown in Table 5-2.

Data No.	$X_{predicted}$	X_{real}
Uncontrolled_01	8.338	8.456
Uncontrolled_02	9.51	9.437
Uncontrolled_03	9.204	9.318
Uncontrolled_04	8.875	8.763
Uncontrolled_05	8.408	8.66

Table 5-2: $X_{predicted}$ and X_{real} of C.V. under the uncontrolled operations.

5.3.2 Equation of the optimum sector angle

The equation of the optimum sector angle was sought geometrically as described in Fig.5-4.



γ : Angle between travelling direction and the current nozzle direction

θ : Wind direction to travelling direction

ϕ : $\gamma - \theta$

ϕ_0 : $90 - \gamma$

Fig.5-7: Geometric model of the shift of a center of volume.

The horizontal shift distance X_{cal} at γ of the nozzle direction is

$$\begin{aligned}
 X_{cal} &= d \times \tan \phi_0 \\
 &= C_{sec} \times (WindSpeed) \times \cos(\phi_0 + \theta) \times \cos \phi_0 \\
 &= C_{sec} \times (WindSpeed) \times \left(\frac{1}{2} \cos \theta + \frac{1}{2} \cos(2\phi_0 - \theta) \right)
 \end{aligned} \tag{5.5}$$

To make this equation simpler to be applied for controlling, $\cos(2\phi_0 - \theta)$ is defined as K which is described as below.

$$\begin{aligned}
 K &= 0.1 && \text{when } 2\phi_0 - \theta \geq 60 \\
 K &= 0.26 && \text{when } 60 > 2\phi_0 - \theta \geq 45 \\
 K &= 0.5 && \text{when } 45 > 2\phi_0 - \theta \geq 30 \\
 K &= 0.71 && \text{when } 30 > 2\phi_0 - \theta \geq 15 \\
 K &= 0.87 && \text{when } 15 > 2\phi_0 - \theta \geq 0
 \end{aligned} \tag{5.5}$$

However, when $270 > \theta \geq 180$,

$$\theta = \theta - 90$$

when $\theta \geq 270$,

$$\theta = 360 - \theta$$

As a conclusion, the equation of the optimum sector angle is

$$\phi_0 = \text{Arc tan} \left(\frac{C_{\text{sec}} \times \frac{1}{2} (1 + K) \times (\text{WindSpeed}) \times \cos(\theta)}{d} \right) \quad (5.6)$$

Each of K , γ follows above condition.

5.4 Trajectory angle

5.4.1 Prediction model of trajectory angle

From the result, each Y value of the Center of volume are plotted on Fig.5-5 to find a linear relationship between Y value and wind speed.

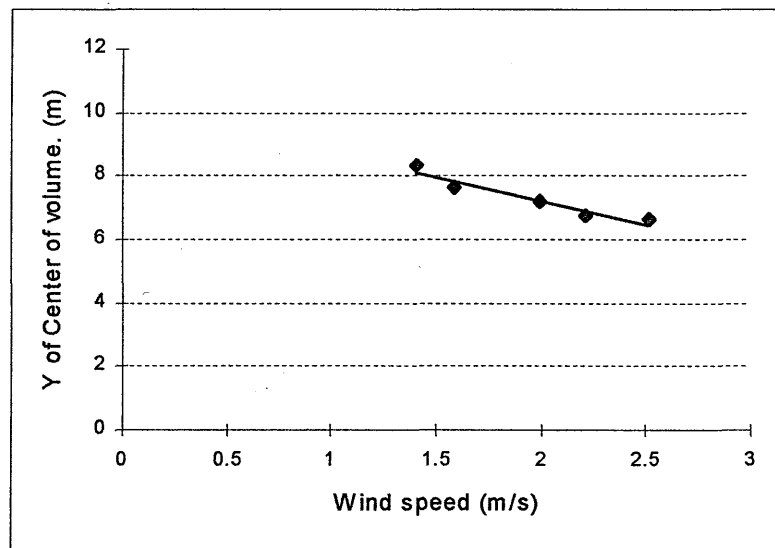


Fig.5-8: The real Y value of Center of volume to the average wind speed.

The regression line is

$$Y = -1.49 \times (\text{WindSpeed}) + 10.2 \quad R^2 = 0.915 \quad (5.6)$$

However, there was no chance that the data at no wind could be collected. So, for controlling, the spot data was used and the value is 8.5 m at upwind and 9.5 m at downwind. The detail is shown in Section 4.2.3.

Fortunately, both experiments had no averaged wind speed which was less than 1.33 (m/s). Therefore, it was judged that the regression line could be applied.

5.4.2 Equations of the optimum trajectory angle

In the previous section, the equation was found to predict Y value of a center of volume. However, to seek a model of the optimum trajectory angle to keep Y of the C.V. constant, it needs a far larger amount of data of this robotic STS. Therefore, the data (von Bernuth (1989)) shown in Fig.5-2, 5-3 was applied for this study even if the average droplet size of this STS has not yet been measured.

The optimum trajectory angles for upwind and downwind are defined respectively due to a difference in the distance of throw between the two wind conditions. First, von Bernuth described the upwind optimum trajectory angle as the following equations.

$$[O.Tup.Angle] = 29.1 - 5.71 \times (WindSpeed) + 0.388 \times (WindSpeed)^2 - 0.0098 \times (WindSpeed)^3 \quad (5.7)$$

(*O.Tup.Angle* stands for the optimum trajectory angle at upwind.)

About the optimum trajectory angle at downwind, a equation was made by taking some intercept points between $Y = 15$ and the lines which indicate maximum radius of throw at each wind speed on Fig.5-2 (von Bernuth(1989)).

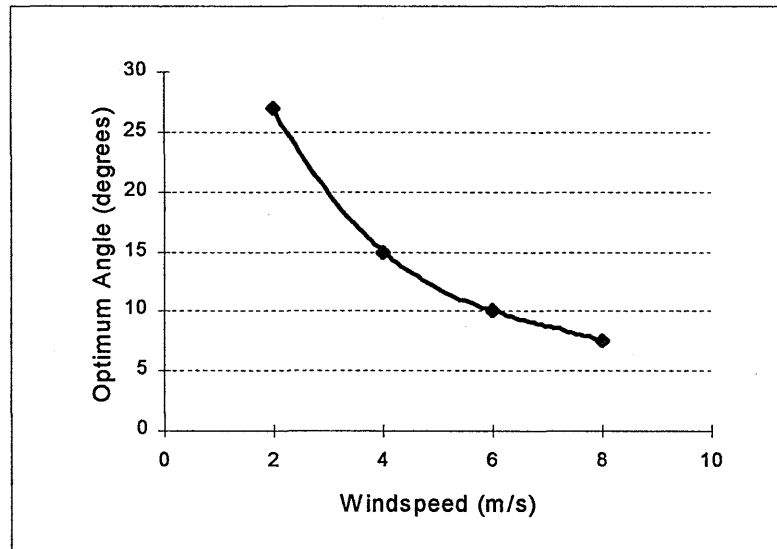


Fig.5-6: The optimum trajectory angle (degrees) to wind speed (m/s) at downwind.

The regression line is:

$$[O.Tdown.Angle] = 50.5 - 15.375 \times (WindSpeed) + 2.0 \times (WindSpeed)^2 - 0.0937 \times (WindSpeed)^3$$

$$R^2 = 1.$$

when $WindSpeed \geq 2$.

(5.8)

When $WindSpeed < 2$, $O.Tdown.Angle$ was set:

$$O.Tdown.Angle = 27.0$$

(5.9)

($O.Tdown.Angle$ stands for the optimum trajectory angle at downwind.)

6. Results of the controlled operations and Discussion

Following the way shown in Section 5.1, two sets of 5 experiments were executed. There was a difference between the first and the second set in the calculation of the optimum angles. Wind data was read every 15 seconds, which could not be shortened 1 second due to the conflict between the motor operation and the data transfer. Therefore, the statistic results are shown as below, although it should be said that there was insufficient data to prove the result perfectly.

6.1 Data of the first set

The control program MAIN503.EXE was applied for the first experiment. The parameter in the control model equation for the sector angle was set 0.7 as described in Section 5.3.2. This means that the relative wind direction is not taken into account of.

To confirm if C.V., which is defined as a point (X_0 controlled, Y_0 controlled), was corrected by the control system, the control model equations (5.1), (5.5) are applied and the calculation results are named X_0 predicted, Y_0 predicted.

The results from the experiment and calculation are shown in Table 6-1, 6-2.

Data No.	Average wind speed(m/s)	Average wind direction (°)	Rate of center row of water (%)	X of the maximum
Controlled_01	2.07	286.92	28.73	1
Controlled_02	1.33	271.85	34.17	0
Controlled_03	1.42	282.5	21.25	1
Controlled_04	2.13	291.9	11.708	1
Controlled_05	2.1	286.53	11.35	1

Table 6-1: The average wind data and the rate of water distribution at $X=0$, X of the maximum water distribution.

Data No.	X_0 controlled	X_0 predicted	Y_0 controlled	Y_0 predicted
Controlled_01	1.75	-0.6	8.15	7.25
Controlled_02	1.35	-0.04	8.70	8.22
Controlled_03	0.88	-0.23	8.49	8.86
Controlled_04	1.22	-0.8	8.65	7.25
Controlled_05	1.15	-0.6	9.48	9.2

Table 6-2: The values of controlled and predicted C.V. in the first experiment.

To make these results more clear, they are visualized as follows.

Other four data are described in Appendix II.

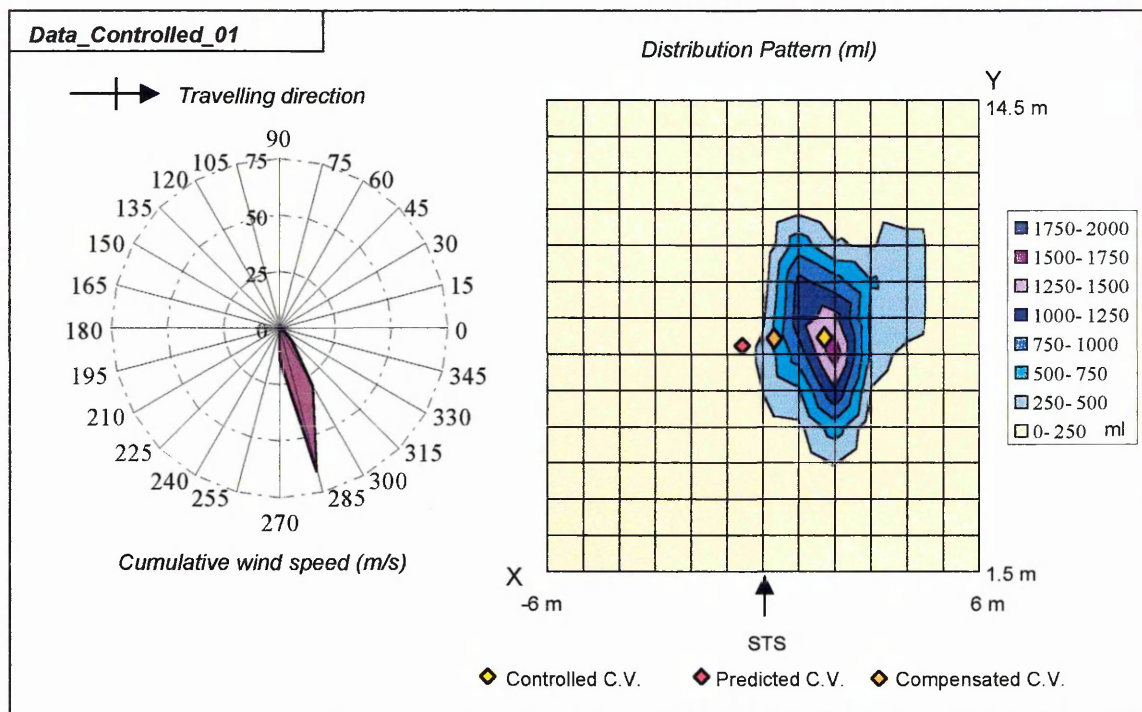


Fig.6-1: The water distribution and the cumulative wind data.

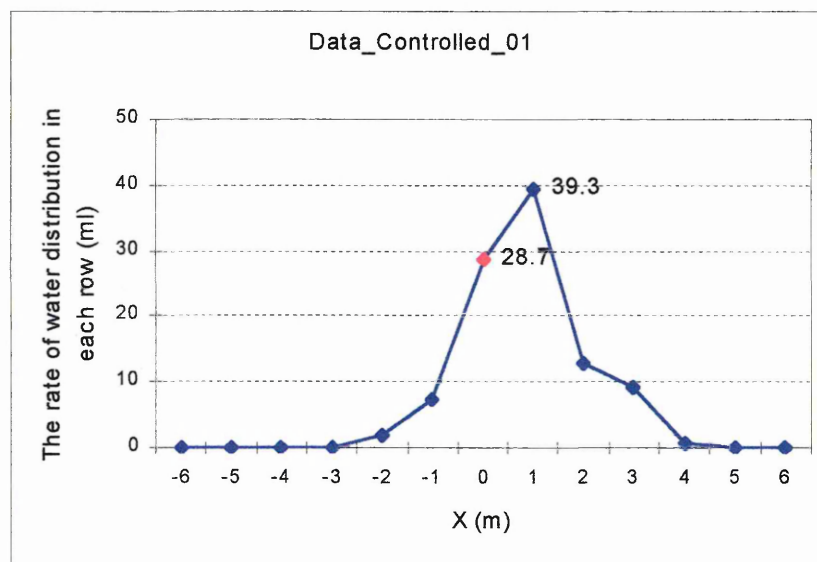


Fig.6-2: The rate of water distribution and the value at X=0.

Pressure (psi)	Total amount of water in catch cans(ml)	Average of wind speed (m/s)	Average of wind direction (°)
38	16244	2.07	286.9

	X	Y
Controlled	1.75	8.15
Predicted	-0.59	7.25
Compensated	0.13	8.15

Table 6-3: The data of Data_controlled_01.

To analyze this result, ANOVA is applied as follows.

Null hypothesis H_0 is

$$H_0 : \mu_{\text{predicted}} = \mu_{\text{controlled}}$$

Alternative hypothesis H_1 is

$$H_1 : \mu_{\text{predicted}} > \mu_{\text{controlled}}$$

when $\mu_{\text{predicted}}$ is the mean of $X_{0 \text{ predicted}}$ and $\mu_{\text{controlled}}$ is the mean of X_0 .

Source Variation	D.F	S.S.	M.S.	F _{calculated}	F _{tabulated 5%}
Treatments	1	1.747	1.747	17.21	5.32
Error	8	0.812	0.1015		
Total	9	2.59			

Table 6-4: ANOVA between the mean of $X_{0 \text{ predicted}}$ and $\mu_{\text{controlled}}$ is the mean of $X_{0 \text{ controlled}}$.

Since,

$$H_0 \text{ is not accepted.}$$

Further,

$$LSD = 0.311$$

when $T_{\text{error d.f.5\% 1-tailed}} = 1.153$.

Since,

$$\mu_{\text{controlled}} > \mu_{\text{predicted}}$$

is accepted.

Therefore, it can not be concluded that it was corrected by this operation.

There are two possible points that caused to control the robotic STS head inaccurately.

First of them is a motor position micro switch pin which has a hysteresis of the range of 7 degrees on both sides of it as described in Section 2.1.1. When the data of C.V. are compensated for the histolysis as shown below, the calculation results become as Table 6-3, which are marked on Fig.6-1 in orange.

$$X_{0 \text{ compensated}} = X - Y \times \tan(7^\circ) \quad (6.1)$$

Data No.	$X_{0 \text{ predicted}}$	$X_{0 \text{ compensated}}$
Controlled_01	-0.59	0.13
Controlled_02	-0.04	0.311
Controlled_03	-0.23	-0.14
Controlled_04	-0.79	0.2
Controlled_05	-0.60	0.13

Table 6-5: The values of the compensated C.V. for motor position micro switch.

Null hypothesis H_0 is

$$H_0 : \mu_{\text{predicted}} = \mu_{\text{controlled}}$$

Alternative hypothesis H_1 is

$$H_1 : \mu_{\text{predicted}} > \mu_{\text{controlled}}$$

when $\mu_{\text{controlled}}$ is the mean of $X_{0 \text{ compensated}}$ and $\mu_{\text{predicted}}$ is the mean of $X_{0 \text{ predicted}}$.

Source Variation	D.F	S.S.	M.S.	F_{cal}	$F_{\text{tab } 5\%}$
Treatments	1	0.179	0.179	3.587	5.32
Error	8	0.399	0.0499		
Total	9	0.578			

Table 6-6: ANOVA between the mean of $X_{0 \text{ compensated}}$ and $\mu_{\text{predicted}}$ is the mean of $X_{0 \text{ predicted}}$.

Since,

H_0 is not rejected.

Therefore, it cannot be said that the compensated C.V. is nearer to the center than the controlled C.V.

As the statistic results show, the horizontal shift of C.V. can be improved that if the motor micro switch did not have the hysteresis, the horizontal values of C.V. would have been nearer to the center row.

The second point is a fixed parameter, C'_{sec} , in the equation of the optimum sector angle. In this experiment, the average relative wind direction was small enough to suggest that the value of K could not be ignored.

The vertical shift of C.V. is analyzed by ANOVA as follows.

Null hypothesis H_0 is

$$H_0 : \mu_{\text{predicted}} = \mu_{\text{controlled}}$$

Alternative hypothesis H_1 is

$$H_1 : \mu_{\text{predicted}} < \mu_{\text{controlled}}$$

when $\mu_{\text{predicted}}$ is the mean of $Y_{0 \text{ predicted}}$ and $\mu_{\text{controlled}}$ is the mean of $Y_{0 \text{ controlled}}$.

Source Variation	D.F	S.S.	M.S.	F_{cal}	$F_{\text{tab 5\%}}$
Treatments	1	0.723	0.723	1.38	5.32
Error	8	4.189	0.524		
Total	9	4.912			

Table 6-7: ANOVA of $Y_{0 \text{ predicted}}$ and $Y_{0 \text{ controlled}}$.

Since,

H_0 is not rejected.

Therefore, it is not possible to say about the first experiment that there is a significant difference between the controlled operation and the predicted values.

6.2 Data of the second experiment

In the second experiment, MAIN504.EXE was applied. The parameter in the control model equations for the sector angle was changed as described in Section 5.3.2.

The results are shown as below.

Data No.	Average wind speed(m/s)	Average wind direction (°)	Rate of water distribution at $X = 0$ (%)	X of the maximum
Controlled 11	6.33	284.5	44.2	0
Controlled 12	7.21	232.2	26.6	0
Controlled 13	4.17	288.2	38.0	0
Controlled 14	6.23	227.1	34.0	0
Controlled 15	4.42	291.2	42.2	0

Table 6-8: The average wind data and the rate of water distribution at $X=0$, X of the maximum water distribution.

To analyze C.V., the control model equations, (5.1), (5.5) are applied and the calculation results are called X_1 predicted, Y_1 predicted. In this experiment, the data whose wind speed is over 6 m/s upwind and 7 m/s downwind is removed because the water supply was stopped.

Data No.	X_1 controlled	X_1 predicted	Y_1 controlled	Y_1 predicted
Controlled 11	-0.74	-1.4	6.73	5.6
Controlled 12	-0.74	-1.02	5.62	3.57
Controlled 13	-0.57	-1.42	6.56	5.54
Controlled 14	-0.54	-2.61	6.42	3.5
Controlled 15	-0.08	-1.29	6.52	5.97

Table 6-9: The values of controlled and predicted C.V. from the second experiment.

In the calculation of the predicted values, the data read when wind speed over 6 upwind and 7 m/s downwind was ignored because the water supply was stopped.

Fig.6-3 describes the results clearly.

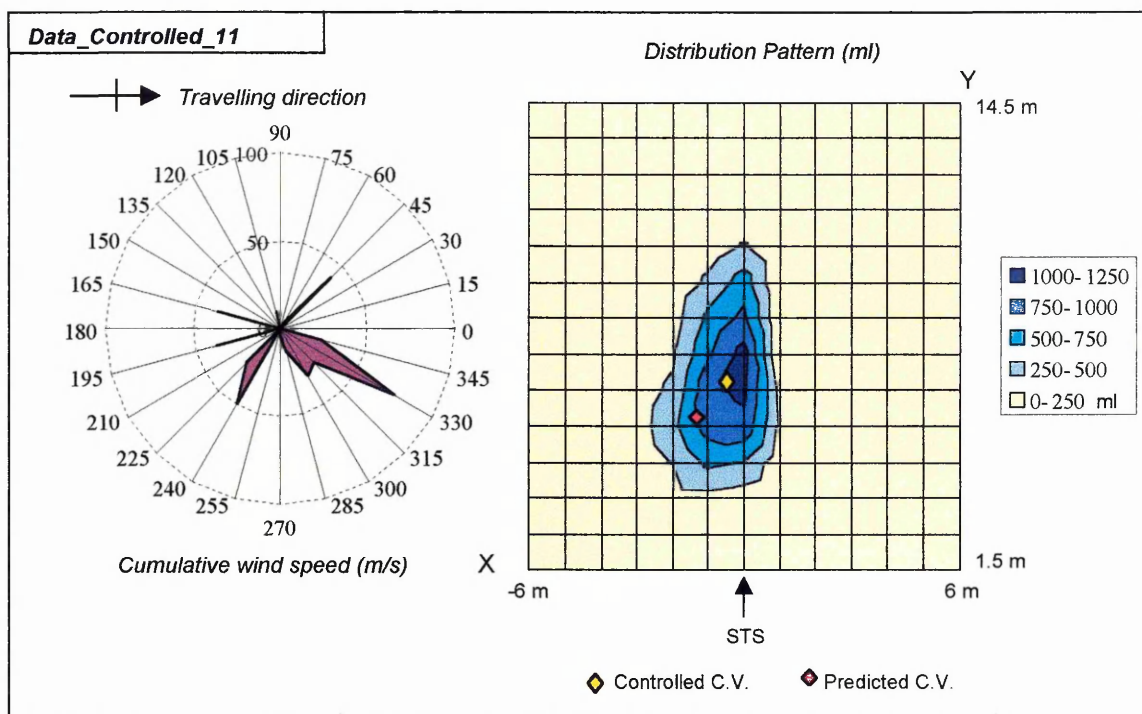


Fig.6-3: The water distribution and the cumulative wind data of Data_Controlled_11.

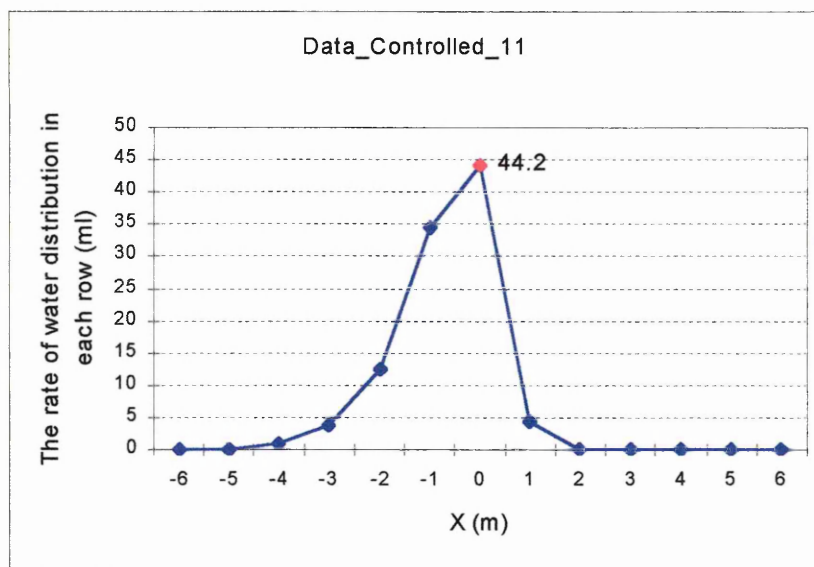


Fig.6-4: The rate of water distribution and the value at X=0 of Data_Controlled_11.

Pressure (psi)	Total amount of water in catch cans(ml)	Average of wind speed (m/s)	Average of wind direction (°)
38	12250	6.33	284.45

	X	Y
Controlled	-0.70	6.725
Predicted	-1.40	5.60

Table 6-10: The data of Data_controlled_11.

To analyze the horizontal value of C.V., X_L , ANOVA is applied to judge whether $X_{1 \text{ controlled}}$ is compensated for the distortion of wind.

Data No.	$X_{1 \text{ controlled}}$	$X_{1 \text{ predicted}}$
Controlled 11	-0.74	-1.4
Controlled 12	-0.74	-1.02
Controlled 13	-0.57	-1.42
Controlled 14	-0.54	-2.61
Controlled 15	-0.18	-1.29
Average	-0.546	1.548

Table 6-11: The average of $X_{1 \text{ controlled}}$ and $X_{1 \text{ predicted}}$.

Null hypothesis H_0 is

$$H_0 : \mu_{\text{predicted}} = \mu_{\text{controlled}}$$

$$H_1 : \mu_{\text{predicted}} > \mu_{\text{controlled}}$$

Source Variation	D.F	S.S.	M.S.	F_{cal}	$F_{\text{tab 5\%}}$
Treatments	1	2.5	2.5	11.9	5.32
Error	8	1.68	0.21		
Total	9	4.18			

Table 6-12: ANOVA of the mean of $X_{1 \text{ controlled}}$ and that of $X_{1 \text{ predicted}}$.

Therefore, H_0 is rejected.

$$LSD = 0.334$$

when $T_{\text{error df.5\% 1-tailed}} = 1.153$.

Since, from the averages in Table 6-9,

$$\mu_{\text{predicted}} > \mu_{\text{controlled}}$$

is accepted.

Therefore, it can be concluded that the horizontal shift of the water distribution is corrected by the control system.

The same analysis is applied for the vertical shift of C.V.

Data No.	$Y_{1 \text{ controlled}}$	$Y_{1 \text{ predicted}}$
Controlled 11	6.73	5.6
Controlled 12	5.62	3.57
Controlled 13	6.56	5.54
Controlled 14	5.37	3.5
Controlled 15	6.52	5.97
Average	6.09	4.84

Table 6-13: The data of $Y_{1 \text{ controlled}}$ and $Y_{1 \text{ predicted}}$ and their averages from the second experiment.

Null hypothesis H_0 is

$$H_0 : \mu_{\text{predicted}} = \mu_{\text{controlled}}$$

Alternative hypothesis H_1 is

$$H_1 : \mu_{\text{predicted}} < \mu_{\text{controlled}}$$

, when $\mu_{\text{predicted}}$ is the mean of $Y_{I \text{ predicted}}$ and $\mu_{\text{controlled}}$ is the mean of $Y_{I \text{ controlled}}$.

Source Variation	D.F	S.S.	M.S.	F_{cal}	$F_{\text{tab } 5\%}$
Treatments	1	4.373	4.373	4.843	5.32
Error	8	7.227	0.903		
Total	9	11.66			

Table 6-14: ANOVA between the mean of $Y_{I \text{ controlled}}$ and that of $Y_{I \text{ predicted}}$ from the second experiment.

Since,

H_0 is accepted with 5% error.

However, it is very near the tabulated value, therefore, it might be affirmed that the value of $Y_{\text{controlled}}$ is bigger than that of the uncontrolled with larger amount of data.

6.3 Total amount of water

This system stops supplying water by closing the valve when the trajectory angle is over 6 m/s upwind and over 7 m/s downwind. The figures were calculated from the equations of the optimum trajectory angle (5.7), (5.8). The comparison between the uncontrolled data and controlled data is analyzed to confirm the effectiveness.

The total amount of the collected water in the uncontrolled and the second controlled executions are shown below.

Data No.	Total amount of water (ml)
Uncontrolled_01	16065
Uncontrolled_02	13319
Uncontrolled_03	14452
Uncontrolled_04	15268
Uncontrolled_05	14449
Average	14710

Table 6-15: Total amount of the collected water in the uncontrolled experiment.

Data No.	Total amount of water (ml)
Controlled_11	12250
Controlled_12	11140
Controlled_13	15285
Controlled_14	10235
Controlled_15	12846
Average	12351

Table 6-16: Total amount of the collected water in catch cans in the second experiment.

Therefore, the rate of the number of data which is over such values of wind speed to total number of data, 60, is applied to find a relationship between the total amount of water and the wind speed. The result is shown in Fig.6-5 and its regression line is described as (6.2).

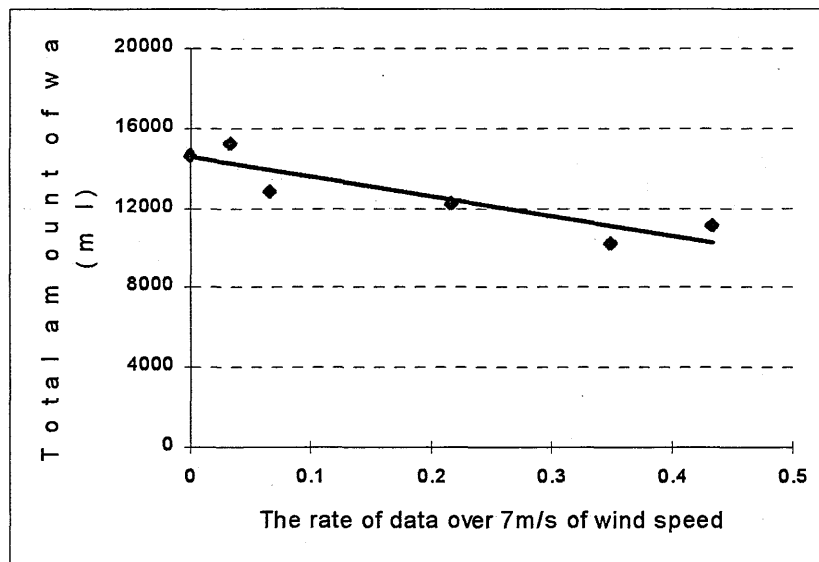


Fig6-5: The relationship between total amount of water and the rate of data number which indicate over 6 m/s upwind, 7 m/s downwind.

The regression line is

$$Y = -9868 \times X + 14554 \quad R^2 = 0.81 \quad (6.2)$$

So, it can be said that the valve system worked well enough to save water.

Supposed that this equation can be applied for any other wind conditions, the amount of saved water, V_r , is

$$V_r = \frac{(14710 - Y)}{14710} \times [\text{Total amount of supplied water}] \quad (6.3)$$

Therefore, as the size of the irrigation is larger, the valve system becomes more effective.

7. Conclusion and Recommendation

7.1 Conclusion

In terms of the hardware, it can be concluded that it was successful. The structure of the robotic STS head was stable and no leakage occurred to it under both uncontrolled and controlled operations. The environmentally protected boxes also did not leak water. The electric connections were held rigid enough to resist to the vibration produced by travelling a rough road.

The software worked stable even though there was a big complexity owing to using both a software and hardware interrupt. This means that the software could drive the stepper motors speedy enough to adjust the jet direction to the instant windy conditions, while it enabled the embedded computer to communicate with the external computer interactively and correctly. Users can know the state of the system, the wind data, the instant rotational positions of the stepper motors.

According to the results as shown in the second set of experiments, it can be concluded that horizontal distortion of water distribution was corrected by this control system. Therefore, the control system of the sector angle for which the geometric model was applied was adequate. However, the trajectory angle could not be shown that it was corrected. It needed a larger amount of data, which could suggest a more appropriate model of the optimum trajectory angle. Furthermore, commercially ineffective water distribution was avoided under windy conditions as shown in Section 6.2.3. This means that the cut-off valve worked well enough to make this system more effective.

The chemigation pump worked only if 'F' was pressed on the user's computer before the water supply was started. In this study, it can make chemigation easy though the pump was too small to feed chemicals into the main water. So, for the next improvement, the type of pump, which is suitable to this work, is recommended.

As a final conclusion, it can be said that the approach of the robotic STS system was meaningful. Therefore, the system should be improved to seek more effective design.

7.2 Recommendation

7.2.1 The structure

1) Sealing of the rotate joints

Each of the rotating joints was supported by a bolt which did not make the two plates at the joint parallel. This caused water to leak. To use small motors without any gears, it can be recommended to make use of water pressure in order to lessen the friction torque and also to keep the joint parallel by putting some adequate space at the side of the joint which lets in water.

2) Fixing the shaft bolt

It is difficult, but most important to fix the shaft bolts in order to drive motors without missing any step angles. There are some points to be taken into account which are the tolerance of the shaft key, the distortion of the center of the allen bolts, the friction between the screw of the allen key and the nut and between the shaft key and the nut. In this small model, some glue helped fix the shaft bolts, however, a proper way should be sought for redesigning.

7.2.2 System

1) Motors

Instead of stepper motors, DC servo motors are recommended to be used because it possible to calculate the rotational position and speed, which allows this system to be applied the feed back control. Furthermore, even a small sized DC motor has larger torque than that of the same sized stepper motor.

2) Reckoning of the rotational positions.

The micro switch described in Section 2.1.1 did not work well while motors ran because of the hysteresis of the micro switch pins. The range of the hysteresis is 7 degrees on both sides of the center of the micro switch pin. To know the rotational position accurately, there are two solutions to be tried.

a) Micro switches

When the sector motor position pin turns the micro switch on from smaller than 90° , the current angle is reset to be 82.875° . When the sector motor position pin turns the micro switch on from

larger than 90° , the current sector angle is reset 97.125° . The values of the angles are shown in Section 2.1.1. This should also be applied to operate the trajectory angle.

b) Encoder

To know the motor position, a servo motor is suitable as written in the former section, otherwise, an encoder with a stepper motor can be recommended.

3) Prediction and control models

a) Prediction model

A multi phase model (Grose, Weatherhead) to simulate the water distribution can be applied to predict the water distribution pattern in order to help design a vegetation map. Furthermore, it can improve the control models.

b) Control model

To seek more precise equations to set the optimum sector and trajectory angles, the control model should take into account the relative wind angles. The variables in the control model, K and d , should be changed with regards to the instant condition. To realize that, the multi phase model should be applied to know the characteristics of this STS.

4) Chemigation pump

8000 Series high pressure pumps 12 VDC provided by SHURflo is recommended for chemigation.. It can operate up to 4.1 bar.

5) Wind sensor

Ultrasonic Wind Sensor suits to this system rather than ones used here due to the following advantages .

It is ready to be connected to a computer by RS232 and the data can be read every 1 second.

There is no dead band on wind direction.

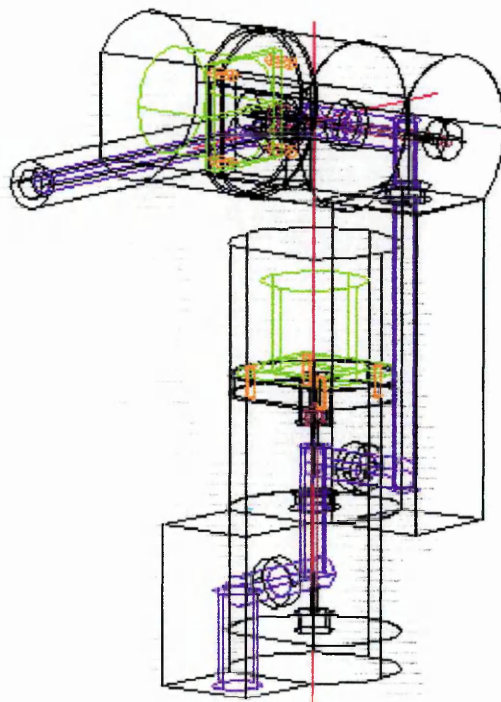
Therefore, it can be said that this new sensor will make the sprinkler system more accurate.

6) DGPS

As explained in Section 3.8, DGPS should be attached in order to know the position of the sprinkler to apply a vegetation map in a large field.

Appendix I

Designs of the robotic STS by CAD Assembly



Designs of the robotic STS by CAD

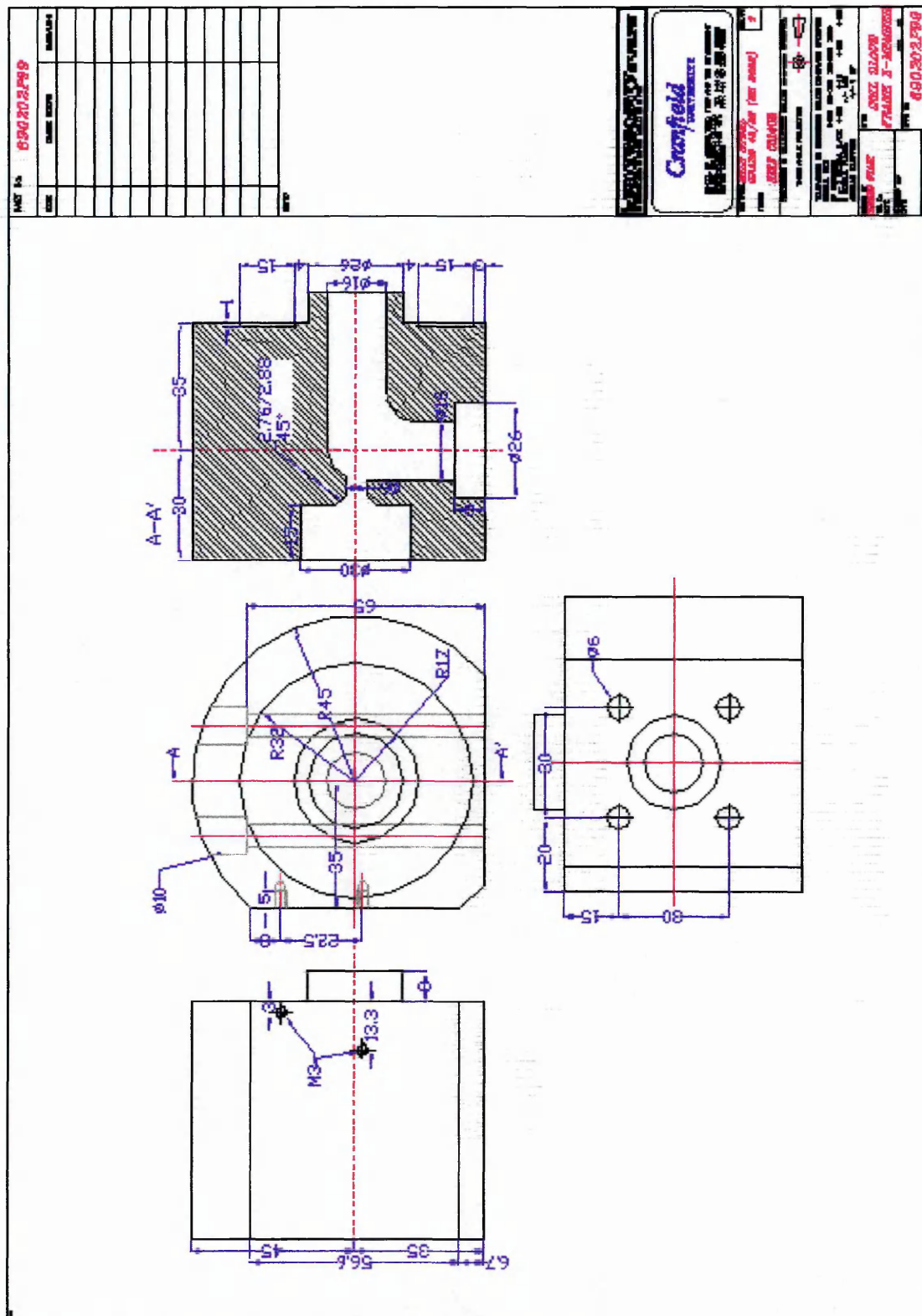


Fig. I-1 : Main Part 1

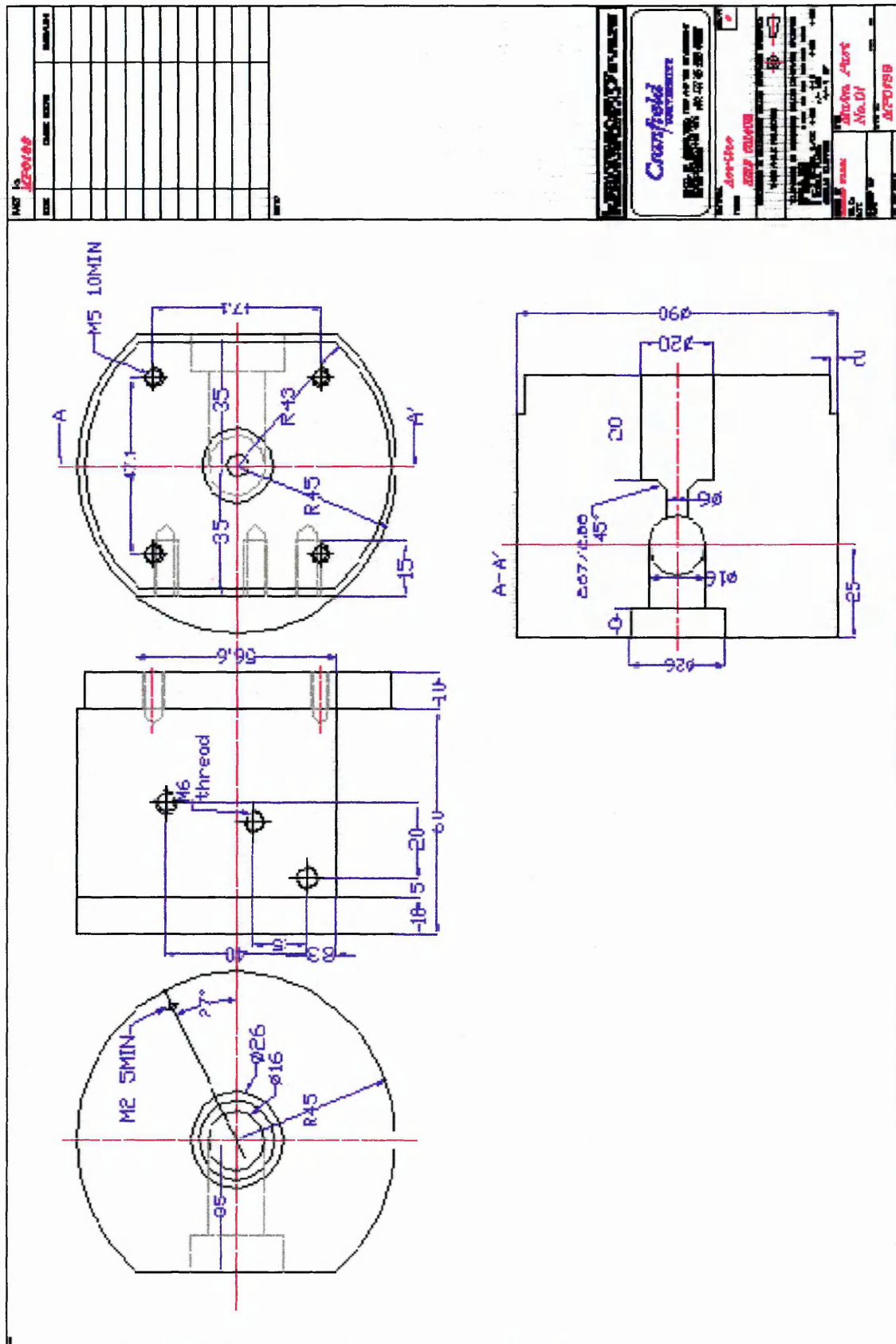


Fig. I-2 : Main Part 2, 5

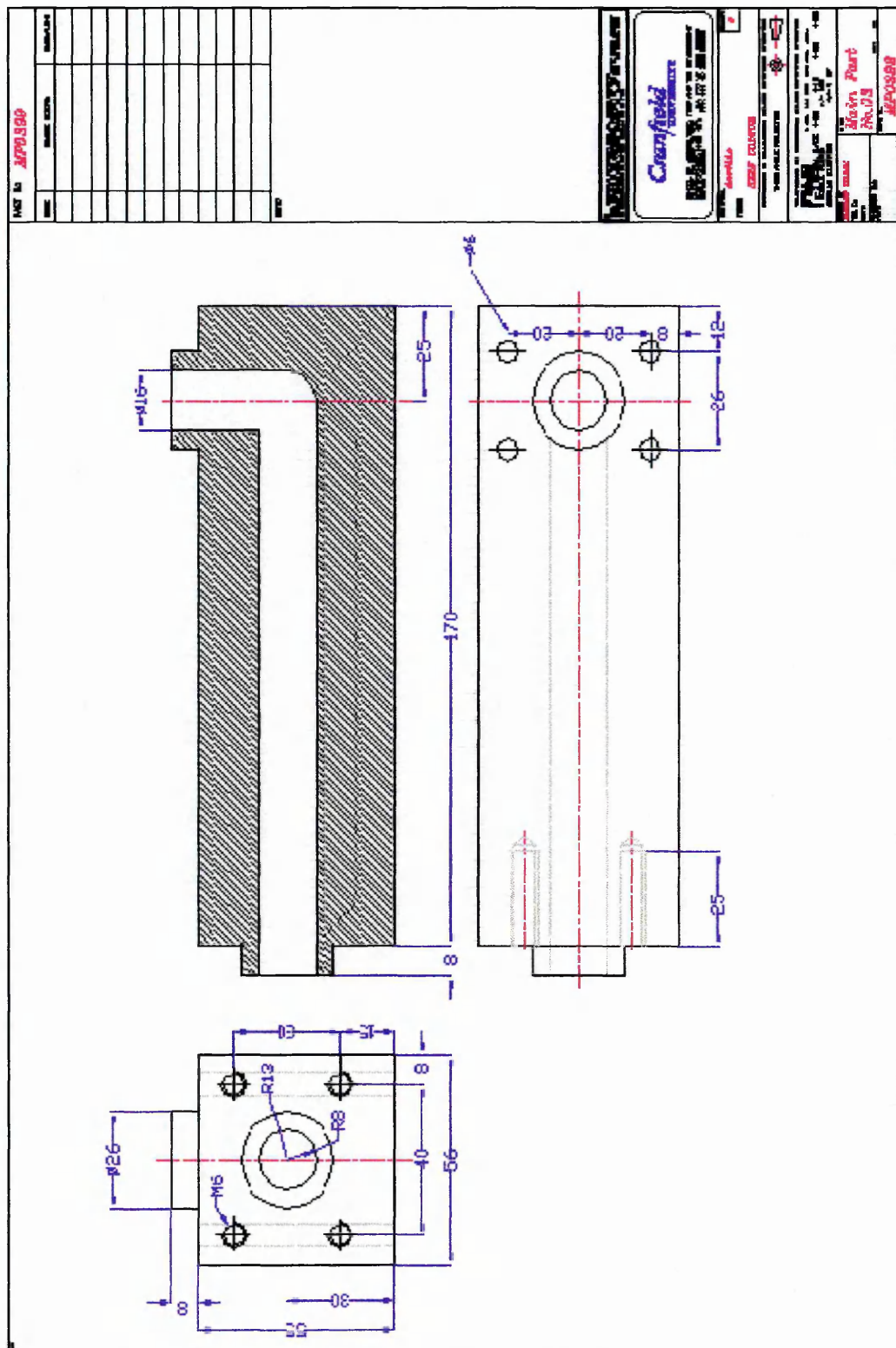


Fig.I-3: Main Part 3

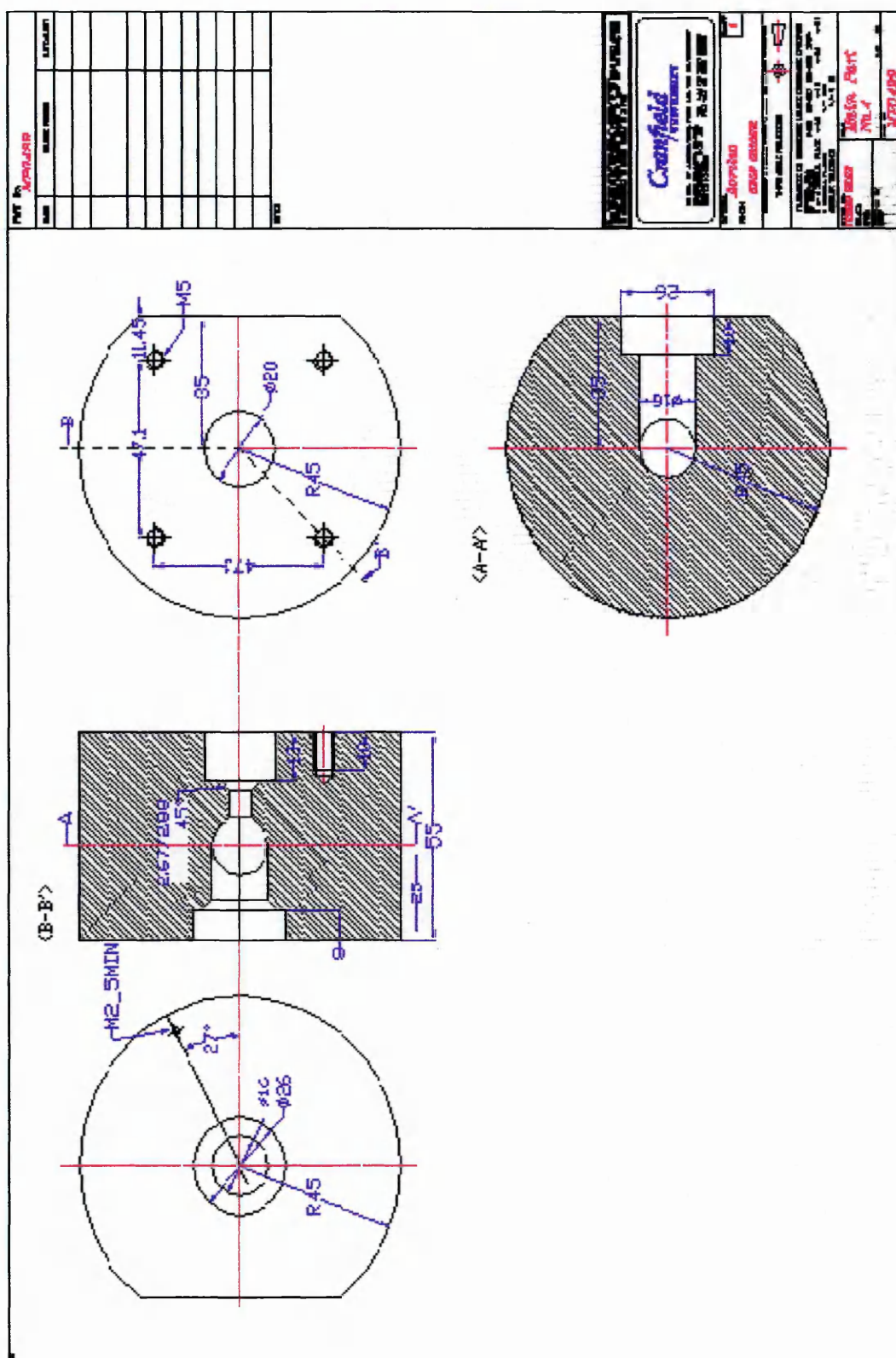


Fig.I-4: Main Part 4

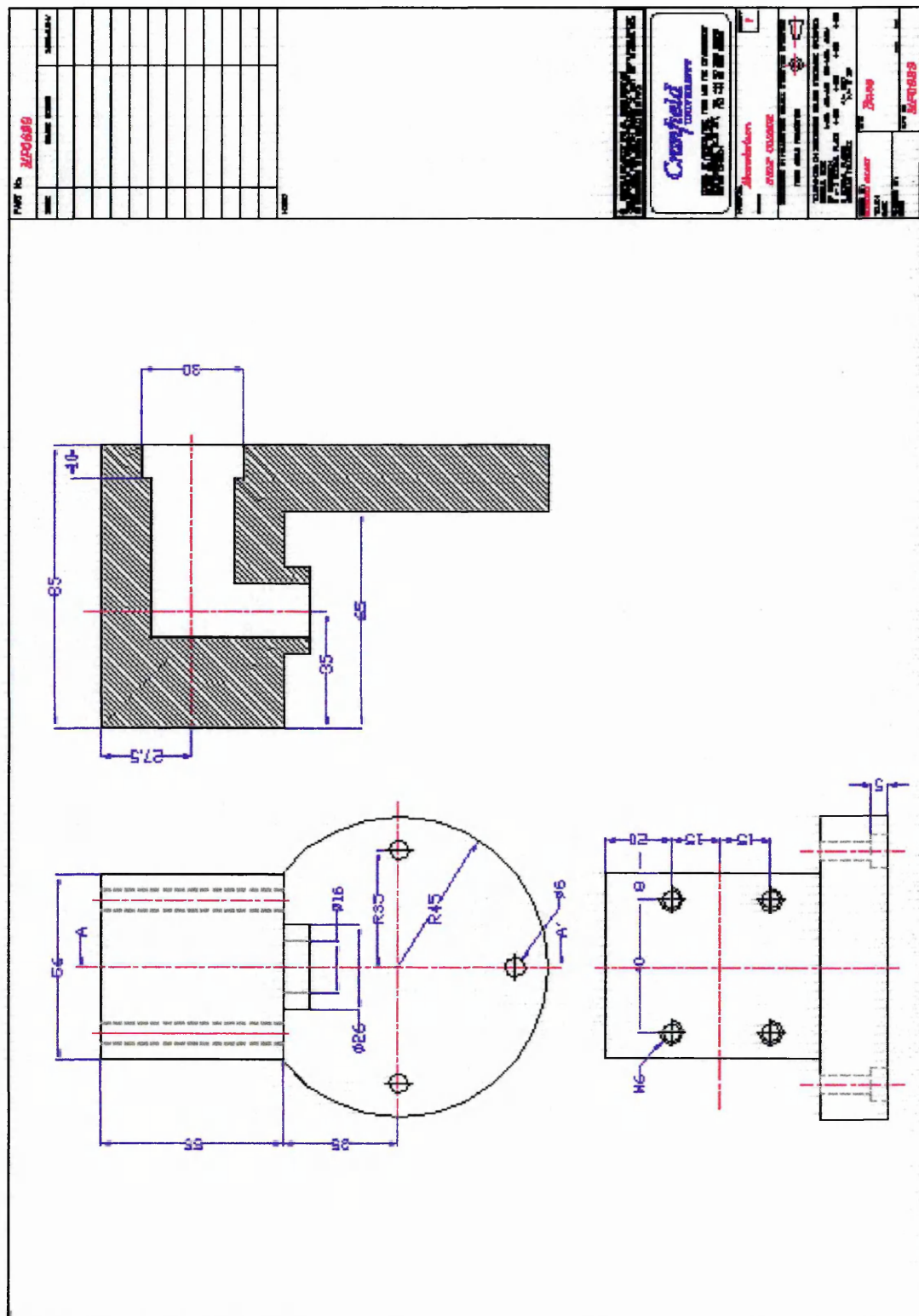


Fig.I-5: Main Part 5

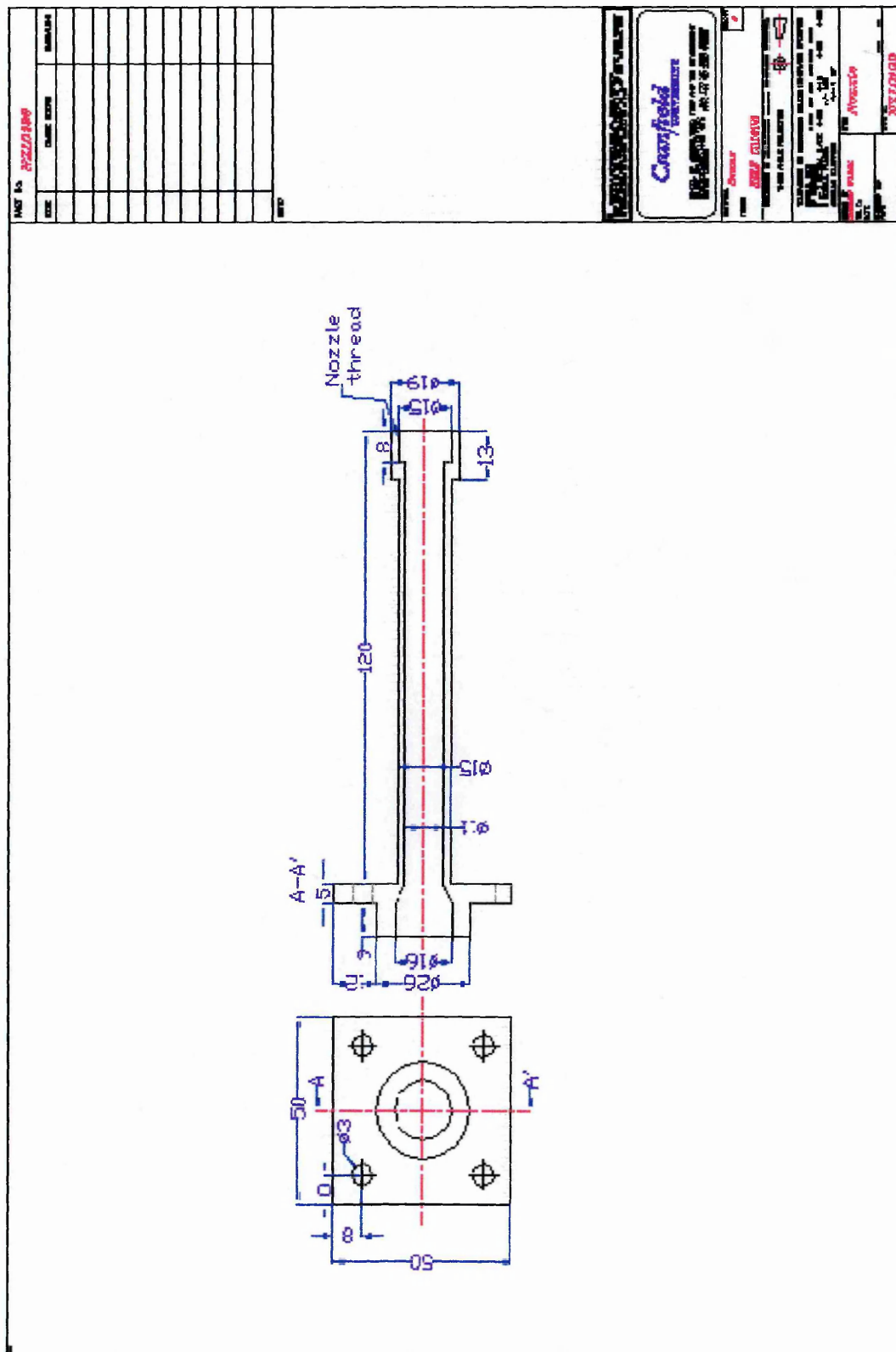


Fig. I-6 : Nozzle

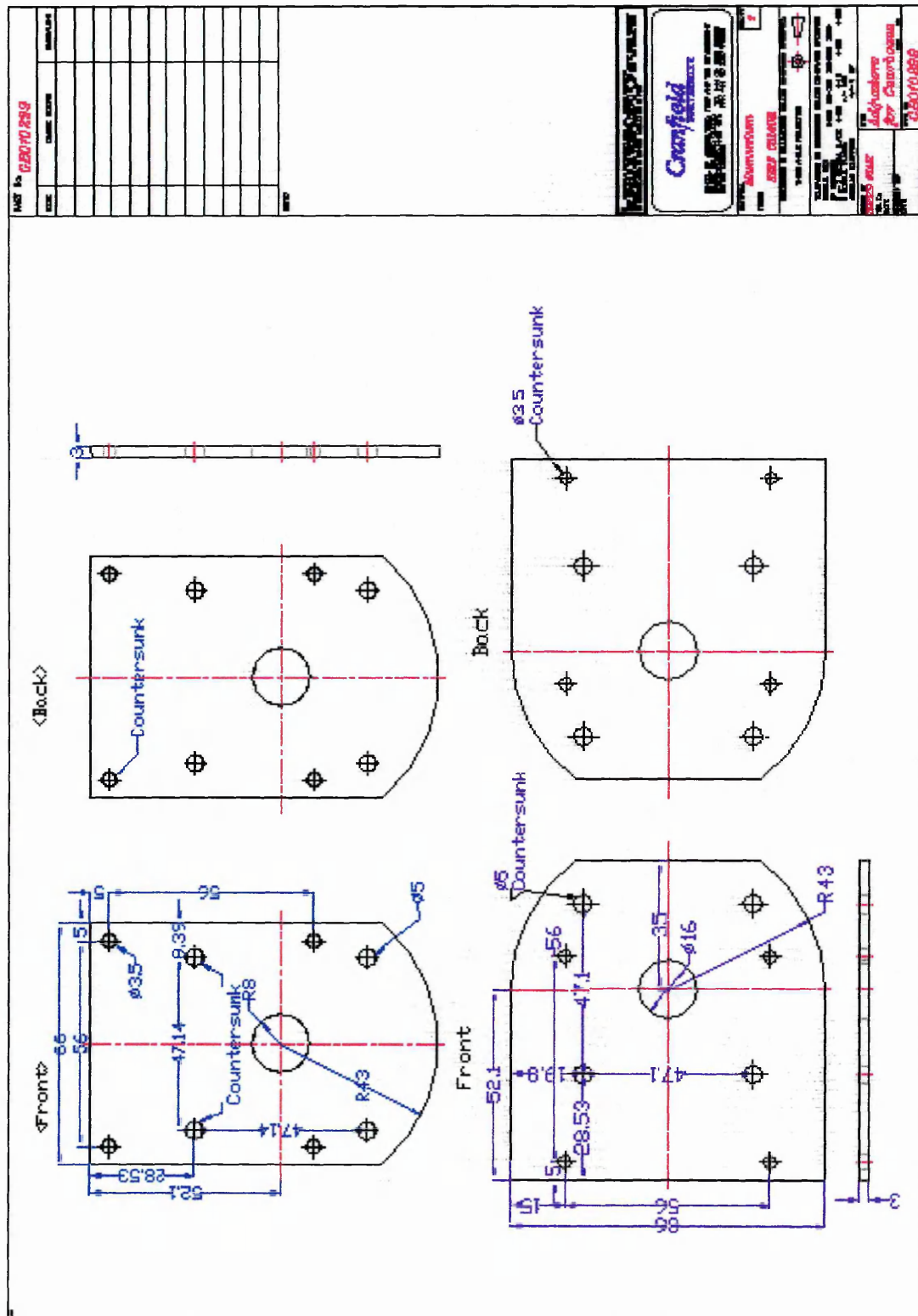


Fig.I-7: Gearbox plates

Assembly

When assembling the parts of the robotic STS head, there are two important points, one of which is to seal the connection between two parts and the other is to make the rotate joint less friction. Further, there are some complexities in the assembling order, so that the following pictures are needed to tell how to assemble a gearbox, Part 1, 2, and a shaft key, which is the same as Part 4,5, and also to make the connection understandable.

Step 1: First, the gearbox is attached to the gearbox plate by 4 screws, and after joint the gearbox without the lid to the shaft bolt by tightening the socket screw at the adequate position which the hole end of coupler does not reach that of the gear shaft.

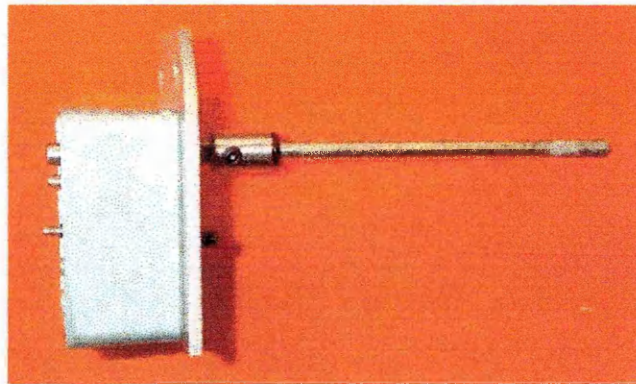


Fig.I-9: Step 1

Step 2: Keep the lid opened and attach the gear to Main Part 1. 2 screws are tightened from the inside of the gearbox.

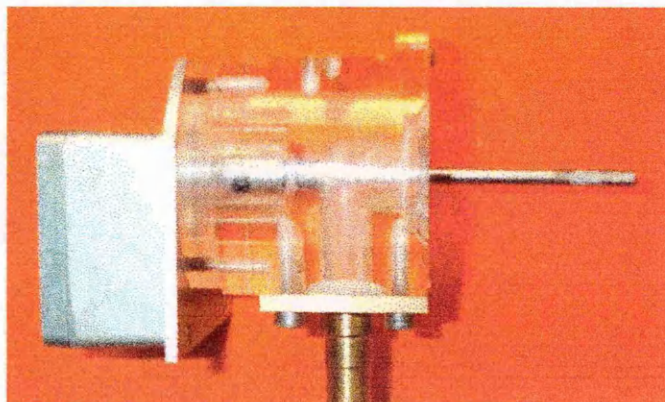


Fig.I-10: Step 2

Step 3, 4 : Put the joint plate and the O-ring 1 on Part 2 (or 5) and the shaft bolt is inserted to the part 2(or 5) after some silicon rubber might be put on the bolt.

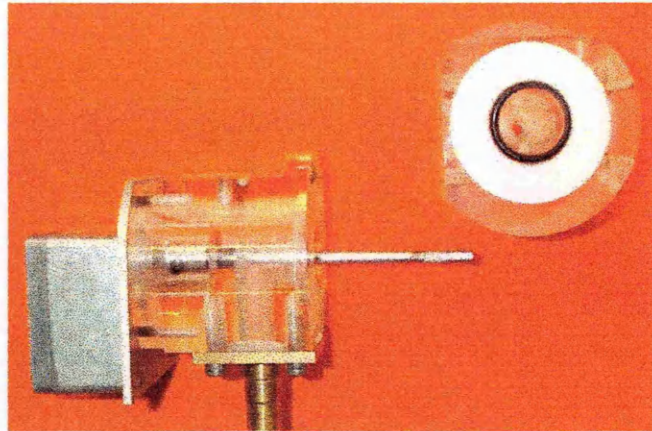


Fig.I-11: Step 3

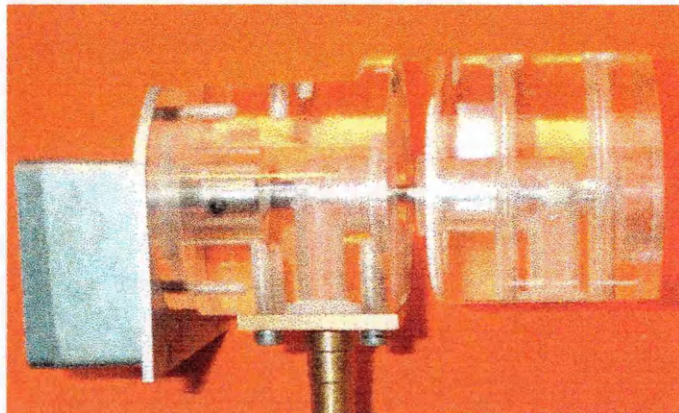


Fig.2-12: Step 4.

Step 5: Fit the end of the shaft bolt to the key before two screws in, and Part 1 and Part 2 are tightened up by a nut. After that, take off the nut and tighten it up again with some super glue which prevent the screw from rotating inside the nut.

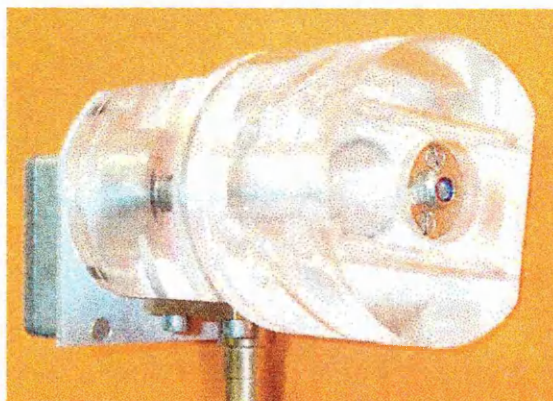


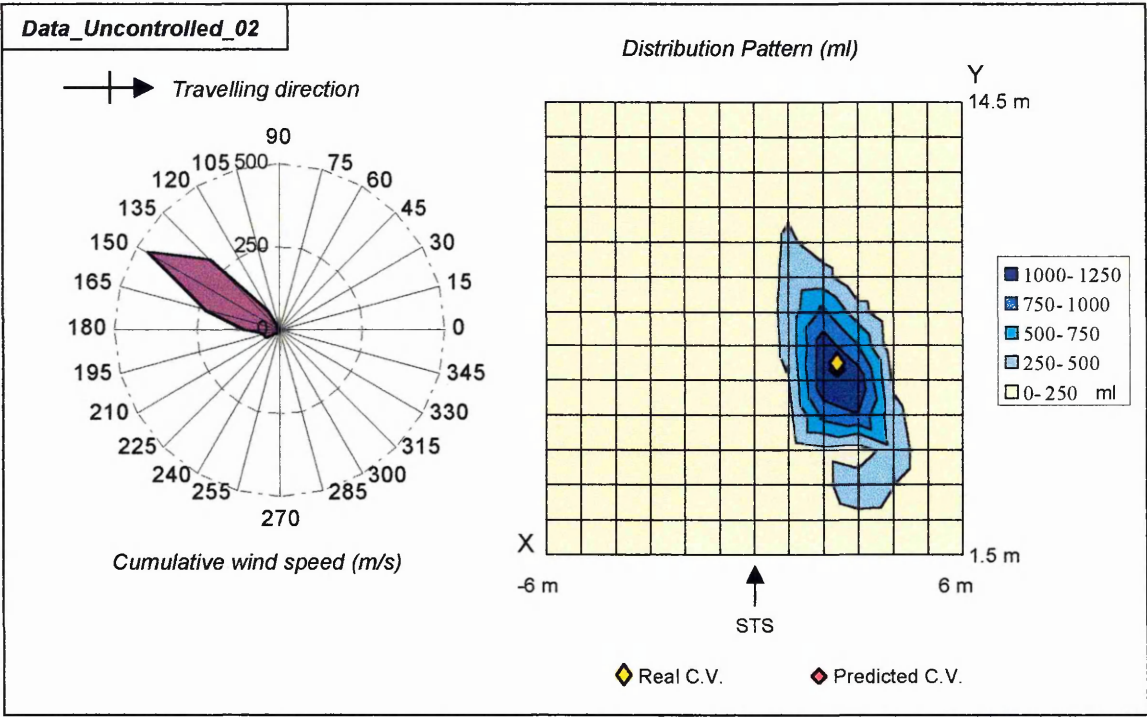
Fig.2-10: Step 5

Appendix II

Data_Uncontrolled02-05

Data_Controlled02-05

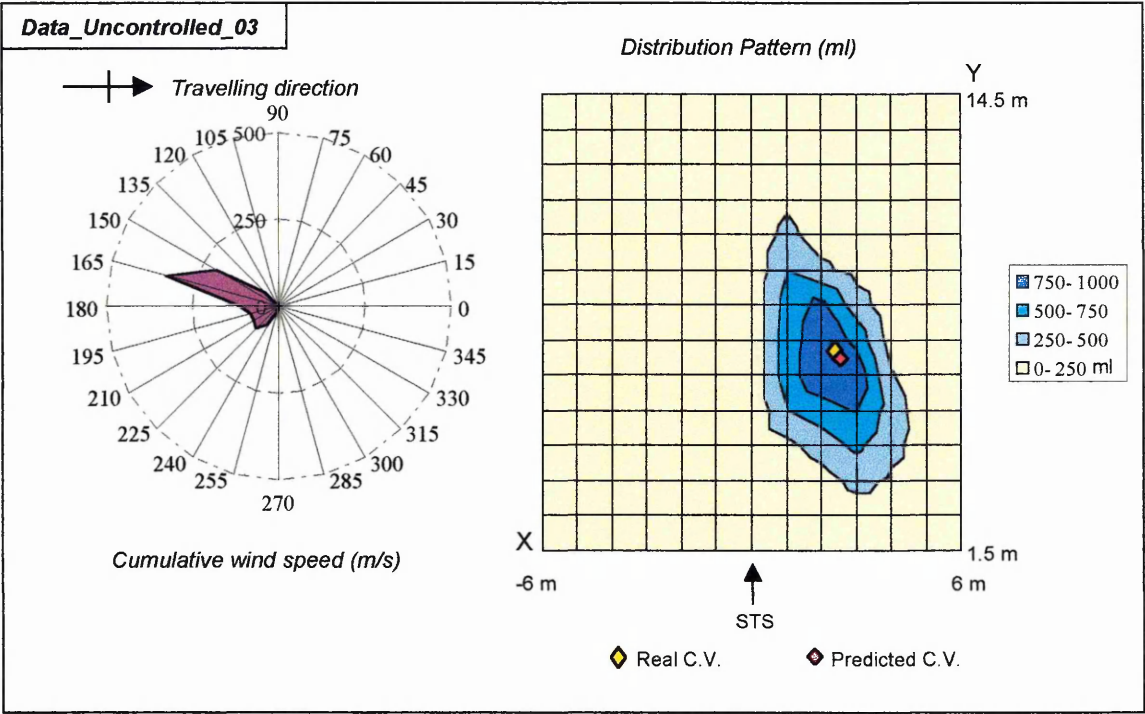
Data_Controlled12-15



Pressure (psi)	Total amount of water in catch cans(ml)	Average wind speed (m/s)	Average wind direction (°)
38	13319	2.515	174.5

Real C.V. (X _{real} , Y _{real})	Predicted C.V. (X _{predicted} , Y _{predicted})
(2.44, 6.63)	(2.51, 6.45)

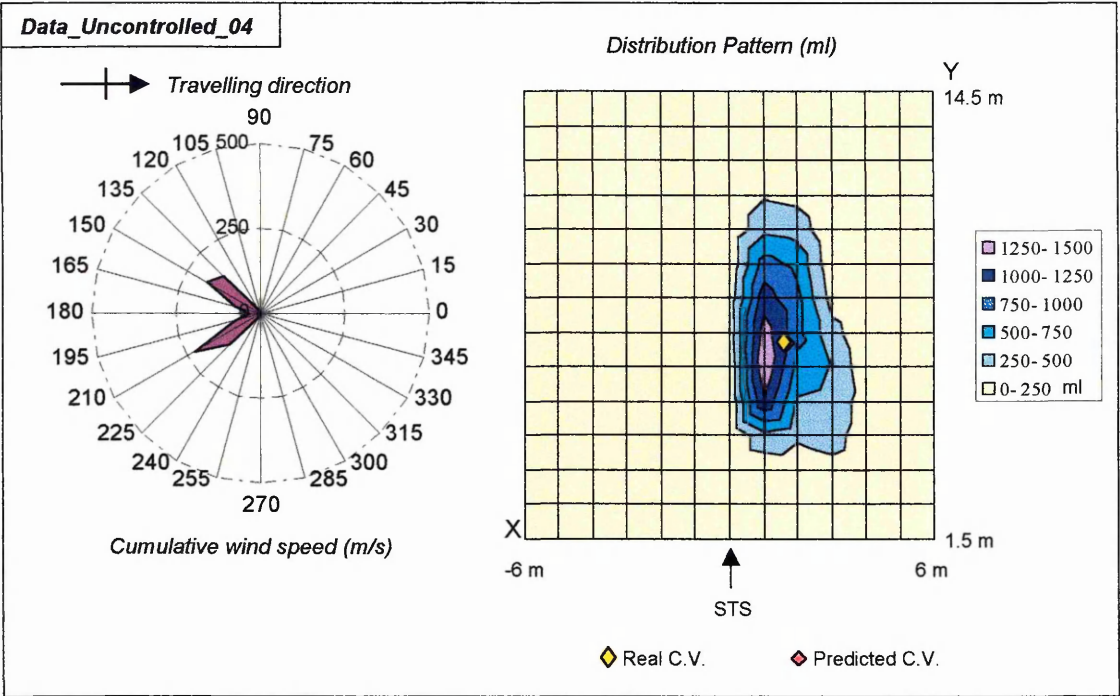
Fig.II-1: Data_uncontrolled_02.



Pressure (psi)	Total amount of water in catch cans(ml)	Average wind speed (m/s)	Average wind direction (°)
38	14452	2.21	185.2

Real C.V. (X _{real} , Y _{real})	Predicted C.V. (X _{predicted} , Y _{predicted})
(2.32, 7.23)	(2.20, 6.91)

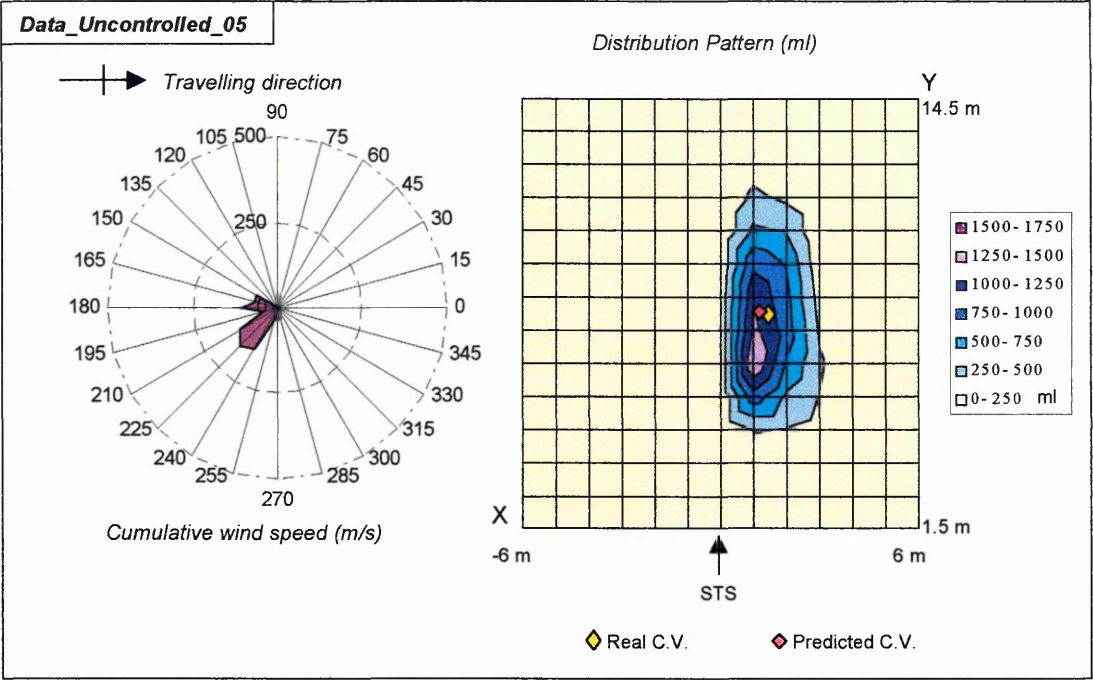
Fig.II-2: Data_uncontrolled_03.



Pressure (psi)	Total amount of water in catch cans(ml)	Average wind speed (m/s)	Average wind direction (°)
38	15268	1.99	200

Real C.V. (X _{real} , Y _{real})	Predicted C.V. (X _{predicted} , Y _{predicted})
(1.763, 6.73)	(1.175, 7.23)

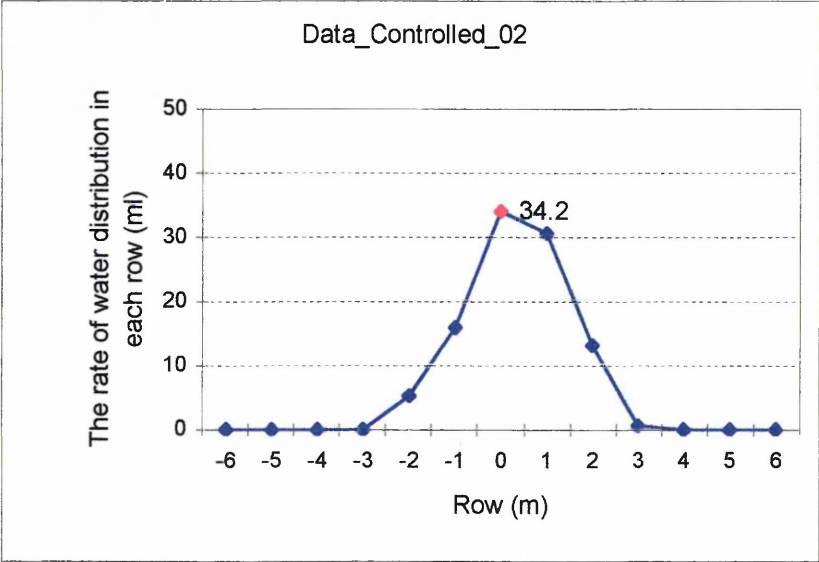
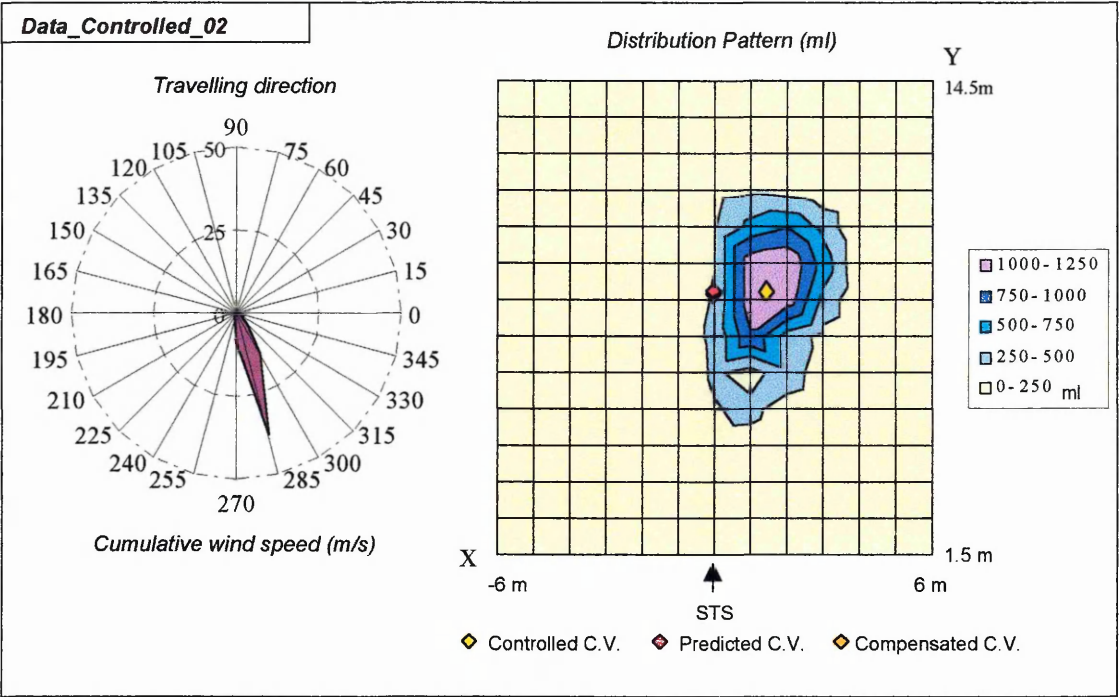
Fig.II-3: Data_uncontrolled_04.



Pressure (psi)	Total amount of water in catch cans(ml)	Average wind speed (m/s)	Average wind direction (°)
38	14449	1.59	208

Real C.V. (X _{real} , Y _{real})	Predicted C.V. (X _{predicted} , Y _{predicted})
(1.66, 7.62)	(1.405, 7.83)

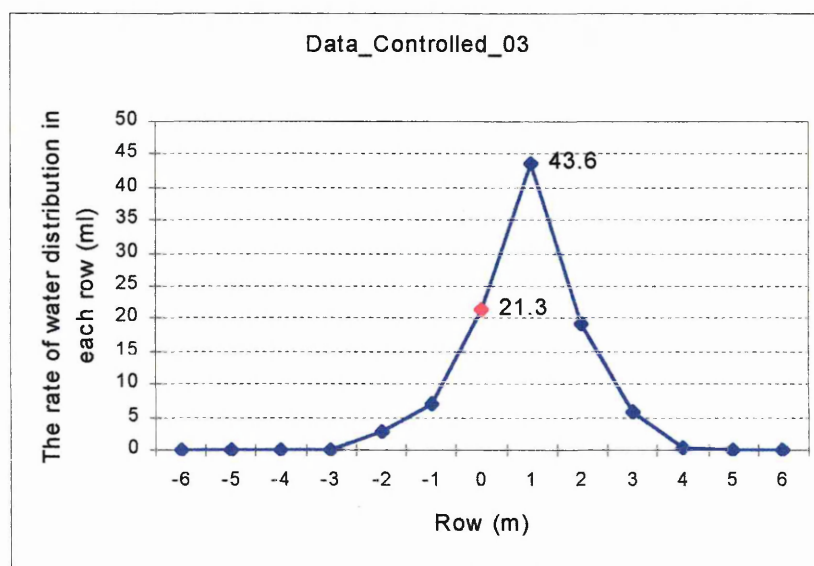
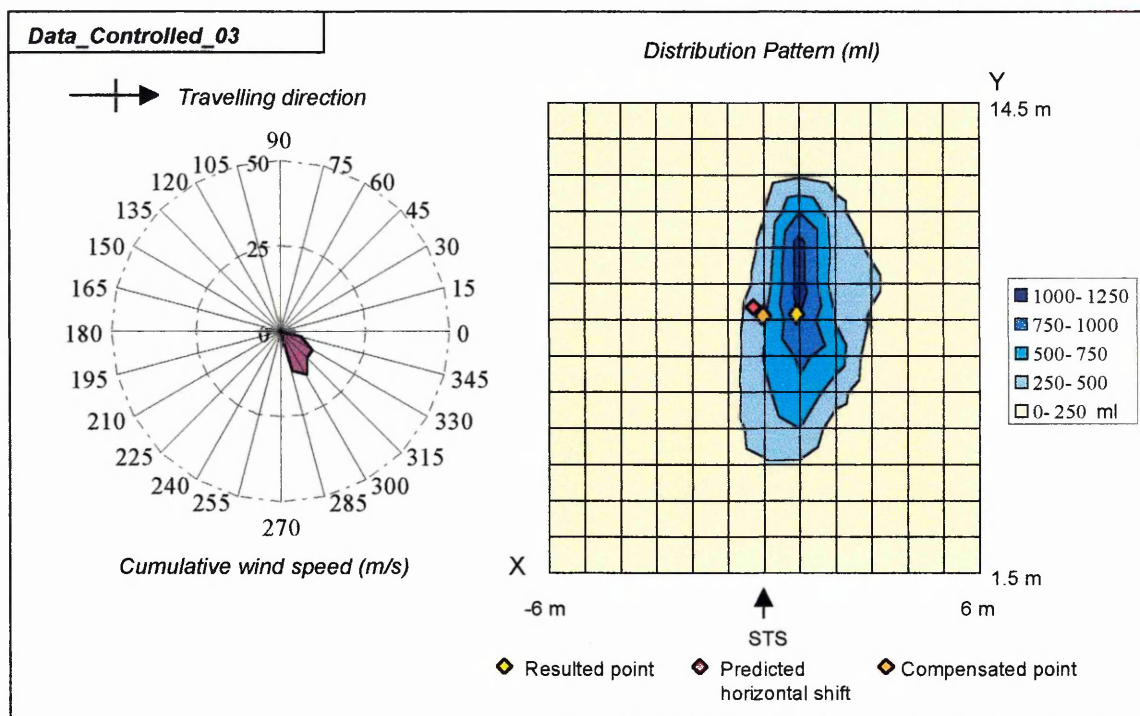
Fig.II-4: Data_uncontrolled_05.



Pressure (psi)	Total amount of water in catch cans(ml)	Average of wind speed (m/s)	Average of wind direction (°)
38	13812	1.33	271.9

	X	Y
Controlled	1.35	8.7
Predicted	-0.04	8.22
Compensated	0.311	8.7

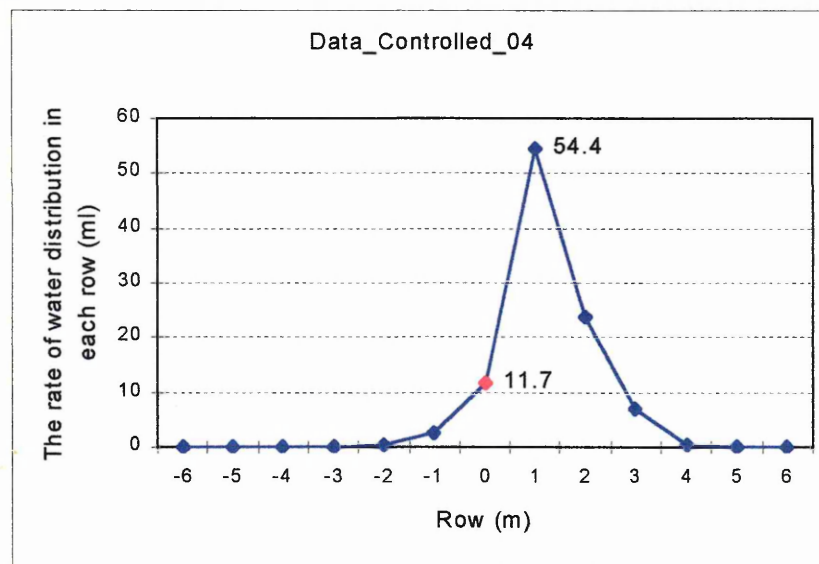
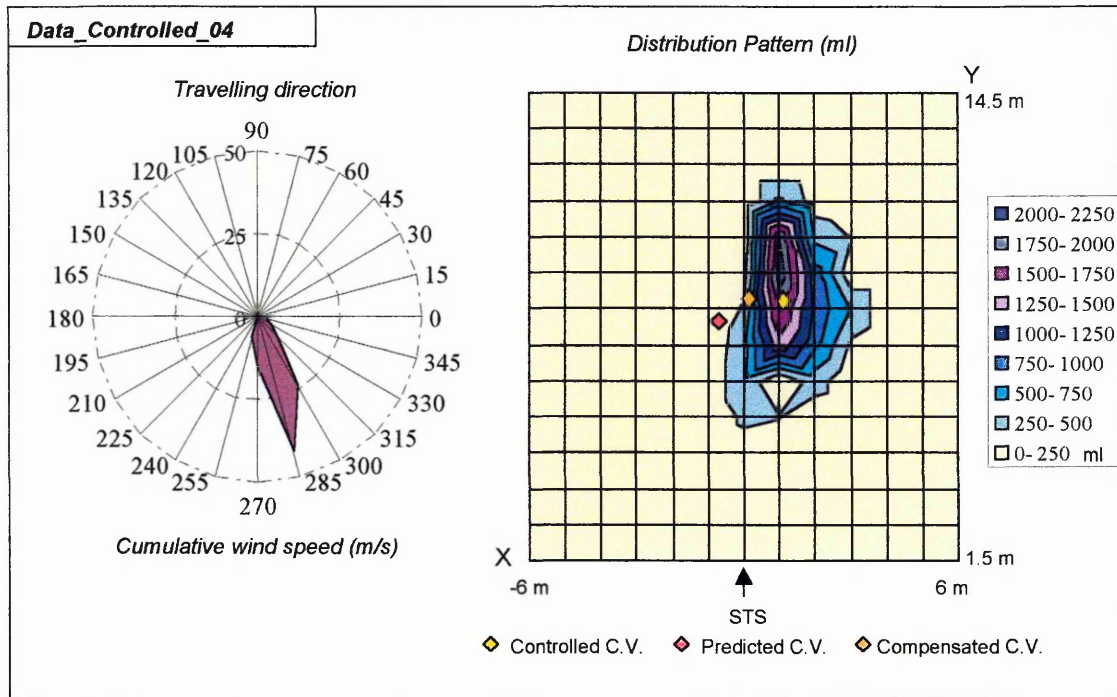
Fig.II-5: Data_controlled_02.



Pressure (psi)	Total amount of water in catch cans(ml)	Average of wind speed (m/s)	Average of wind direction (°)
38	14695	1.42	282.5

	X	Y
Controlled	0.88	8.49
Predicted	-0.23	8.68
Compensated	-0.14	8.49

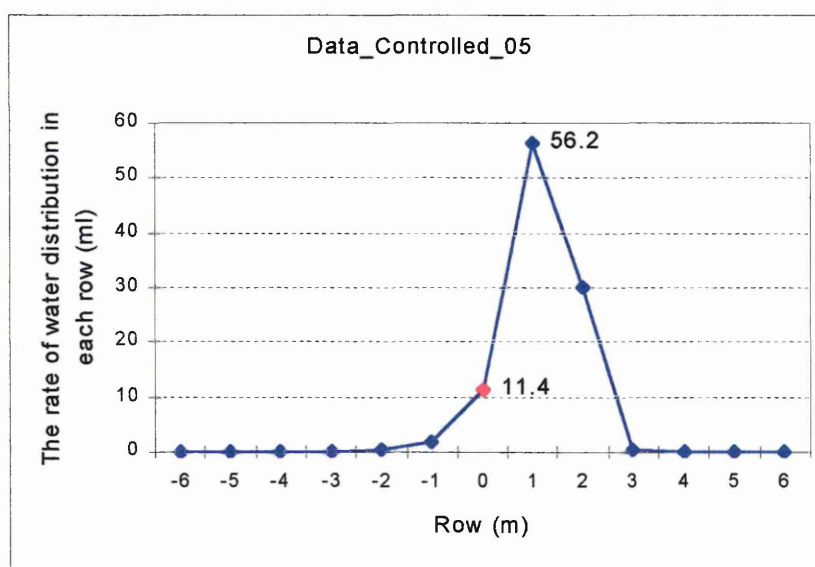
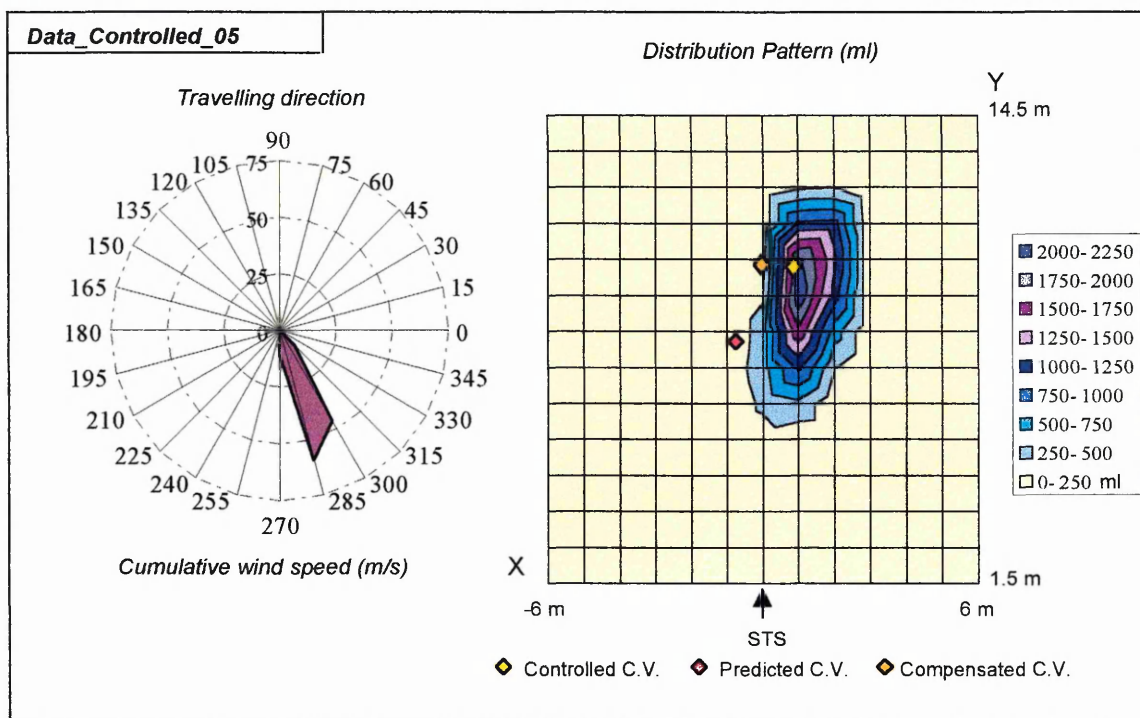
Fig.II-6: Data_controlled_03.



Pressure (psi)	Total amount of water in catch cans(ml)	Average of wind speed (m/s)	Average of wind direction (°)
38	15160	2.13	291.9

	X	Y
Controlled	1.22	8.65
Predicted	-0.79	7.25
Compensated	0.2	8.65

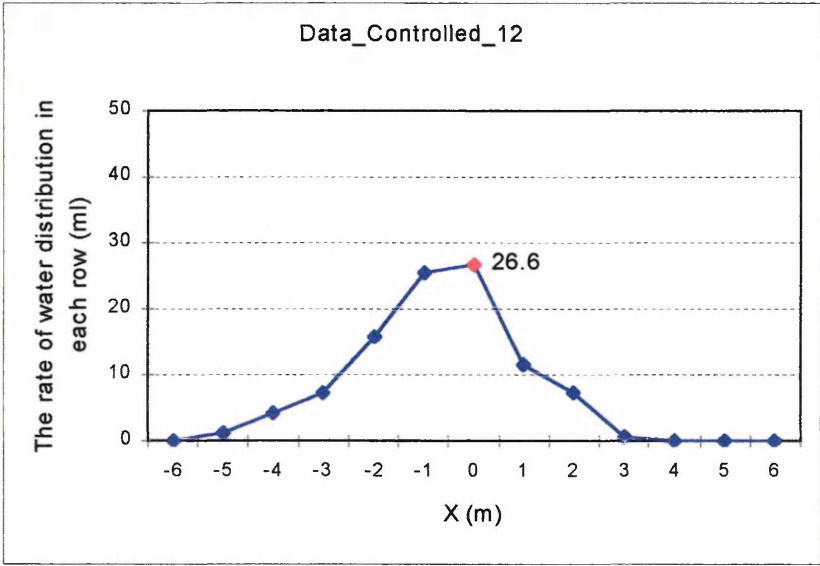
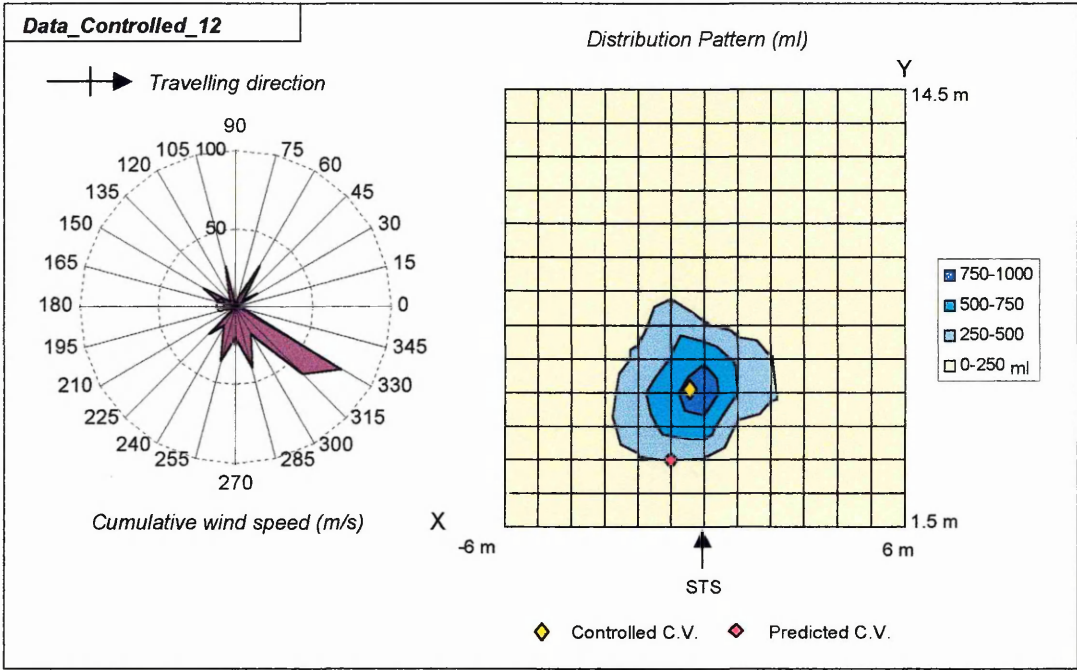
Fig.II-7: Data_controlled_04.



Pressure (psi)	Total amount of water in catch cans(ml)	Average of wind speed (m/s)	Average of wind direction (°)
38	15677	2.1	286.53

	X	Y
Controlled	1.15	9.48
Predicted	-0.6	8.98
Compensated	0.13	9.48

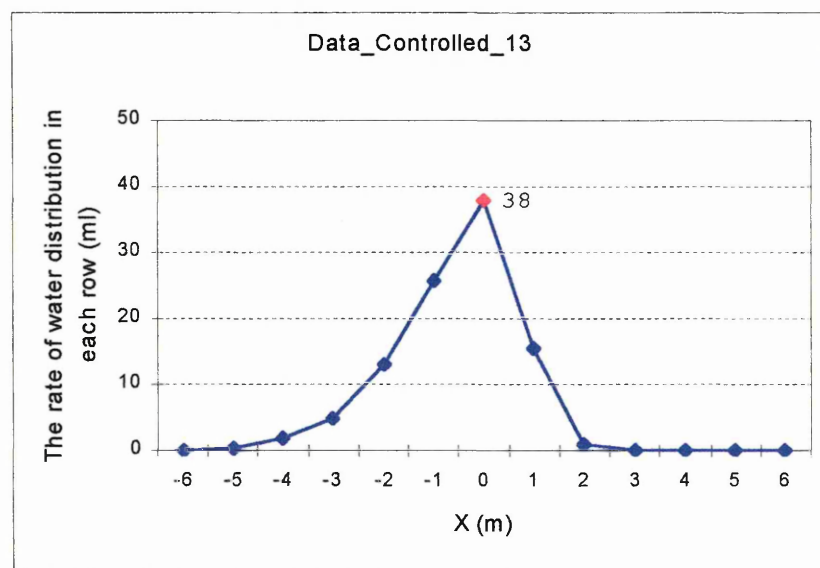
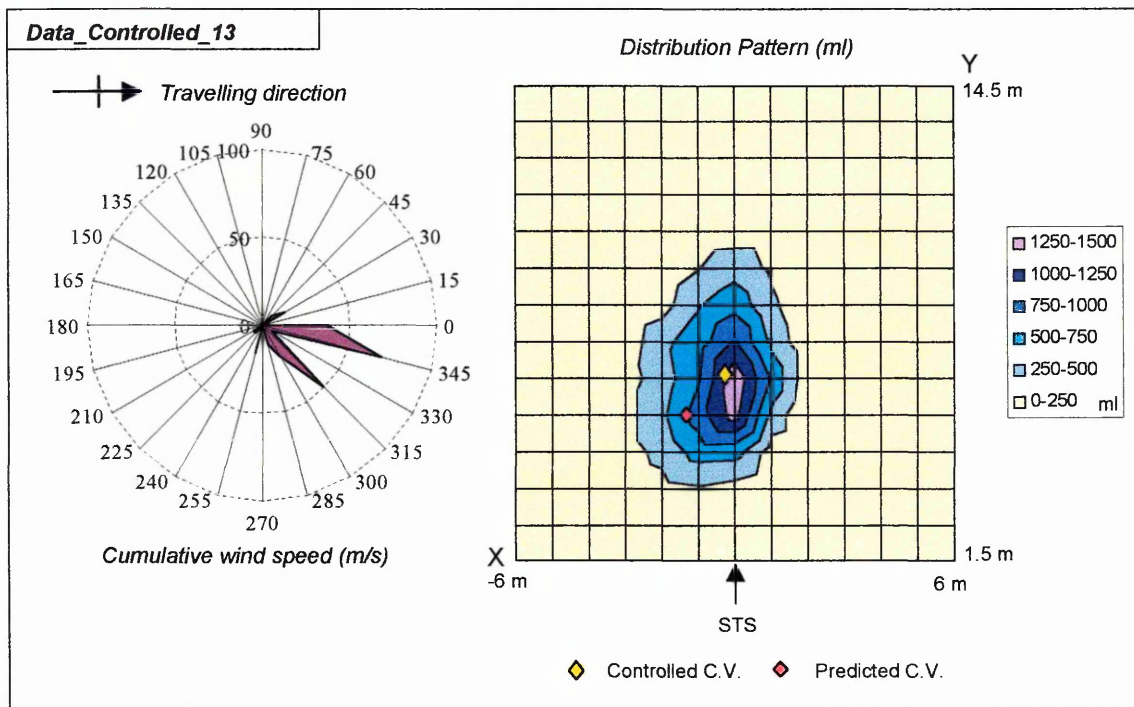
Fig.II-8: Data_controlled_05.



Pressure (psi)	Total amount of water in catch cans(ml)	Average of wind speed (m/s)	Average of wind direction (°)
38	11140	7.21	288.2

	X	Y
Controlled	-0.74	5.62
Predicted	-1.02	3.57

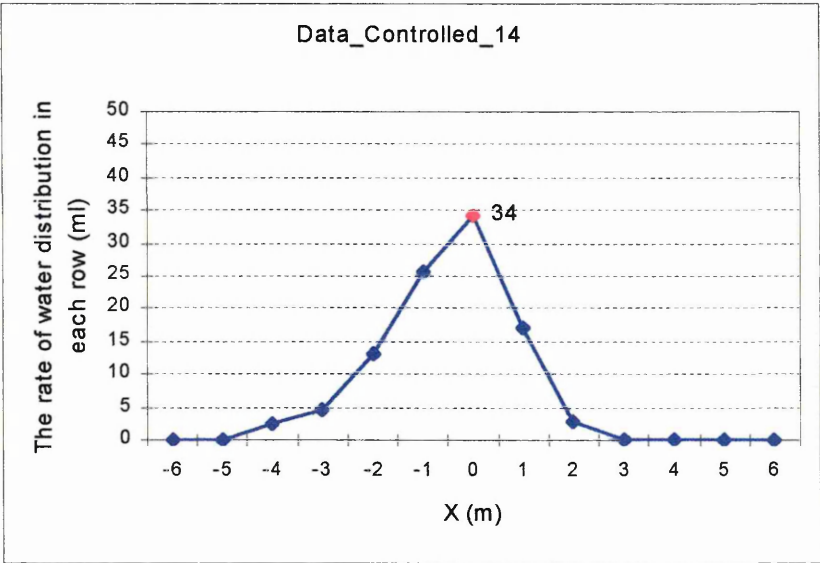
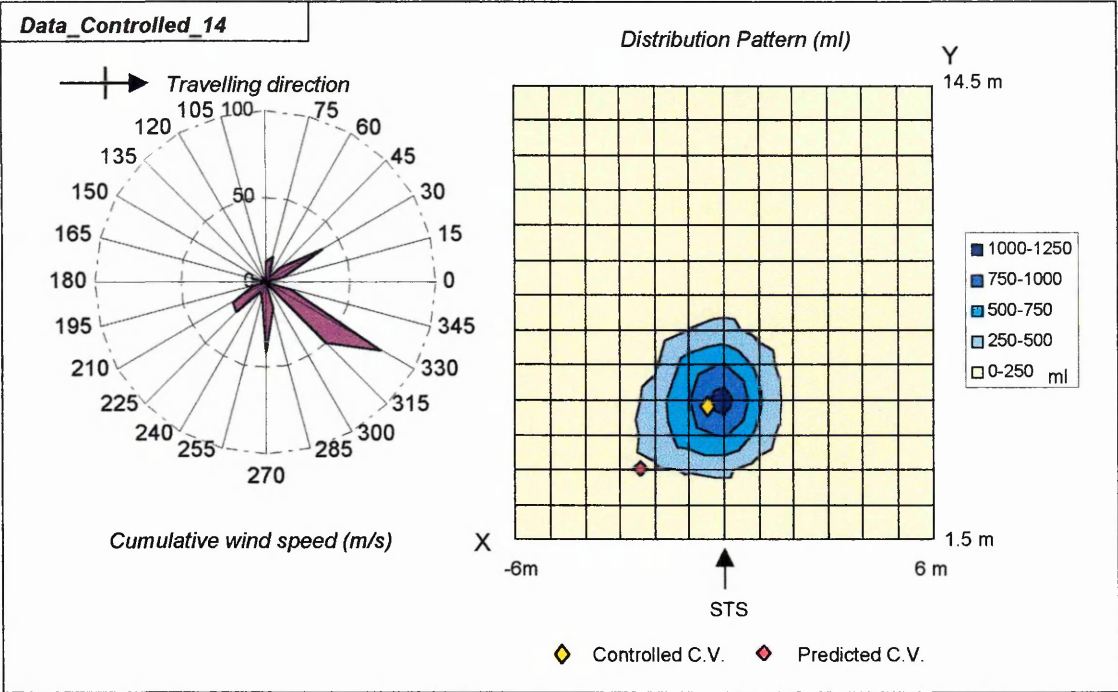
Fig.II-9: Data_controlled_12.



Pressure (psi)	Total amount of water in catch cans(ml)	Average of wind speed (m/s)	Average of wind direction (°)
38	15285	4.17	288.2

	X	Y
Controlled	-0.57	7.56
Predicted	-1.42	5.54

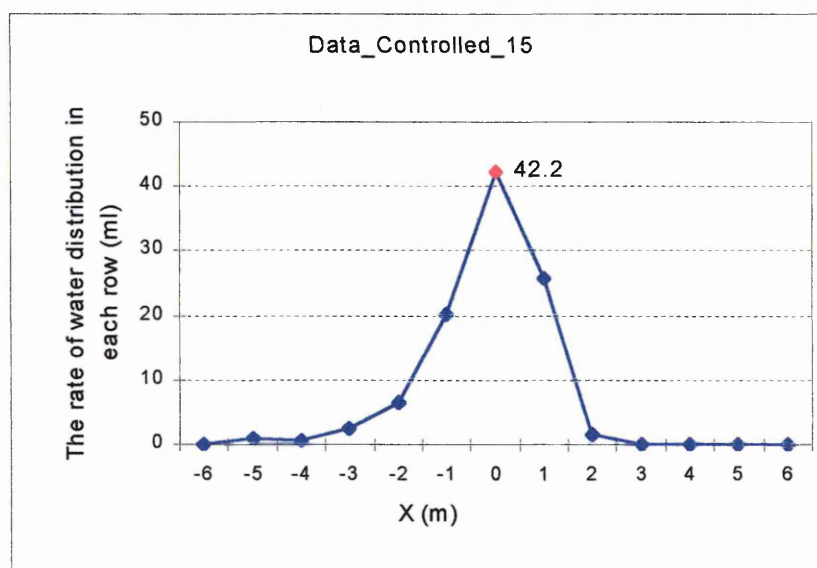
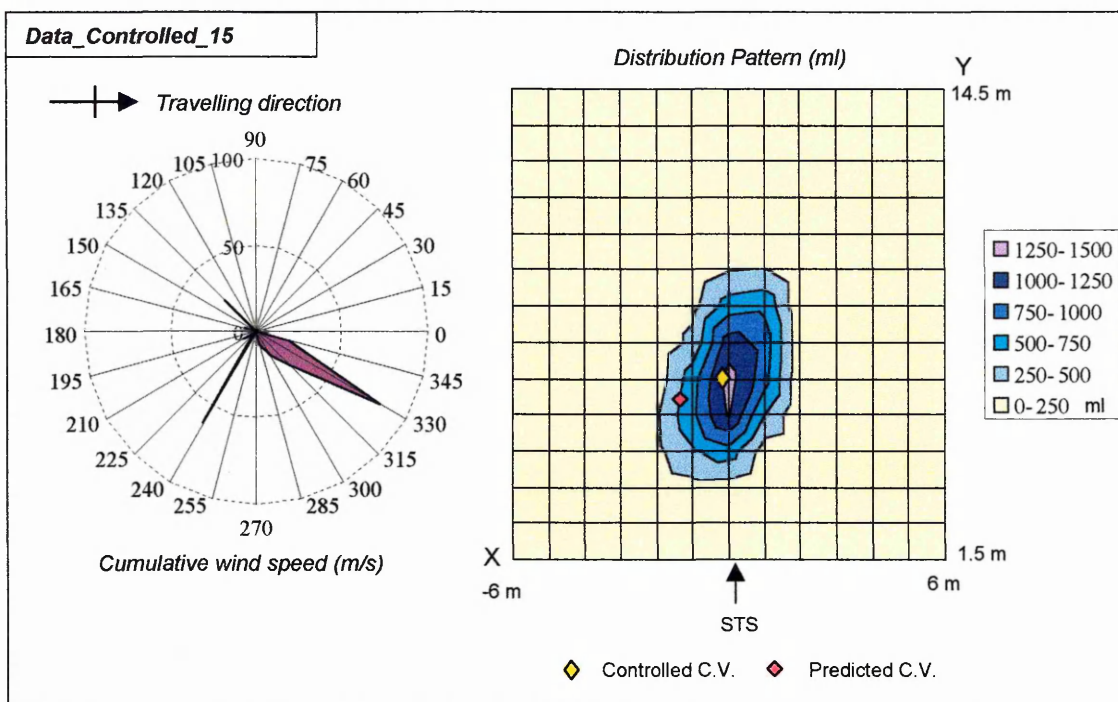
Fig II-10: Data_controlled_13.



Pressure (psi)	Total amount of water in catch cans(ml)	Average of wind speed (m/s)	Average of wind direction (°)
38	10235	6.23	227.1

	X	Y
Controlled	-0.54	5.37
Predicted	-2.61	3.5

Fig.II-11: Data_controlled_14.



Pressure (psi)	Total amount of water in catch cans(ml)	Average of wind speed (m/s)	Average of wind direction (°)
38	12846	4.42	291.2

	X	Y
Controlled	-0.18	6.52
Predicted	-1.29	5.97

Fig.II-12: Data_controlled_15.

Appendix III

How to use the main control programs

How to use these programs

First, all of files which include EXE files, Autoexec.bat transferred between those two computers easily by using an application called WIN LINK though COM1. When EXE file should be changed for controlling, Autoexec.bat file should be changed on your computer and sent by WIN LINK. After that, it is recommended to restart the embedded computer.

1. If you are ready to start this sprinkler system, press "ENTER".
2. A message "Choose water or fertilizer" comes up. If you select water, press "w", otherwise, press "f". (See if Set_pres() is available or not in main().)
3. When you see a message "Set pressure", open the main valve to put water into the sprinkler.
4. If pressure reaches the set value, you can see the message "Done".
5. Automatically it starts initializing the positions.
6. When the initialization is finished, a message is displayed "Initialized" and start controlling the motors by calculating the aimed angle from the wind data.
7. When 15 minutes have passed, the program is terminated and a message "Complete" is turned up on your screen.

Appendix IV

Test and control programs

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