AM 22: Flight Dynamics and Control for an Indoor UAV

Submitted by

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SUMMARY

The objective of this project is to develop a prototype of a semi-autonomous controlled UAV that is able to conduct flight missions in an indoor environment within a building. It involves the study of aerodynamics and propulsion characteristics of a chosen flying platform and the design of a semi-autonomous control system that comprises basic control and communication modules, as well as collision avoidance system (CAS) to ensure safe operation within the indoor environment. The developed control system is required to be integrated with the existing systems of the chosen UAV.

The paper begins by discussing the operations requirements in an indoor environment, followed by the selection of the flying platform and the required components. A quad-rotor radio-controller UAV was chosen for this project mainly due to its size, allowable payload and maneuverability. The flight dynamics of the platform were analyzed and the findings have suggested modification to the platform and aided the development of the control system.

There are two parts that form the developed control system: on-board CAS and ground station. The on-board CAS consists of sensors, a radio frequency module and a microcontroller that is responsible to transmit sensor data back to ground station for control decision making. On the other hand, the ground station consists of two microcontrollers with one receiving sensor data and making control decision, and the other generating the corresponding signal that will be transmitted via transmitter to the UAV. The main aim of the control is to avoid colliding into obstacles.

The serial communications between the microcontrollers involved were investigated with the aim to establish effective communication at highest possible speed. The signals from the transmitter were studied carefully in order to enable perfect duplication of the signals by the microcontrollers. After all the subsystems were successfully tested, the combined system was then integrated with the UAV and various flight tests were performed, including both ground and actual flight tests. The results show that the developed system is able to integrate well with the existing system of the UAV and it is able to avoid colliding into walls and corners in an indoor environment.

This project was done in collaboration with Mr. Muhamad Azfar bin Ramli who was responsible for the aerodynamics and propulsion components of the project.

A paper based on this project [10] was presented at the Republic of Singapore Air Force (RSAF) Aerospace Technology Seminar on March 2007.

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CHAPTER 1:

INTRODUCTION

This project is an industrial collaborative project sponsored by DSO National Laboratories. This project was done in collaboration with another Final Year Student covering the areas of aerodynamics, propulsion system, flight dynamics and control system. In this thesis, the analysis of flight dynamics of an unmanned aerial vehicle (UAV) and the design of its control system will be discussed and presented.

1.1 OBJECTIVES

The aim of this project is to design a semi-autonomous control system for a UAV to enable it to conduct flying mission in an indoor environment within a building. This control system will comprise basic control and communication modules, as well as a collision avoidance system (CAS) to ensure safe operation within the indoor environment.

1.2 PROBLEM DEFINITION AND BACKGROUND

Unmanned Aerial Vehicle (UAV) generally can be described as a smaller scale aerial vehicle, as compared to a commercial aircraft, that is able to sustain stable and controllable flight operations by its control system. This control system can be pre-programmed to follow a certain flight path or remotely-controlled from a ground station, without a pilot on-board the aircraft and hence the name “unmanned”. It has the advantage of saving labor cost and reducing need of placing human life in risky situations. One of its many applications is to conduct unmanned reconnaissance and surveillance mission whereby human presence or intervention is undesirable.

In the context of outdoor application, the aircraft has more options to evade obstacles and avoid collisions because there is less space constraint. It can also utilize GPS to enable autonomous flight following pre-planned flight path and thus provide more control over flight destination.

In an indoor environment, on contrary, weak reception of GPS signals and limited space restricts the avoidance options and thus posed additional challenges to the operations of the UAV. Hence, it is important to study how small-scale sensors can be used to provide visibility of the environment to enable safe operation.

1.3 ORGANIZATION OF THESIS

This thesis comprises 9 chapters. Chapter 1 introduces and defines the objectives of this project. Chapter 2 discusses the indoor operation requirements. Chapter 3 discusses the selection of platform. Chapter 4 analyses the flight dynamics of the platform. Chapter 5 describes the development of control system. Chapter 6 discusses issues relating to communication and signal generation. Chapter 7 describes the system integration and various flight tests. Chapter 8 evaluates the developed system and recommends several improvements. Chapter 9 concludes and provides direction of future development.

CHAPTER 2:

INDOOR OPERATIONS REQUIREMENTS

In an indoor environment, the common flight "terrains" that the UAV may encounter are enclosed space, doorway, narrow corridor and staircase, while the common obstacles are walls, ceiling, columns, furniture and humans.

In an enclosed space of a four-wall bounded room, for example, the UAV must be able to avoid colliding into walls. This means that if it is moving towards or near to the wall, it must be able to slow down to halt at a safe distance between itself and the wall. Subsequently, it should turn away from that direction to another path that is clear of obstacles.

Although the flow condition of an indoor environment is relatively more controlled than the outdoor environment, flow disturbances will still be present and these will affect the performance of the UAV. To better appreciate the level of disturbance, some measurements of wind speed at position very close to sources of disturbance typically exist in indoor environment were carried out:

Table 2.1: Measurement of maximum wind speed from various sources at position close to the source

Source	**Max Wind Speed (m/s)**
Strong air-con draft	2.5
Ventilation shaft	2.0
Mild breeze at corridor	1.0

To ensure optimum performance, the UAV should either be able to counteract the disturbance or avoid flying near the source of disturbance.

On the other hand, due to the limited space indoor, the allowable size of the UAV is also limited. With reference to a typical width of a doorway of about 100cm, the maximum length of the UAV must be smaller than 80cm. A smaller size usually means a smaller payload that the UAV is able to carry. Hence, wise choice has to be made to carefully select suitable sensors during the design of the control system.

For the purpose of this project, the scope is defined to consider only an enclosed space with walls and a low level of flow disturbances, as illustrated in Figure 2.1 below.

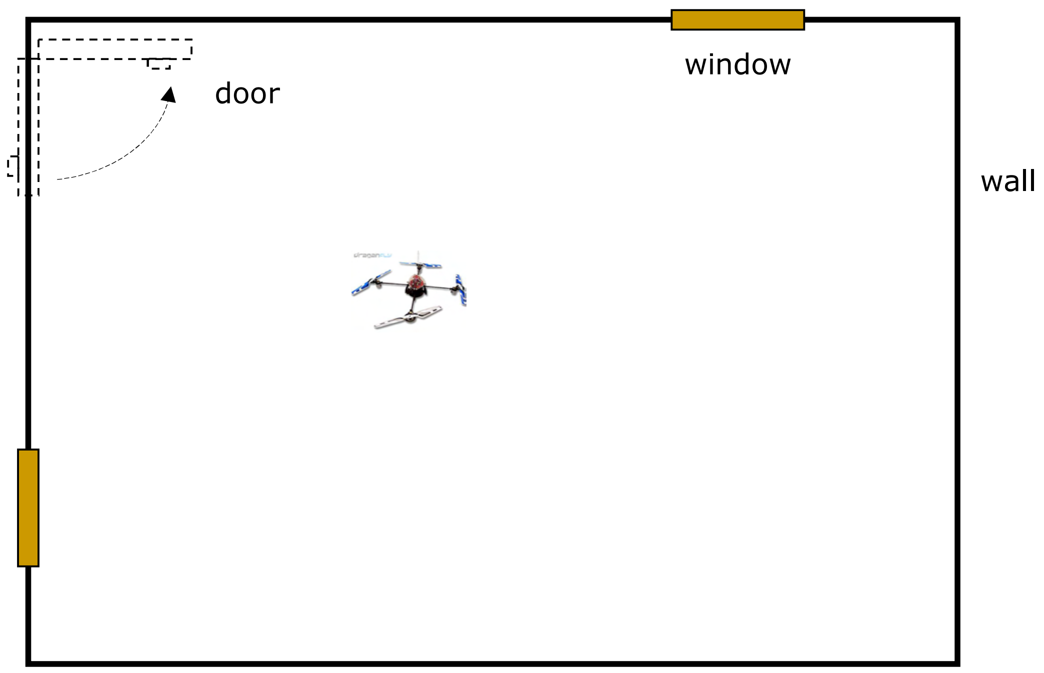


Figure 2.1: Illustration of a simplified indoor environment

CHAPTER 3:

SELECTION OF FLYING PLATFORM

Due to time constraint, the option of building a UAV from scratch is not desirable. This is because much time is needed to design, fabricate and test the built aircraft. Other than time, the cost of components needed for building aircraft was also surveyed and it is comparable with the price of a brand new radio controlled (RC) UAV available in the market. Hence, the wiser choice would be purchasing a RC UAV off the shelf.

3.1 ADVANTAGES AND DISADVANTAGES

The benefit of purchasing off the shelf is that the RC UAV is made ready-to-fly. The on-board system is already in working condition and its control system has already been designed to enable stable and controllable flight performance. Thus, there is no need to spend time on design, fabrication and testing of the UAV and hence save time and cost.

Despite the lucrative benefits, there are also problems with purchasing off the shelf, namely the cost and difficulty to modify. For this project, a small aircraft with high payload is desirable. In other words, a high performance RC aircraft is required and this means a higher cost for the UAV. Besides, to fulfill the objective of this project the purchased UAV have to be modified to enable semi-autonomous flight. RC aircrafts purchased off the shelf do not come along with the detail schematics of the electronics on-board; hence this poses a challenge for modification of the UAV. However, this problem can be solved as will be presented in later section.

3.2 CHOICES OF PLATFORM

There are a lot of RC UAVs designs available in the market. In terms of size, the ultra light fixed-wing aircrafts are feasible, but due to the fact that they cannot hover, they require more space to maneuver and it is very difficult to navigate them around in an indoor environment. Blimp is also a feasible option, but it provides virtually zero payload and it is very sensitive to air flows and thus will easily drift. Besides, it can only pitch and yaw but cannot roll and this limits the obstacle avoidance options and may hinder effective collision avoidance.

Hence, the option narrows down to rotorcraft types of UAVs. There are three common designs of RC rotorcrafts, namely the conventional main rotor tail rotor design, the co-axial rotor design and the quad-rotor design.

3.2.1 CONVENTIONAL MAIN ROTOR DESIGN

Advantages:

- Plenty of choices of models available in the market
- Longer flight time
- High payload
- Easy to get parts locally

Disadvantages:

- High performance model are usually very expensive and gas-powered (not suitable for indoor flight)
- Complex control mechanism, hence difficult to modify
- Dangerous for indoor flight, large rotor exposed is vulnerable to expensive damage
- Require high level of skills and years of experience to operate
- Noisy

Figure 3.1: Conventional RC Helicopter

3.2.2 CO-AXIAL ROTOR DESIGN

Advantages:

- Meet indoor size requirements
- Relatively simpler control mechanism
- Durable, rotor not easily damaged

Disadvantages:

- Short flight time (4 – 7mins)
- Extremely low payload

Figure 3.2: Co-axial rotor designs

3.2.3 QUAD-ROTOR DESIGN

Advantages:

- Meet indoor size requirements
- High payload
- Simple control mechanism and easy to control
- Durable, rotor not easily damaged

Disadvantages:

- Expensive and limited choices
- Aircraft and parts not readily available from local market
- Short flight time (12 – 15mins)

Figure 3.3: Quad-rotor design

3.3 THE CHOSEN PLATFORM

Of all the three designs, it is obvious that quad-rotor design is a better design for the purpose of this project. The two main reasons are this design is easier to modify and also easier to integrate the developed control system, as compared to the two other designs. Besides, their rotors are also smaller and can be enclosed, thus enabling safer flight. There are not many models of quad-rotor UAV available in the market and Draganflyer V Ti from Draganflyer Innovations was eventually chosen mainly because it offers the highest amount of payload and flight time. The detailed features of Draganflyer V Ti can be found in Appendix A.

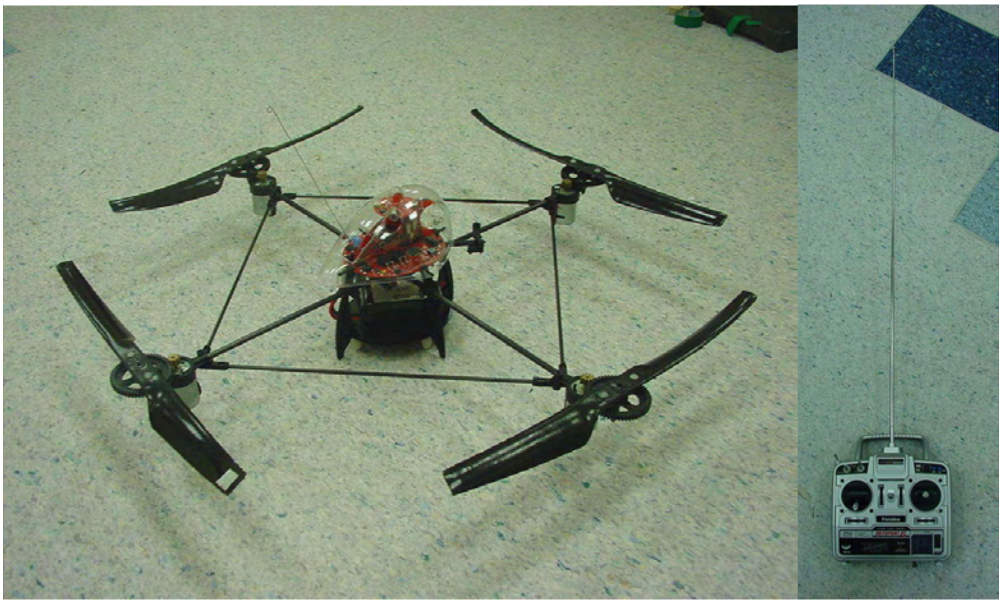


Figure 3.4: Purchased Draganflyer with its transmitter

CHAPTER 4:

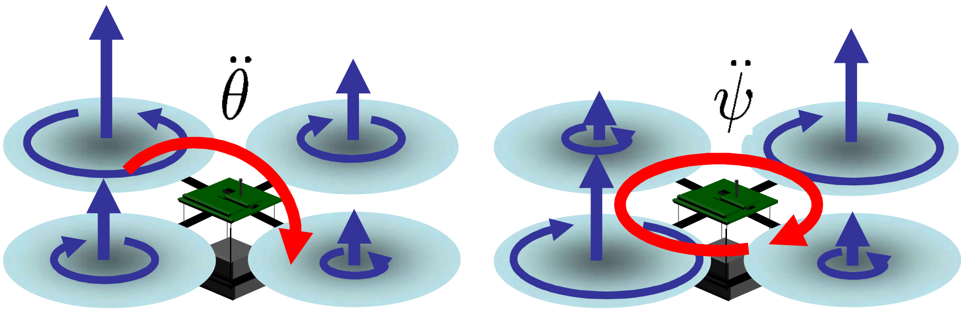
FLIGHT DYNAMICS ANALYSIS

Before proceeding on designing the control system, analyses have to be done to understand the dynamics of the chosen platform for better design decisions. Firstly, it is a quad-rotor aircraft, which the lift force is the sum of thrusts produced by its four spinning rotors. Thrust force varies with the amount of current supplied to the motor, which is controlled by its built-in electronics according to the input received from the transmitter.

4.1 BASIC MANEUVERS

The basic maneuvers (roll, pitch and yaw) are achieved by varying the current supplied to different motors that changes the force and torque balances acting on the aircraft. To pitch forward, the amount of current supplied to the front motor is increased and a similar amount of current is decreased from the back motor, while the current supply remains the same for the left and right motors. To pitch backward, the opposite current increment and decrement is to be done on the font and back motors, while the current supply remains the same for left and right motors. Similarly, to roll left and right, it is done by varying the current supplied to the left and right motors, and no changes for front and back motors.

Similar to rotorcrafts, the quad-rotor aircraft has to neutralize all torques generated by its rotating rotors to achieve a stable yaw state. For quad-rotors, this is done by having its front and back rotors rotating at same direction and speed, to produce a torque to counter the opposite torque produced by its left and right rotors which also rotate at same direction and speed, but opposite of the front and back rotors. Thus, in order to yaw right, current supplied to both left and right motors are decreased and current supplied to both front and back motors are increased.



(a) (b)

Figure 4.1: Mechanism of Quad-rotor maneuvers (a) Roll or Pitch (b) Yaw

(*Adapted from [4]*)

4.2 DYNAMICS ANALYSIS

The Draganflyer quad-rotor UAV is an under actuated system. It produces motion in six degrees of freedom with input forces from its four rotors. There are three main sources of opposing forces that affect its motion, namely gravity, inertia and air drag.

Firstly, gravity forces acting on the aircraft affects its vertical motion and results in the consumption of energy proportional to its weight. This limits the amount of payload that it is able to carry, considering a meaningful flight time that is required.

Secondly, the aircraft's own inertia opposes the linear and angular acceleration. Specifically, the inertia due to the mass of the motors resists the angular acceleration about the yaw axis, hence helps to stabilize the yaw motion. Also, by having the centre of gravity below the aerodynamic centre of the aircraft through placing the heaviest component – the batteries at lowest point of the aircraft, the inertia due to the mass of the batteries resists both roll and pitch motion. In short, the inertia has resulted in a dampening effect that helps to stabilize the aircraft's motions.

Thirdly, the aircraft's linear and rotary motion is opposed by the air drag acting on it. However, since drag is proportional to velocity and considering the slow translational velocity of the aircraft, the drag forces are small except for those in opposition to the rotation of the rotor. Consequently, air drag provides damping to the rotor velocity and hence slows the response of the aircraft to external forces, such as wind gusts.

On the other hand, its control system has built-in closed-loop control that uses feedback from its 3 solid-state gyroscopes on-board to help stabilizes its roll, pitch and yaw. This has greatly enhanced the damping effect on the aircraft's roll, pitch and yaw movements and hence its stability.

Due to its design, the four forces produced by the rotating rotors are cross-coupled[1]. Thus, it is impossible to maneuver the aircraft in an uncoupled way, such as having it to rotate while maintaining horizontal. Besides, when the aircraft move from hover to roll, the resulting gyroscopic torque due to changes in angular momentum vectors of the four rotors will cause it to pitch forward or backward depending on the rolling direction.

As the Draganflyer yaws while its fours rotors are spinning in the horizontal plane, the rotor blades experience coriolis acceleration. This acceleration will result in the application of torque to the rotor blades and hence to the aircraft. This torque will cause distortion to the aircraft structure, particularly the cross-tubes. When a rotor is distorted or unbalanced, the angular momentum vector may not have the same direction as the angular velocity vector. Consequently, the rotor blade will spin with a constant angular velocity but with a varying momentum. As a result, the blades will wobble and misalign. As the rotor blades are made of flexible material, generally they are able to dampen some level of vibration. However, if they are badly out of alignment considerable vibration will occur[1]. Figure 4.2 below shows the schematic representation of force balance of the Draganflyer.

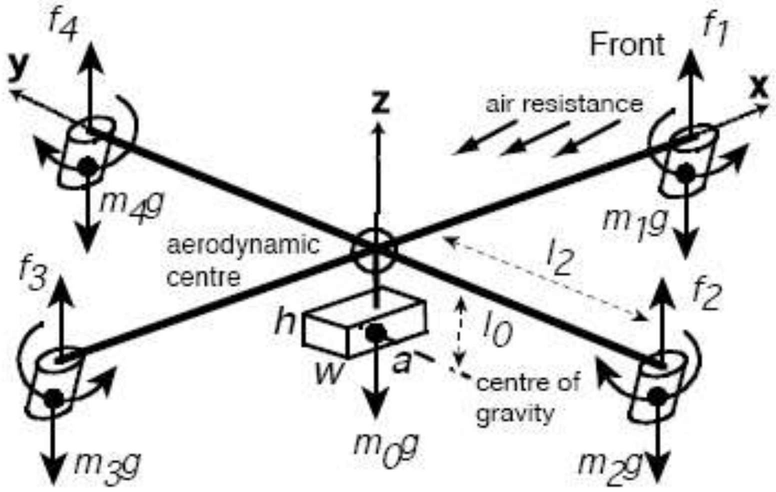


Figure 4.2: Schematic representation of force balance (*Adapted from [1]*)

Thus, from the analysis above, we have understood how the aircrafts make the basic maneuvers and have analyzed the stability of the aircraft. Generally, it can be said that the Draganflyer is a rather stable platform and this is beneficial for the purpose of this project as a stable UAV is required for indoor operations. Besides, from the analysis by [1], it has been shown that the aircraft is a complex system with under-actuated control and coupled dynamics. It was also learned that the yaw motion will result in considerable distortion to the aircraft structure and may induce vibration problem. Vibration is not desirable as it will affect the accuracy of sensor readings and consequently the effectiveness of the control system that is going to be developed. To address to this problem, four reinforcement bars were added to the existing cross-tubes, as can be seen in Chapter 7.

CHAPTER 5:

DEVELOPMENT OF CONTROL SYSTEM

5.1 OVERVIEW OF CONTROL ARCHITECTURE

In order to preserve the Draganflyer in its original condition for possible future development, and also due to lack of detailed information of the existing systems, it was proposed that no modification is to be done to the existing systems.

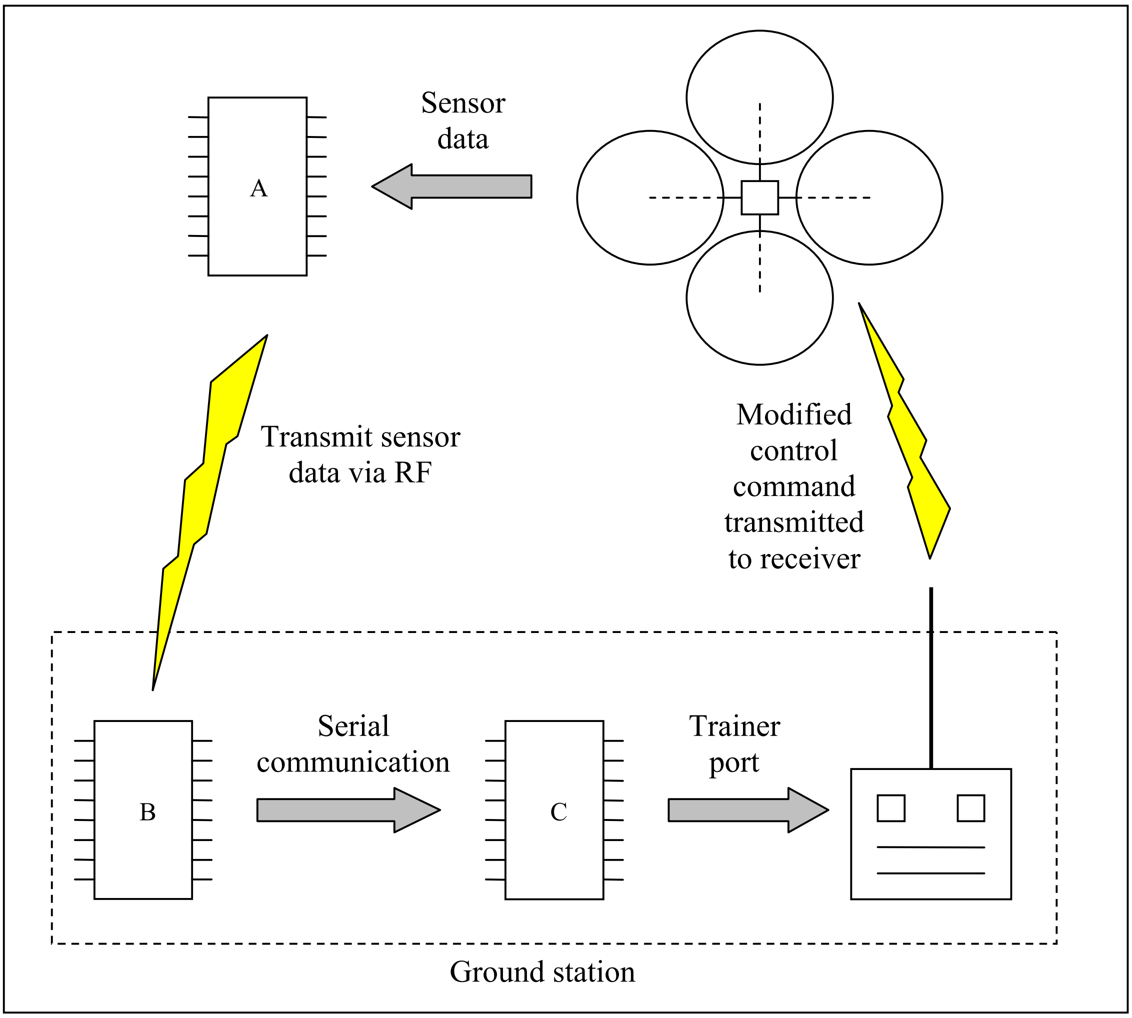


Figure 5.1: Overview of proposed control system

Figure 5.1 shows the overview of control architecture of the proposed control system, which does not require any modification to the existing systems. It is designed to be an add-on module and thus require minimum system integration effort with the existing systems. The role of the add-on module can be likened to having a computer to replace the role of the pilot to control the UAV.

As can be seen, the entire system is made up of two subsystems: On-board Collision Avoidance System (CAS) and Ground station. The CAS consists of a microcontroller (labeled A), four infrared ranging sensors, a tilt sensor and a radio frequency (RF) communication module, all of which will be installed on-board the UAV. On the other hand, the ground station is made up of two microcontrollers (labeled B and C), a RF communication module and the transmitter that comes along with the UAV.

As a brief description of how the system works, first of all microcontroller A will obtain distance readings and tilt readings from the sensors and these data will be sent via radio signal to microcontroller B on ground. After necessary calculations and decision making, control commands will be sent via serial communication to microcontroller C for corresponding signal pulse generation. Subsequently, the generated signal will be sent out to the on-board receiver through its transmitter via trainer port connection.

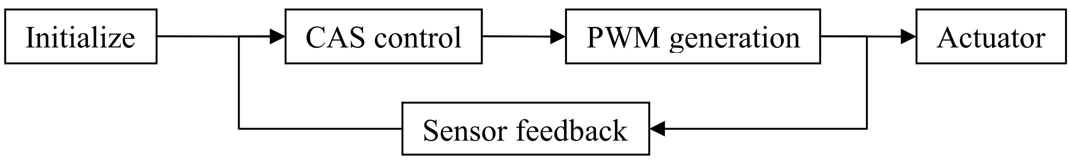


Figure 5.2: Schematic of control architecture

5.2 CONTROL ALGORITHM

The control algorithm used is shown schematically as follow. It is a simple algorithm with the aim of designing a short algorithm and to minimize the program runtime. Upon obtaining the sensor data, it will check all four directions for obstacles. The safety threshold set was 100cm. If there is obstacle within 100cm range in front, it will move backward. Likewise, if there is obstacle on the left, it will move right. If it detects obstacle on both front and left, it will move backward and right, as illustrated in Figure 5.3 below. If no obstacles are detected, it will proceed to move forward. After every maneuver, the leveling control will kick in to bring the UAV back to level before it proceeds to check for obstacles again. This is because the built-in gyro will maintain the maneuver for a while before it will slowly come back to level again, even if the transmitter's control stick is back at neutral position. The leveling control will limit the traveling speed of UAV and enhance the effectiveness of obstacle avoidance. Besides, for situation in which the UAV sense obstacles on both left and right, it will only be allowed to maneuver in forward and backward direction. The same condition is applied if obstacles are detected on both front and back. Schematic of the algorithm is shown in Figure 5.4.

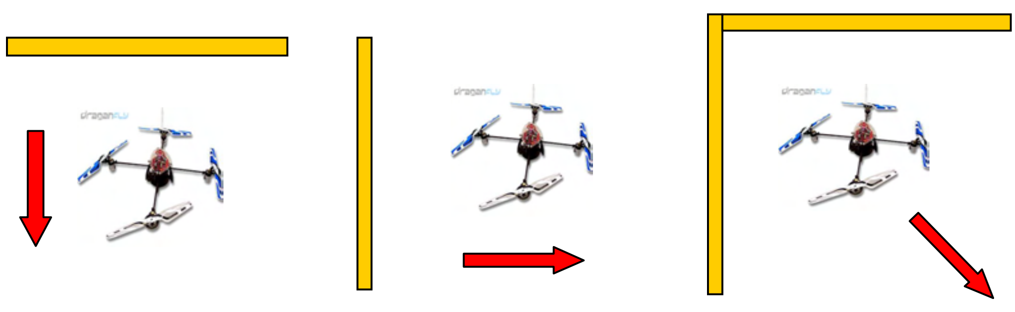


Figure 5.3: Graphical illustration of control algorithm

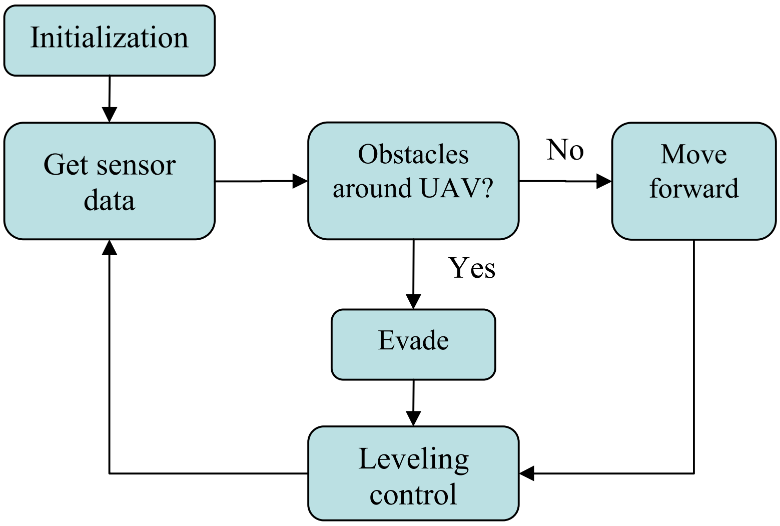


Figure 5.4: Schematic diagram of control algorithm

5.3 COMPONENTS SELECTION

As mentioned in previous section, due to the limited amount of payload that the UAV is able to carry, the components selection must be carefully done to maximize functionality while minimizing the payload required. While weight is the topmost priority, other main considerations are sensor output time, component availability and cost. Sensor output time is critical as it will affect the signal generations, which will be discussed in detail in later section. Component availability is important because it is not desirable to delay the progress of the project just to wait for a critical component to be shipped from overseas. As with all other projects, budget is always a consideration.

5.3.1 OBSTACLE DETECTION

In order to provide visibility of the environment, ranging sensors including laser, sonar and infrared (IR) can serve the purpose. However, laser is not suitable because usually the equipment is bulky and expensive, thus not suitable for our application. Although sonar sensor seems good due to its accurate distance measurement, it was found that it will give erroneous readings when it is sensing at an angle with target surface. Besides, the sensor output time changes significantly as the measuring distance changes, thus affect the signal generation. Hence, IR sensors were ultimately chosen because of its low cost, light weight, availability from local market, reasonably accurate sensing, low current consumption, and most importantly, unlike sonar, it does not give erroneous result when it is sensing at a non-perpendicular sensing surface. For obstacle detection, the longer the sensor sensing range the better it is. However, the best IR sensor available is Sharp GP2Y0A02YK which has a reasonable sensing range of 20cm – 150cm and each weighs only 5grams.

Figure 5.5: Sharp GP2Y0A02YK infrared sensor (left) and

Parallax PING))) sonar sensor (right)

5.3.2 LEVELING CONTROL

Due to the nature of control of the UAV, after it roll or pitch according to the control command from the transmitter, it will not immediately stabilize back to level position. This is dangerous as it continues to roll or pitch, it will continue to move and may soon encounter an obstacle. Thus, it is important to always bring the UAV back to level after every roll or pitch performed.

For this purpose, a dual-axis microprocessor-based tilt sensor with signal conditioning 0719-1719-99 from The Fredericks Company was chosen to obtain tilt angle of the platform with respect to ground. It uses the principle of electrolytic sensors and produce pulse outputs of tilting of both X and Y axes. It is chosen because it has a signal conditioning board which is able to filter out certain level of noise and vibration-induced error. The whole board weighs 21 grams.

Figure 5.6: Microprocessor-based Dual-axis tilt sensor 0719-1719-99

5.3.3 MICROCONTROLLERS

As for microcontroller, the additional considerations include the RAM capacity, and simple programming and debugging. Although it is not as cheap and large RAM capacity as PIC microcontroller, Basic Stamp was chosen mainly because they are readily available from the lab and it is able to deliver to all our requirements. It is extremely easy to program and debug using its unique programming language, Pbasic and its compiler Basic Stamp Editor v2.2.6. It can also be easily interfaced with any computer via serial or USB port and is able to support serial and I^2C input. Most importantly, it can easily duplicate and generate the pulse signal from the transmitter which has important application in this project. Besides, it is also widely used in many robotics and RC applications and has forums which provide much troubleshooting information.

Initially all microcontrollers used are BS2, however it was found that pairing up BS2 with BS2PE would allow faster yet effective transfer rate for the RF communication between the on-board system and the ground system. Since BS2PE is faster in terms of code execution speed, so BS2PE is used for on-board system (microcontroller A) while BS2 is used for microcontroller B on ground. Besides, it was also found from the experiments that signal generation using BS2 is not as effective as BS2SX because of its inability to produce the pause pulse of 400μs. Smallest time unit of PULSOUT function for BS2 is 2ms whereas for BS2SX is 0.8ms[3]. As such, BS2SX can produce the pause pulse more precisely than BS2. Hence, BS2SX is used for microcontroller C on ground which is responsible for signal generation.

The datasheets of the main components used can be found in Appendix B-E. The complete architecture of the control system is shown graphically in Figure 5.7-5.9 and can be found in Appendix L.

5.4 SENSOR CALIBRATION

Before putting into application, sensors need to be calibrated. Since the tilt sensor has already been calibrated by manufacturer for operating in typical room temperature of 25^0C, and it has also been verified to operate normally from experiments, hence no further calibration is needed. However, due to the fact that the Sharp IR sensor's output is of non-linear relationship with the measured distance, proper calibration is necessary. Calibration curves that were produced from experiment based on the guidelines provided by the distributor, Acroname[2] were used to obtain calibration constants which will be used in the programming codes. The details of the calibration can be found in Appendix F. An accuracy of +/- 1 to 3cm can be obtained using the calibration constants.

5.5 SENSOR EVALUATIONS

After calibration, it is required to evaluate the performance of the sensors before integrating them into the system. There are issues regarding the infrared sensor, in particular the mounting orientation and its vision cone. The mounting orientation issue arises because it was found that different mounting orientation, vertical or horizontal, will affect the distance readings in different sensing condition. Experiments were done to investigate which mounting orientation will give the best measurements. Besides, the vision cone angle of the sensor is also measured to determine how wide its region of detection is.

5.5.1 NON-PERPENDICULAR SENSING

When the sensing surface is not perpendicular with the IR sensor, although not as bad as the measurements by a sonar sensor, it still gives some level of error in distance measurement. Figure 5.11 below shows the measurements taken when sensor is at certain angle with the sensing surface at a fixed distance of 50cm, using both horizontal and vertical mounting orientation with respect to the ground. The experimental results show that vertical mounting gives less error over a wide range of angle as compared to horizontal mounting, with error ranging from 2cm at 10 degrees angle to 10cm at 80 degrees angle. The experimental setup can be found in Figure 5.12 in Appendix G.

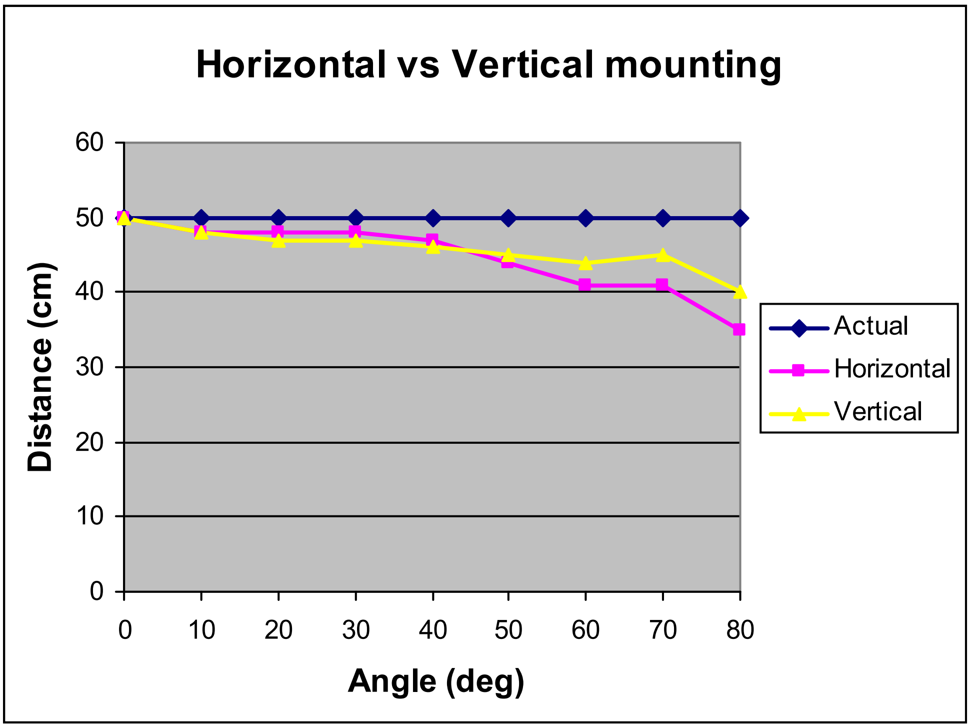


Figure 5.11: IR sensor sensing at various angles with respect to sensing surface with 2 different mounting

5.5.2 CORNER SENSING

Other than sensing at an angle with the sensing surface, sensing at corner will also bring some error to the distance measurements. To identify the significance of the error, measurements were done at known distances and the readings were compared with their respective actual distances. The measurements were done at two corner angles: 90^0 and 110^0. Corners of angle less than 90^0 are not considered as other two sensors at the sides will forbid the Draganflyer from approaching that sharp corner. Figure 5.13 shows the measurements obtained at corner angle of 90^0. Measurements obtained for corner angle of 110^o can be found in Figure 5.14 in Appendix G.

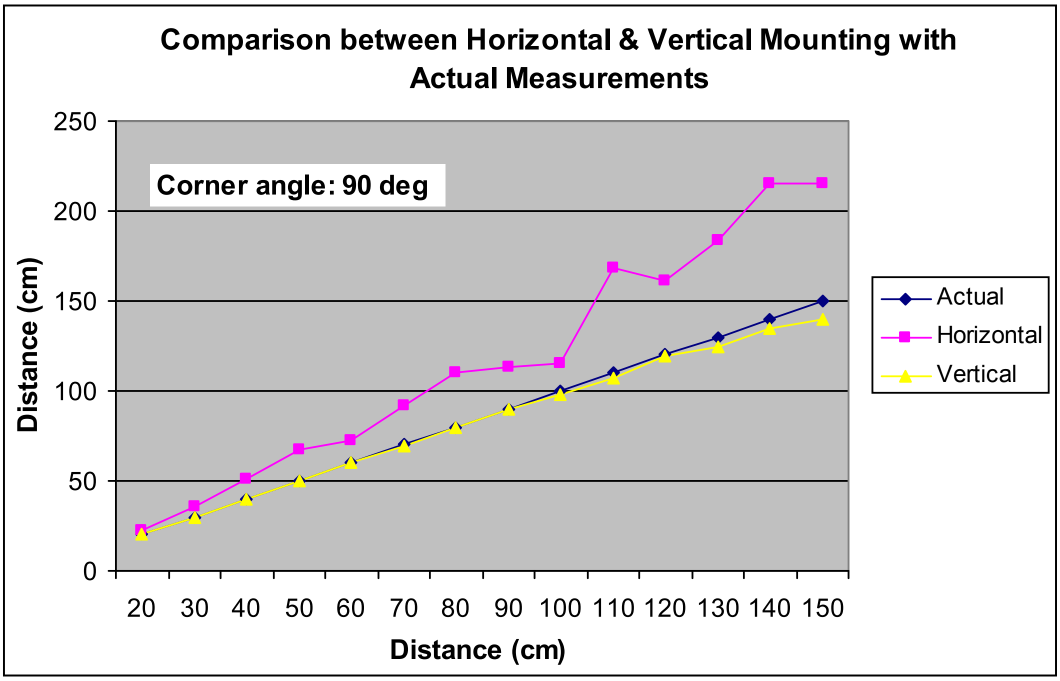


Figure 5.13: Measurement at corner angle of 90^0

As can be seen, both experiments at corner angle of 90^0 and 110^0 reveal that vertical mounting orientation will give better accuracy in distance measurements.

Hence, the experimental results above agreed with each other that mounting the IR sensor vertically will give less error in distance measurement. Since there is no problem with the sensor detecting the floor when it is still on ground, the IR sensors will be mounted vertically with respect to the ground.

5.5.3 VISION CONE

The vision cone of the IR sensor was plotted by connecting the points at each measurement distance whereby the sensor begins to detect the presence of the obstacle. Figure 5.15 below shows the experimental setup and the IR sensor's vision cone. From the vision cone plotted, the cone angle was measured to be 8^0 wide.

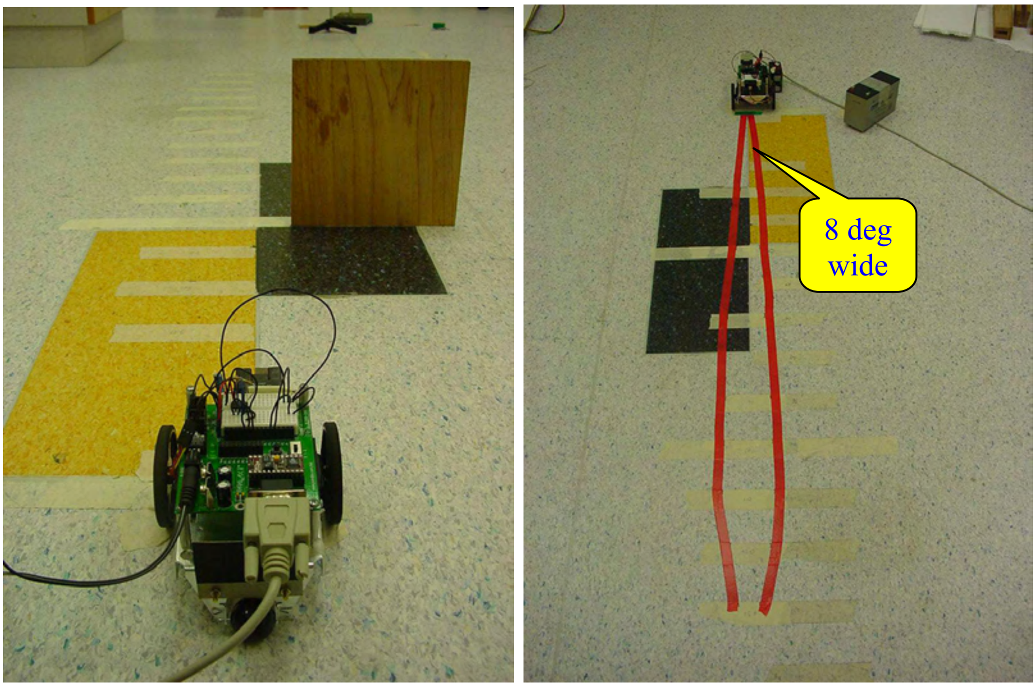


Figure 5.15: (Left) Experimental setup for vision cone measurement and (Right) Vision cone of IR sensor

CHAPTER 6:

COMMUNICATION AND SIGNAL GENERATION

As can be seen from the control architecture in earlier section, there are three microcontrollers involved in the control system. The microcontrollers communicate with each other via serial communication in which the data is transmitted one bit at a time over a single path. In order to have meaningful communication and effective data fetching between the microcontrollers, it is important to synchronize the communication. Since timing is a critical issue during signal generation and there are many serial communications involved, time required for each serial communication needs to be investigated.

6.1 SYNCHRONIZATION METHOD

For basic stamp microcontrollers, there are basically two methods of synchronizing serial communication between the microcontrollers: (a) Flow Control Method (FCM) and (b) Wait Method (WM).

In simple terms, Wait Method can be seen as the receiver will keep waiting until it receives a sync byte from the sender and then only the communication is established. Flow Control Method is the other way whereby the sender will not send until receiver side indicates that is ready to accept, by use of the flow control pin. The question is which synchronization method is more time effective. This was done by comparing the time needed for each serial communication established by both methods.

The experiments were done by sending various numbers of bytes of data using both methods and the time needed for each serial communication was observed from the digital oscilloscope. The results were plotted into graphs of time required for each serial communication versus the number of bytes sent and received. The graphs can be found in Appendix H.

The general observation from the graphs is that the time required varies linearly with the number of bytes sent or received. It can also be observed that FCM requires less time compared to WM. Every extra byte sent or received by FCM will require an additional time of about 1.1ms; on the other hand, it is about 1.2-1.3ms for WM. However, FCM can only be established between wired connections, wireless communication will still require WM.

Hence, FCM will be used in serial communication between microcontroller B and C on the ground station since they can be physically connected by wire, and WM will be used in the wireless communication between microcontroller A and B, which links the on-board system with the ground.

6.2 TRANSMITTER SIGNAL ANALYSIS

As the microcontroller will take over the transmitter's role to generate the control signal that will command the control of the UAV, it is important to analyze the control signal to ensure that same form of signal is generated as compared to the original signal generated from the transmitter. Using a digital oscilloscope, the signal form is found to be pulse width modulation (PWM) signal that consists of seven channels of pulse information. Out of the seven channels, only five are meaningful to the control of the UAV, which includes roll, pitch, throttle, yaw and Thermal Intelligence switch. The seven pulses and a long synchronization pulse make up a pulse train. Figure 6.3 below shows the schematic representation of a seven channel pulse train. Images of the signals from the digital oscilloscope can be found in Appendix I.

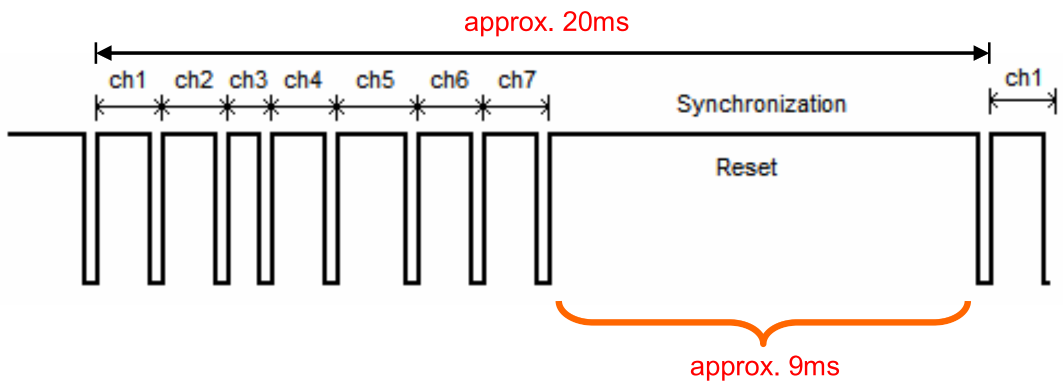


Figure 6.4: Schematic representation of a 7-channel pulse train

It can be observed that the time span of each pulse train is approximately 20ms. The width of each channel ranges from about 1–2ms, all of a magnitude of approximately 4.8V. The neutral pulse width is about 1.52ms. The constant pause width was measure to be 400µs. Besides, the longest pulse in a pulse train is called the synchronization pulse of a pulse width of 9ms. While the pause between the pulses is important to segregate the pulses into different channels, the synchronization pulse is also critical to separate one pulse train from another.

6.3 TIME CRITICALITY

Since the control signal generation is entirely on the hand of the microcontroller C, the signal generation condition must be the same as those from the transmitter. However, besides generating PWM signals, it also has to receive control command from microcontroller B in order to generate the pulses that corresponds to the intended control command. It would not be a problem if the microcontroller is able to execute both tasks simultaneously, however all Basic Stamps can only do one task at a time. Hence, the challenge is to ensure that the signal generation is not affected by serial communication, while maintaining as fast a signal update rate as possible.

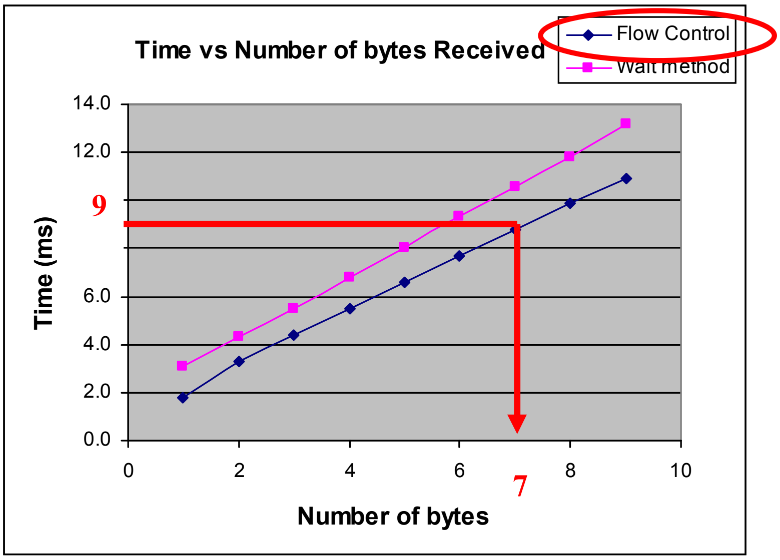
For communication between microcontroller A and B, it was measured that A requires 11.8ms to obtain distance measurement data from all 5 IR sensors and 28ms for tilt sensor. Hence, the signal update rate between A and B is about 40ms, which is equivalent to a frequency of 25Hz. On the other hand, besides time needed to serial-in sensor data, B on ground requires additional 3ms for control decision making.

Timing is most critical for microcontroller C. As seen in Figure 6.4, the only time which C is “free” to serial-in control command from B is during the synchronization pulse of 9ms. It was found from experiments that the UAV’s receiver allows a width range of 5-33ms for the synchronization pulse, outside that range would result in dangerous and uncontrollable operation which would cause harm to the operator and damage the UAV. These imply that the program code has to be kept as concise as possible so that the program runtime will not delay the signal update between the microcontrollers which in turn affect the length of the sync pulse. As a preventive measure in case of communication break down between A and B, a timeout function is used to prevent too long waiting time to serial-in control command that will result in long sync pulse, as can be seen from the programming codes.

All these have explained why timing is so critical during signal generation by the microcontroller and hence the reason why the sensor output time is one of the important considerations during component selection.

6.4 SIGNAL GENERATION

From previous analysis on serial communication, as shown below, with 9ms by Flow Control Method the microcontroller C is able to receive seven bytes of data. However, only four bytes of data are required, which represents control command for roll, pitch, throttle and yaw.



Duplicate copy of Figure 6.1 from Appendix I

As for the fifth channel which represents the Thermal Intelligence function of the UAV, since this function cannot be used in an indoor environment, it does not require any calculation for control decision and can be set as a constant to configure it to always be in the off mode. Similar is set for the remaining two channels.

Basic Stamp microcontrollers has built-in command which enables easy generation of the PWM pulse by a simple PULSOUT command[3]. The programming codes can be found in Appendix J. To verify the pulse signal generation, the signal generated from the transmitter were captured and compared with those generated by microcontroller C (BS2SX), as shown in Figure 6.4. The signal update rate between C and the UAV is about 21ms, which is equivalent to a frequency of 47Hz.

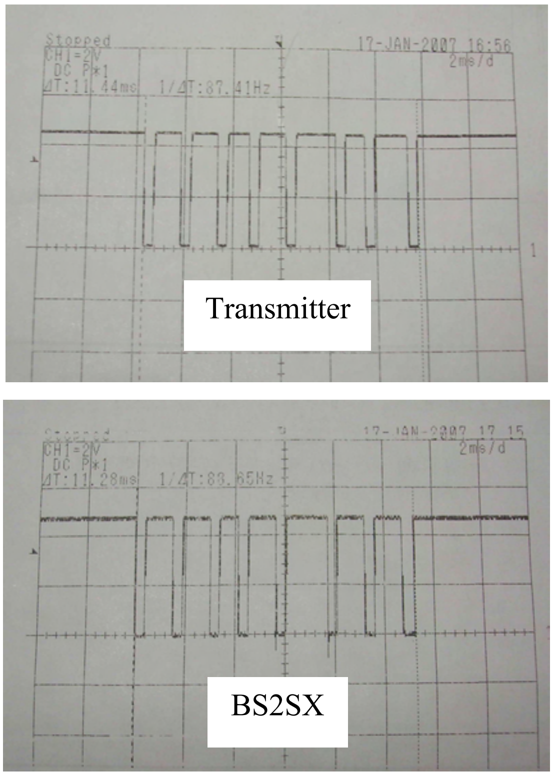


Figure 6.5: Comparison of signal generated by transmitter and BS2SX

6.5 TRAINER PORT CONNECTION

The replacement of control by microcontroller C from transmitter is made possible by the trainer port connection. The trainer port function is meant to allow two transmitters to be connected to each other with one acting as the master and another as the student. The senior pilot would hold the master and control signals are generated by it alone. During training, the student pilot's transmitter is turned off to avoid interference and power is supplied from the master. When the senior pilot decide to allow the student to take over control of the UAV, he will turn on trainer function and the control signals are now generated by the student's transmitter but the signals are transmitted out via master. The inputs from the control sticks of the master are bypassed when trainer function is turned on. This trainer function that allows take over control of the UAV from the transmitter by a third party is utilized for the control of the UAV for this project, in which the third party is the microcontroller C instead of a student pilot.

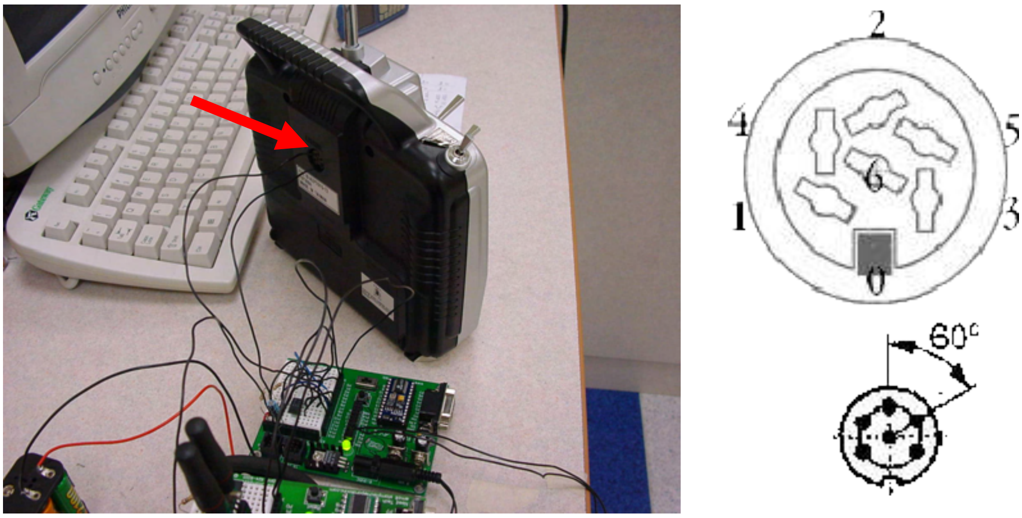


Figure 6.6: Trainer port connection

Figure 6.6 above shows the trainer port connection between the basic stamp board and the transmitter’s trainer port. Two wires from the board are connected to the trainer port, in which one carries the signal generated by the microcontroller (connected to pin 2 of trainer port) and the other is the ground (connected to pin 6 of trainer port).

CHAPTER 7:

SYSTEM INTEGRATION & FLIGHT TESTS

With all the subsystems being configured, the developed control system is ready for system test. The control system will go through several ground tests before being integrated with the UAV. System integration also includes the design of printed circuit board (PCB). After ground tests and the developed control system are fully integrated with the UAV, the UAV will be put to test in actual indoor environment.

7.1 GROUND TEST

The purpose of ground test is to test the reliability of the control system and to test how well the Collision Avoidance System would work. Firstly, the wireless communication between the on-board system and ground station is tested. The baud rate for the transmission was set to the highest rate and it was found that in close range (distance between two RF modules is less than approximately 15cm), no data transmission was observed. However, beyond the 15cm limit and as long as the two are within the specified range of 45m, the transmission works very well.

Secondly, an initial stage mock system was developed to test reliability of the signal generation and the CAS algorithm. In order to prevent any unforeseen event such as loss control of the UAV or any unexpected behavior which would result to accident or damage, the UAV is temporarily "grounded" on the floor by heavy weights at its four corners and hanged from the ceiling by a spring balance. The mock system and the “grounded” UAV are shown in Figure 7.1 and 7.2 below.

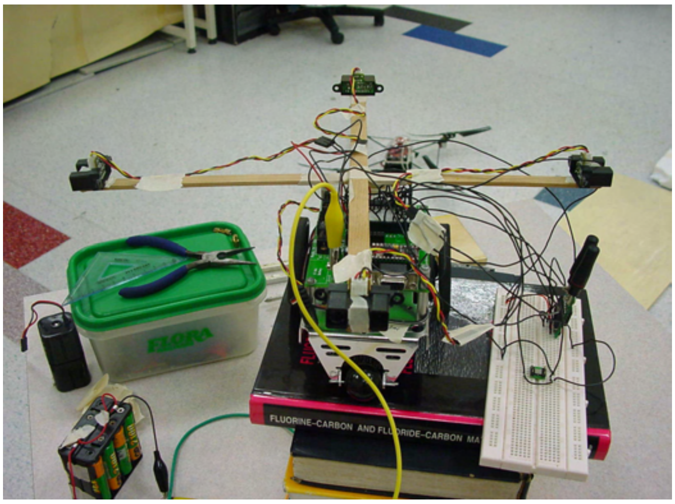


Figure 7.1: Mock system on the ground

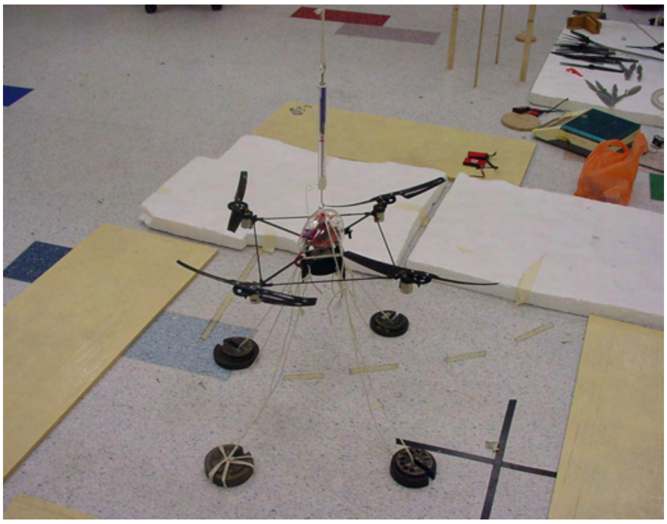


Figure 7.2: UAV “grounded”

The tests have helped to debug several errors and shortcomings in the programming codes. After several editing and improvements were made, the control system and the algorithm proved to work well.

7.2 PCB DESIGN

Due to the excess weight and size of the basic stamp development board, the UAV does not have sufficient payload to carry the board. Also, it is also not able to fit into the limited space available on-board. Thus, there is a need to design a PCB that is able to fit in all the sensors and electronics required for the CAS system that is light-weight and is able to slot in easily into the limited compartment on-board the UAV. The PCB will include one basic stamp microcontroller BS2PE, four infrared sensors, one 8-bit eight channel analog to digital converter (ADC), one 5V DC voltage regulator, two 100Ω resistors, one 0.1µF and one 10µF capacitor. Pin sockets are soldered onto the PCB instead of the component's pin itself to prevent damage from mishandling during soldering. The PCB design diagram can be found in Appendix K.

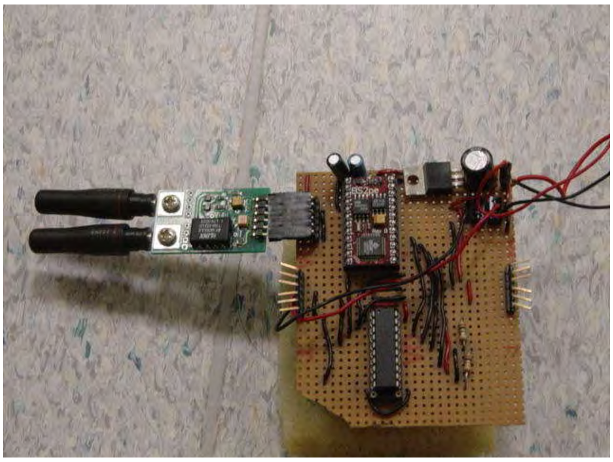


Figure 7.3: PCB with components soldered

7.3 SYSTEM INTEGRATION

With the designed PCB, the CAS is ready to be installed on-board. As with most system integration, several issues arise during the integration process.

7.3.1 VIBRATION

As inherent in motor-operated systems, vibration from the running motors will cause inaccuracy in sensor readings, especially the tilt sensor. Although the built-in signal conditioning board of the tilt sensor does help to filter out some vibration error, the tilt readings still fluctuate quite significantly. Sponge was used to "sandwich" the PCB and the tilt sensor from the vibrating platform, as shown in Figure 7.4. This has further reduced the vibration error to an acceptable level, thus enabling good leveling control. Also, from dynamics analysis we know the cross-tubes may distort and suffer considerable stress during flight operation. Thus, four reinforcement bars were placed to strengthen the structure and reduce vibration level, as shown in Figure 7.5.

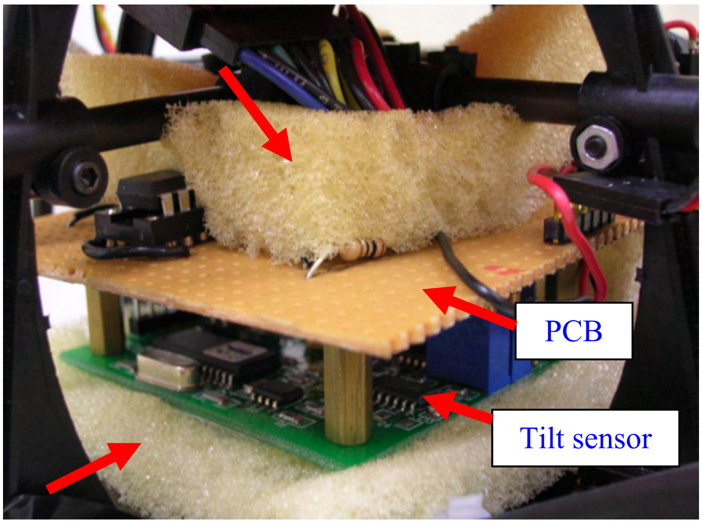


Figure 7.4: Sponge used to reduce vibration

7.3.2 SENSOR LAYOUT

As mentioned, the IR sensors will be mounted vertically. Since there is no readily available location, four vertical bars were attached onto the cross-tubes of the UAV and the sensors are mounted vertically onto the bars. Care has been taken to place the sensor such that will not detect the UAV's components or the ground as obstacles during operation. The sensor layout can be seen from Figure 7.5 below.

7.3.3 BATTERIES

Since the PCB and tilt sensor has taken up the space initially used to place the UAV's battery, the battery has to be relocated to the bottom and foam is shaped to protect it from impact with ground. For power supply to PCB, regular 9V battery is unable to provide meaningful operation time. An 8.4V Li-Po battery is able to supply sufficient power but each weighs 74g. Subsequently, it was found that it is feasible to tap power from Draganflyer's battery which has a voltage of 11.8V when fully charged. The obvious benefit is we do not need an additional battery on-board to power the PCB.

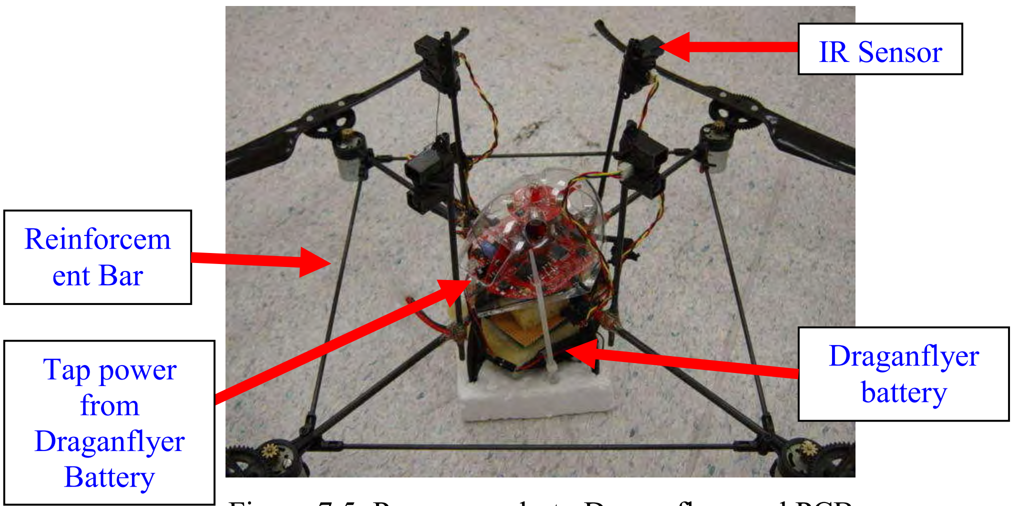


Figure 7.5: Power supply to Draganflyer and PCB

7.4 COMPLETE SYSTEM

The complete system is shown in Figure 7.6 and 7.7 below. Below being released for actual flight test, the complete system has undergone another ground test to ensure that all subsystems are working fine.

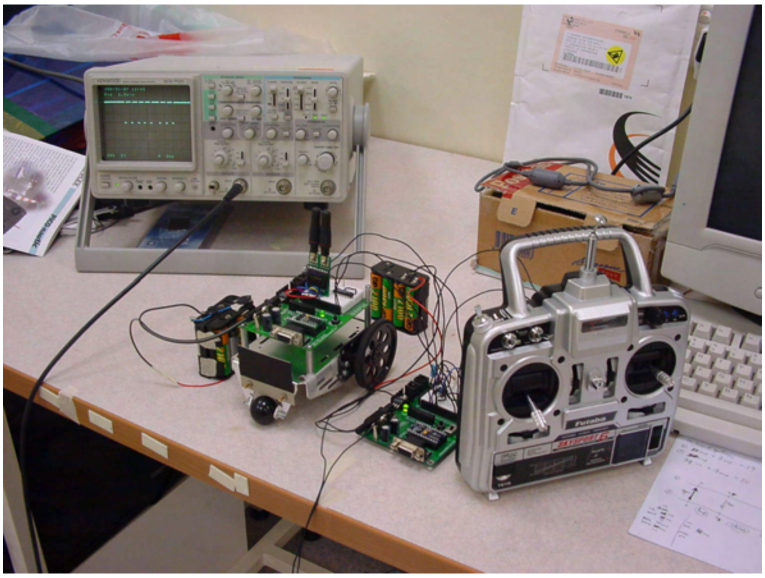


Figure 7.6: Ground Station

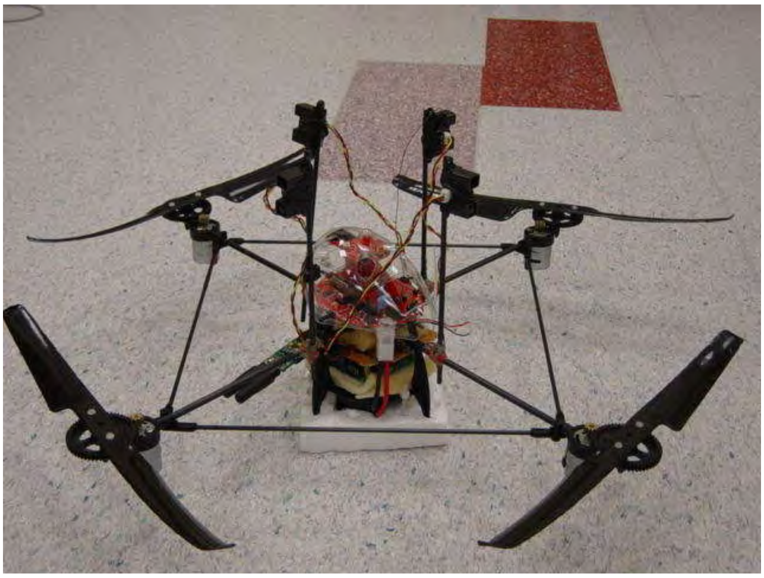


Figure 7.7: On-board CAS integrated with UAV

7.5 FLIGHT TEST

The flight test was done indoor with usual lightings and normal room temperature. Wood boards were used to enclose and simulate a four wall-bounded are of dimension 400 x 380cm, as shown in Figure 7.7 below.

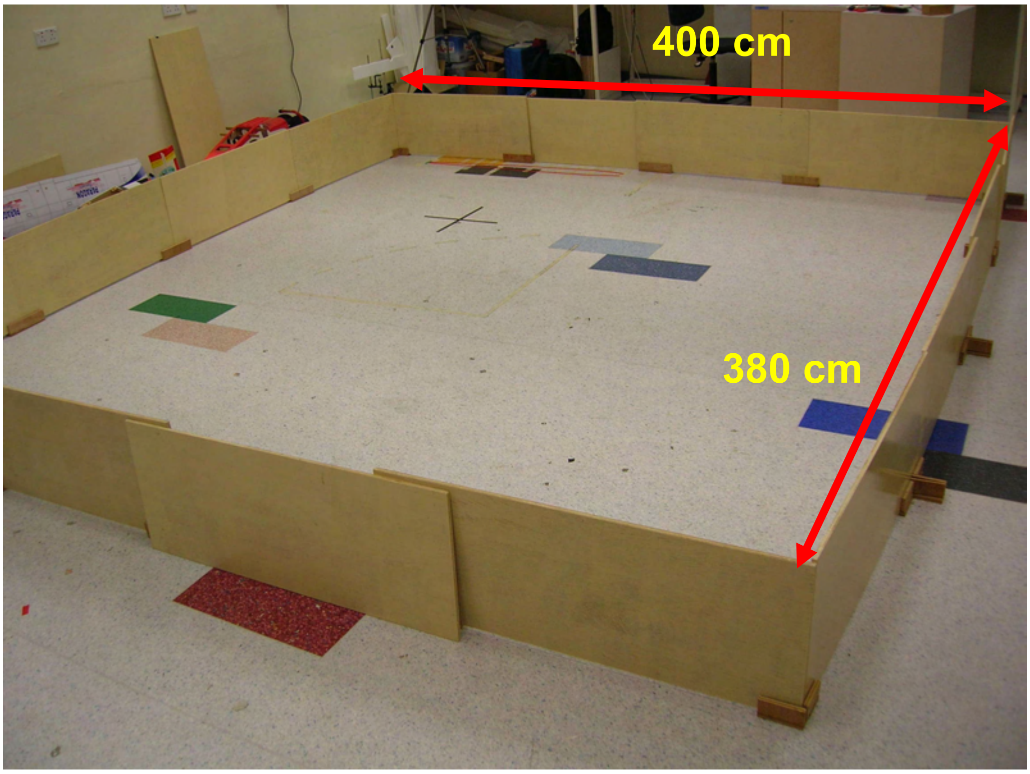


Figure 7.8: Flight test environment

CHAPTER 8:

SYSTEM EVALUATION AND RECOMMENDATIONS

8.1 SYSTEM EVALUATION

As seen from the flight test videos, with the aid of CAS the UAV has successfully avoided collision with both walls and corners. Below are the snapshots captured from the flight tests videos.

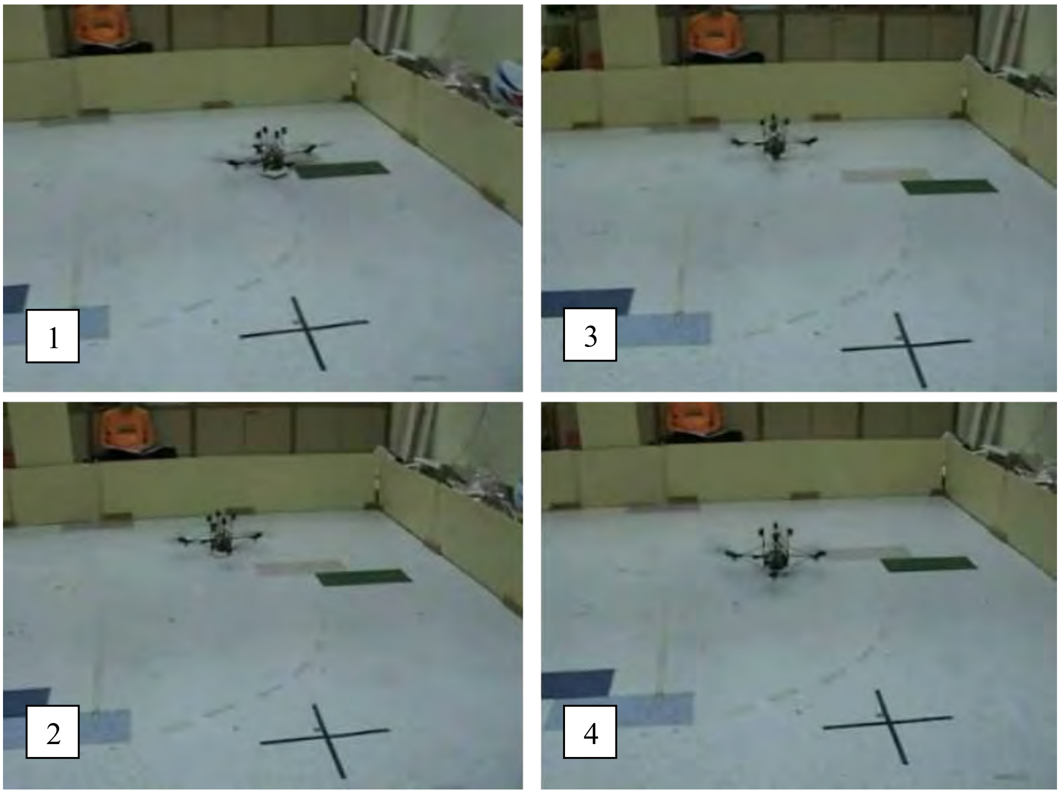


Figure 8.1: Snapshots of UAV evaded wall

In frame 1, the UAV is moving towards a wall. In frame 2, the UAV brakes in front of the wall. In frame 3, the UAV has stopped and start to move away from the wall. Frame 4 shows the UAV has moved away from the wall.

8.2 RECOMMENDATIONS

Although the collision avoidance is successful, the system is not yet perfect. Some recommendations are discussed as follow.

8.2.1 HOVER

In order to navigate through indoor environment of highly restricted spaces, it is required that the UAV is able to hover precisely in one location. However, due to the limited payload and non-availability of precision electronics, the developed system is unable to achieve precise hovering control of the UAV. To improve the hovering control, advance tilt sensing systems coupled with complex tilt control algorithm are required. Otherwise, the option of aircraft type should be revisited in search for more stable aircraft.

8.2.2 IR SENSOR

Due to the restrictions on sensor output time, the number of IR sensors that can be installed on-board is limited, and hence the sensing coverage. The vision cone of the IR sensors is only 8 degrees wide. With only four installed, there are wide areas of uncovered loop holes that will hinder effective obstacle avoidance. To improve visibility of the environment, more sensors should be mounted and this implies that ADC of faster processing speed and fast microcontroller with multi-tasking ability are required. Another option would be using a sensor of wider sensing vision cone; however sensor of this kind currently available would usually have very limited sensing range.

On the other hand, the IR sensors are not always reliable at all operating conditions. Due to its working principle, the distance measurements are subject to error if heat sources such as fire are present or under direct sunlight. Besides, it is also subject to error in a highly humid environment. Thus, IR can only work well in normal indoor environment. To improve reliability of sensor measurement, sensor that operates by a different working principle such as sonar or optic can be considered for different operation environment. It should be noted that sonar sensor measurement can be affected by temperature and data output time varies with distance measured; whereas optical sensor is affected by highly reflective environment.

8.2.3 WIRELESS COMMUNICATION

The on-board system and ground station is linked by radio frequency wireless communication. According to the specification of the RF module, the maximum separation between the UAV and the ground station allowable is 45m. There is a foreseeable problem with this short range in certain condition such as a long range surveillance mission in which the operator and the ground station is required to stay outdoor while letting the UAV to perform reconnaissance mission inside a building. In such situation, relay stations can be deployed to establish the long range communication. Another solution to this problem would be having the entire system on-board without needing to route back the sensor data to request for control decision. With the entire system on-board the UAV, decisions can be made internally and hence a faster and more effective collision avoidance control can be established.

8.2.4 ALGORITHM

The algorithm written for current system is too simple for complex operation requirements. For more effective collision avoidance and navigation within the actual indoor environment, more complex algorithm should be implemented. One possible improvement is to implement PID control for better control over the magnitude of pitch and tilt in accordance to the distance from the obstacle. The ideal avoidance control would be the closer it is from the obstacles, the more it should tilt to evade from it.

CHAPTER 9:

CONCLUSION AND FUTURE DEVELOPMENTS

This project has highlighted the possibility of using basic sensors with simple algorithm coupled with the developed non-intrusive control system that can be add-on to a readily available platform to enable semi-autonomous control in an indoor environment supported with an anti-collision system. The subsystems has been designed and tested carefully before the combined systems were integrated with the UAV. The system has gone through various ground tests before being tested in actual environment. The flight tests result has shown that the developed system is able to integrate with the existing system of the purchased UAV and it is able to avoid colliding into walls and corners in an indoor environment. Overall, the requirements for this project have been met.

This project can serve as a foundation for future projects dealing with collision avoidance of UAV in an indoor environment. Future direction of development would be to develop more sophisticated algorithms and sensing system in order to achieve precise navigation control and more advance collision avoidance decision.

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8) Net-Scale Technologies Inc, "*Autonomous off-road vehicle control using end-to-end learning—Final Technical Report*", DARPA-IPTO, Arlington VA, July 2004.
9) O. Daniel Gott, "*The smart car project: A case study in computer-mediated contro*l", Master of Science thesis, State University of New York, May 2003.
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APPENDICES

APPENDIX A

Main Features of Draganflyer V Ti:

(Adapted from www.rctoys.com)

- Payload of 4 – 11oz (approximately 113 – 311g)
- Unloaded weight of 450g
- Estimated optimum thrust of approximately 900g*
- 12 - 15mins flight time*
- Good Stabilization system
- Able to self-level when flying outdoor (Thermal Intelligence^{TM})
- Strong carbon fibre structure (Extremely durable)
- 76cm rotor tip to rotor tip

  (*typical door size: 98-100cm*)

*without additional payload

APPENDIX B

<u>Datasheet of Sharp IR GP2Y0A02YK:</u> (provided by manufacturer)

SHARP GP2Y0A02YK

GP2Y0A02YK

Long Distance Measuring Sensor

■ Features

1. Less influence on the colors of reflected objects and their reflectivity, due to optical triangle measuring method
2. Distance output type
   (Detection range: 20 to 150cm)
3. An external control circuit is not necessary
   Output can be connected directly to a microcomputer

■ Applications

1. For detection of human body and various types of objects in home appliances, OA equipment, etc

■ Absolute Maximum Ratings

(T_a=25°C)

Parameter	Symbol	Rating	Unit
Supply voltage	V_{CC}	−0.3 to +7	V
*1 Output terminal voltage	V_O	−0.3 to V_{CC} +0.3	V
Operating temperature	T_{opr}	−10 to +60	°C
Storage temperature	T_{stg}	−40 to +70	°C

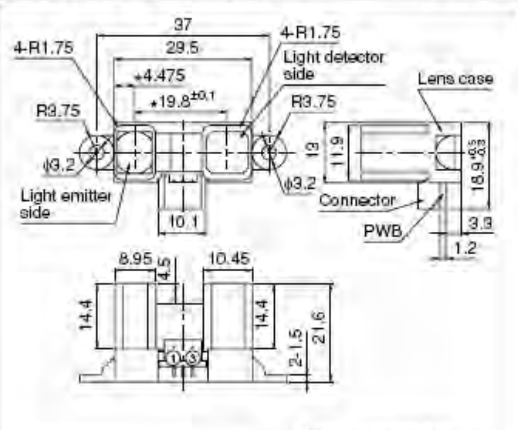
*1 Open collector output

■ Recommended Operating Conditions

Parameter	Symbol	Rating	Unit
Operating Supply voltage	V_{CC}	4.5 to 5.5	V

■ Outline Dimensions

(Unit : mm)



✼ The dimensions marked * are described the dimensions of lens center position.
✼ Unspecified tolerance : ±0.3mm

Terminal connection
① V_O
② GND
③ V_{CC}

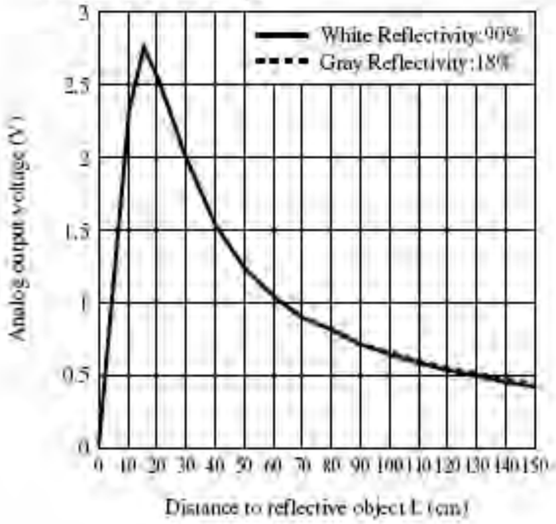
■ Electro-optical Characteristics

(T_a=25°C, V_{CC}=5V)

Parameter	Symbol	Conditions	MIN.	TYP.	MAX.	Unit
Distance measuring range	ΔL	*2 *3	20	−	150	cm
Output terminal voltage	V_O	*2 L=150cm	0.25	0.4	0.55	V
Difference of output voltage	ΔV_O	*2 Output change at L=150cm to 20cm	1.8	2.05	2.3	V
Average dissipation current	I_{CC}	−	−	33	50	mA

Note) L:Distance to reflective object
*2 Using reflective object:White paper (Made by Kodak Co. Ltd. gray cards R-27 · white face, reflective ratio;90%)
*3 Distance measuring range of the optical sensor system

Fig.3 Analog Output Voltage vs. Distance to Reflective Object



APPENDIX C

<u>Datasheet of Tilt Sensor 0719-1719-99:</u> (provided by manufacturer)

0729-1719-99

"Microprocessor Based, Dual Axis, Signal Conditioner Assembly"

Sensor Operating Specifications:

Tilt sensor part number............0717-4304-99

Operating Range (max.)..................... ± 45°
Linear Range.................................... ± 25°
Null Voltage........................ ≤ 0.025 Volts
Null Current (max.) ...... 0.2 mA (continuous)
Null Impedance (nom) .... 40 K Ohms (25° C)
(measured left to right electrode) see figure 2
Repeatability.................................. 0.1°
Resolution...................... < 0.2 arc minutes
Symmetry (typ.)..................................... 5 %
Null Offset (max)............................. 5.0°
Mech. Crosstalk / Deg. (to 20°)......... 0.025°
Temperature Coefficient
Null.................................... 20 arc sec / °C
Scale..................................... 0.1 % / °C
Stability @ 24 Hrs.......................... 0.1°
Operating Temperature .... -40° C to +85° C
Storage Temperature......... -55° C to +100° C
Time Constant (1) .... ≤ 100 msec
Material .... magnetic

Circuit Board Operating Specifications:

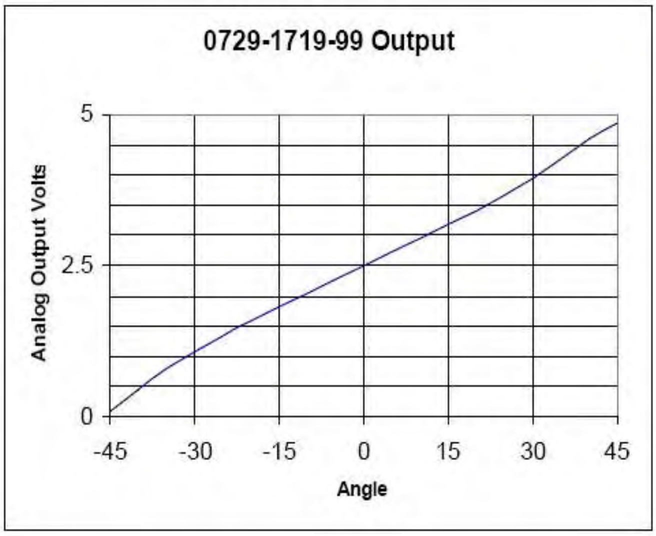
Circuit board part number................1-6200-002

Power supply voltage (range)...........+7 to +16 VDC
Power supply current (typical)..........11.0 mA @ 9VDC

Analog output voltage (max)...........Power supply voltage minus 2 Volts
Analog output load current (max)...........1 mA
Analog output resolution (0 to 5 volts output)..........................1.5 mV

Digital output voltage (typical)...................0 to 5 Volts
Digital output load current (max)................1 mA
Digital output resolution (percent)...............0.1%
(time)...................2.0 usec
Digital output frequency.........................488 Hz

Environmental
Temperature range
Operating.......................-40 to +85 ° C
Storage..........................-55 to +100 ° C



APPENDIX D

Specifications of Basic Stamp BS2, BS2SX and BS2PE:

(Adapted from www.parallax.com)

Released Products	BS2-IC	BS2sx-IC	BS2pe-IC
Package	24-pin DIP	24-pin DIP	24-pin DIP
Package Size (L x W x H)	1.2" x 0.6" x 0.4"	1.2" x 0.6" x 0.4"	1.2" x 0.6" x 0.4"
Environment *	0º - 70º C (32º - 158º F) **	0º - 70º C (32º - 158º F)	0º - 70º C (32º - 158º F)
Microcontroller	Microchip PIC16C57c	Ubicom SX28AC	Ubicom SX48AC
Processor Speed	20 MHz	50 MHz	8 MHz Turbo
Program Execution Speed	~4,000 instructions/sec	~10,000 instructions/sec.	~6000/sec.
RAM Size	32 Bytes (6 I/O, 26 Variable)	32 Bytes (6 I/O, 26 Variable)	38 Bytes (12 I/O, 26 Variable)
Scratch Pad RAM	N/A	64 Bytes	128 Bytes
EEPROM (Program) Size	2K Bytes, ~500 instructions	8 x 2K Bytes, ~4,000 inst.	16 x 2K Bytes (16 K for source)
Number of I/O pins	16 + 2 Dedicated Serial	16 + 2 Dedicated Serial	16 + 2 Dedicated Serial
Voltage Requirements	5 - 15 vdc	5 - 12 vdc	5 - 12 vdc
Current Draw @ 5V	3 mA Run / 50 µA Sleep	60 mA Run / 500 µA Sleep	15 mA Run / 36 µA Sleep
Source / Sink Current per I/O	20 mA / 25 mA	30 mA / 30 mA	30 mA / 30 mA
Source / Sink Current per unit	40 mA / 50 mA per 8 I/O pins	60 mA / 60 mA per 8 I/O pins	60 mA / 60 mA per 8 I/O pins
PBASIC Commands***	42	45	61
PC Programming Interface	Serial (9600 baud)	Serial (9600 baud)	Serial (9600 baud)
Windows Text Editor	Stampw.exe (v1.04 and up)	Stampw.exe (v1.091 and up)	Stampw.exe (v1.33 and up)

APPENDIX E

Datasheet of Analog to Digital Converter (ADC0838):

(Excerpts from published datasheet by National Semiconductor)

National Semiconductor

July 2002

ADC0831/ADC0832/ADC0834/ADC0838
8-Bit Serial I/O A/D Converters with Multiplexer Options

General Description

The ADC0831 series are 8-bit successive approximation A/D converters with a serial I/O and configurable input multiplexers with up to 8 channels. The serial I/O is configured to comply with the NSC MICROWIRE™ serial data exchange standard for easy interface to the COPS™ family of processors, and can interface with standard shift registers or µPs.

The 2-, 4- or 8-channel multiplexers are software configured for single-ended or differential inputs as well as channel assignment.

The differential analog voltage input allows increasing the common-mode rejection and offsetting the analog zero input voltage value. In addition, the voltage reference input can be adjusted to allow encoding any smaller analog voltage span to the full 8 bits of resolution.

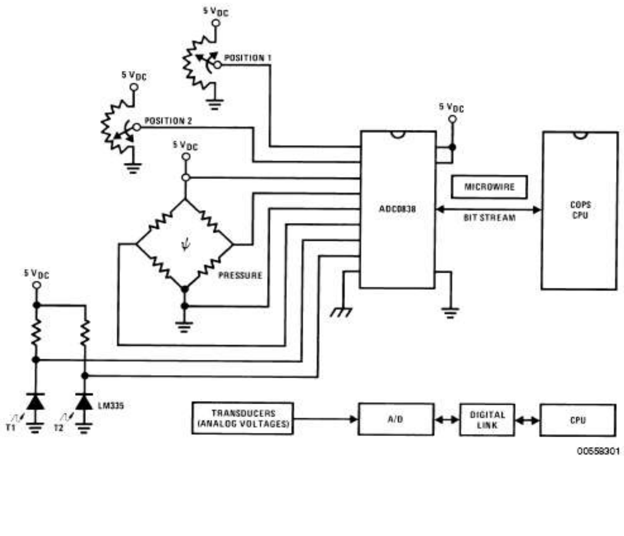
Features

- NSC MICROWIRE compatible — direct interface to COPS family processors
- Easy interface to all microprocessors, or operates "stand-alone"
- Operates ratiometrically or with 5 V_{DC} voltage reference
- No zero or full-scale adjust required
- 2-, 4- or 8-channel multiplexer options with address logic
- Shunt regulator allows operation with high voltage supplies
- 0V to 5V input range with single 5V power supply
- Remote operation with serial digital data link
- TTL/MOS input/output compatible
- 0.3" standard width, 8-, 14- or 20-pin DIP package
- 20 Pin Molded Chip Carrier Package (ADC0838 only)
- Surface-Mount Package

Key Specifications

Resolution	8 Bits
Total Unadjusted Error	±½ LSB and ±1 LSB
Single Supply	5 V_{DC}
Low Power	15 mW
Conversion Time	32 µs

Typical Application



Absolute Maximum Ratings (Notes 1, 2)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

Current into V+ (Note 3)	15 mA
Supply Voltage, V_{CC} (Note 3)	6.5V
Voltage	
Logic Inputs	−0.3V to V_{CC} + 0.3V
Analog Inputs	−0.3V to V_{CC} + 0.3V
Input Current per Pin (Note 4)	±5 mA
Package	±20 mA
Storage Temperature	−65°C to +150°C
Package Dissipation	
at T_A=25°C (Board Mount)	0.8W
Lead Temperature (Soldering 10 sec.)	
Dual-In-Line Package (Plastic)	260°C
Molded Chip Carrier Package	
Vapor Phase (60 sec.)	215°C
Infrared (15 sec.)	220°C
ESD Susceptibility (Note 5)	2000V

Operating Ratings (Notes 1, 2)

Supply Voltage, V_{CC}	4.5 V_{DC} to 6.3 V_{DC}
Temperature Range	$T_{MIN} \leq T_A \leq T_{MAX}$
ADC0832/8CIWM	−40°C to +85°C
ADC0834BCN, ADC0838BCV, ADC0831/2/4/8CCN, ADC0838CCV, ADC0831/2/4/8CCWM	0°C to +70°C

Converter and Multiplexer Electrical Characteristics

The following specifications apply for V_{CC} = V+ = V_{REF} = 5V, $V_{REF} \leq V_{CC}$ +0.1V, $T_A = T_j$ = 25°C, and f_{CLK} = 250 kHz unless otherwise specified. **Boldface limits apply from T_{MIN} to T_{MAX}.**

Parameter	Conditions	CIWM Devices			BCV, CCV, CCWM, BCN and CCN Devices			Units
		Typ (Note 12)	Tested Limit (Note 13)	Design Limit (Note 14)	Typ (Note 12)	Tested Limit (Note 13)	Design Limit (Note 14)	
CONVERTER AND MULTIPLEXER CHARACTERISTICS								
Total Unadjusted Error	V_{REF}=5.00 V (Note 6)							LSB (Max)
ADC0838BCV						±½	**±½**	
ADC0834BCN						±½	**±½**	
ADC0838CCV						±1	**±1**	
ADC0831/2/4/8CCN						±1	**±1**	
ADC0831/2/4/8CCWM						±1	**±1**	
ADC0832/8CIWM			**±1**					
Minimum Reference Input Resistance (Note 7)		3.5	**1.3**		3.5	1.3	**1.3**	kΩ
Maximum Reference Input Resistance (Note 7)		3.5	**5.9**		3.5	5.4	**5.9**	kΩ
Maximum Common-Mode Input Range (Note 8)			**V_{CC} +0.05**			V_{CC} +0.05	**V_{CC}+0.05**	V
Minimum Common-Mode Input Range (Note 8)			**GND −0.05**			GND −0.05	**GND−0.05**	V
DC Common-Mode Error		±1/16	**±¼**		±1/16	±¼	**±¼**	LSB
Change in zero error from V_{CC}=5V to internal zener operation (Note 3)	15 mA into V+ V_{CC}=N.C. V_{REF}=5V		**1**			1	**1**	LSB
V_Z, internal diode breakdown (at V_+) (Note 3) MIN / MAX	15 mA into V+		**6.3** / **8.5**			6.3 / 8.5	**6.3** / **8.5**	V

Converter and Multiplexer Electrical Characteristics

The following specifications apply for V_{CC} = V+ = V_{REF} = 5V, $V_{REF} \le V_{CC}$ +0.1V, $T_A = T_j$ = 25˚C, and f_{CLK} = 250 kHz unless otherwise specified. **Boldface limits apply from T_{MIN} to T_{MAX}.** (Continued)

Parameter	Conditions	CIWM Devices			BCV, CCV, CCWM, BCN and CCN Devices			Units
		Typ (Note 12)	Tested Limit (Note 13)	Design Limit (Note 14)	Typ (Note 12)	Tested Limit (Note 13)	Design Limit (Note 14)	
CONVERTER AND MULTIPLEXER CHARACTERISTICS								
Power Supply Sensitivity	V_{CC}=5V±5%	±1/16	±¼	±¼	±1/16	±¼	±¼	LSB
I_{OFF}, Off Channel Leakage Current (Note 9)	On Channel=5V, Off Channel=0V		−0.2 **−1**			−0.2	**−1**	μA
	On Channel=0V, Off Channel=5V		+0.2 **+1**			+0.2	**+1**	μA
I_{ON}, On Channel Leakage Current (Note 9)	On Channel=0V, Off Channel=5V		−0.2 **−1**			−0.2	**−1**	μA
	On Channel=5V, Off Channel=0V		+0.2 **+1**			+0.2	**+1**	μA
DIGITAL AND DC CHARACTERISTICS								
$V_{IN(1)}$, Logical "1" Input Voltage (Min)	V_{CC}=5.25V		**2.0**			2.0	**2.0**	V
$V_{IN(0)}$, Logical "0" Input Voltage (Max)	V_{CC}=4.75V		**0.8**			0.8	**0.8**	V
$I_{IN(1)}$, Logical "1" Input Current (Max)	V_{IN}=5.0V	0.005	**1**		0.005	1	**1**	μA
$I_{IN(0)}$, Logical "0" Input Current (Max)	V_{IN}=0V	−0.005	**−1**		−0.005	−1	**−1**	μA
$V_{OUT(1)}$, Logical "1" Output Voltage (Min)	V_{CC}=4.75V I_{OUT}=−360 μA I_{OUT}=−10 μA		**2.4** **4.5**			2.4 4.5	**2.4** **4.5**	V V
$V_{OUT(0)}$, Logical "0" Output Voltage (Max)	V_{CC}=4.75V I_{OUT}=1.6 mA		**0.4**			0.4	**0.4**	V
I_{OUT}, TRI-STATE Output Current (Max)	V_{OUT}=0V V_{OUT}=5V	−0.1 0.1	**−3** **3**		−0.1 0.1	−3 +3	**−3** **+3**	μA μA
I_{SOURCE}, Output Source Current (Min)	V_{OUT}=0V	−14	**−6.5**		−14	−7.5	**−6.5**	mA
I_{SINK}, Output Sink Current (Min)	V_{OUT}=V_{CC}	16	**8.0**		16	9.0	**8.0**	mA
I_{CC}, Supply Current (Max) ADC0831, ADC0834, ADC0838		0.9	**2.5**		0.9	2.5	**2.5**	mA
ADC0832	Includes Ladder Current	2.3	**6.5**		2.3	6.5	**6.5**	mA

AC Characteristics

The following specifications apply for V_{CC} = 5V, t_r = t_f = 20 ns and 25°C unless otherwise specified.

Parameter		Conditions	Typ (Note 12)	Tested Limit (Note 13)	Design Limit (Note 14)	Limit Units
f_{CLK}, Clock Frequency	Min			10		kHz
	Max				400	kHz
t_C, Conversion Time		Not including MUX Addressing Time		8		$1/f_{CLK}$
Clock Duty Cycle	Min				40	%
(Note 10)	Max				60	%
t_{SET-UP}, $\overline{CS}$ Falling Edge or Data Input Valid to CLK Rising Edge					250	ns
t_{HOLD}, Data Input Valid after CLK Rising Edge					90	ns
t_{pd1}, t_{pd0}—CLK Falling Edge to Output Data Valid (Note 11)		C_L=100 pF				
		Data MSB First	650		1500	ns
		Data LSB First	250		600	ns
t_{1H}, t_{0H},—Rising Edge of CS to Data Output and SARS Hi–Z		C_L=10 pF, R_L=10k (see TRI-STATE® Test Circuits)	125		250	ns
		C_L=100 pf, R_L=2k		500		ns
C_{IN}, Capacitance of Logic Input			5			pF
C_{OUT}, Capacitance of Logic Outputs			5			pF

Note 1: Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. DC and AC electrical specifications do not apply when operating the device beyond its specified operating conditions.

Note 2: All voltages are measured with respect to the ground plugs.

Note 3: Internal zener diodes (6.3 to 8.5V) are connected from V+ to GND and V_{CC} to GND. The zener at V+ can operate as a shunt regulator and is connected to V_{CC} via a conventional diode. Since the zener voltage equals the A/D's breakdown voltage, the diode insures that V_{CC} will be below breakdown when the device is powered from V+. Functionality is therefore guaranteed for V+ operation even though the resultant voltage at V_{CC} may exceed the specified Absolute Max of 6.5V. It is recommended that a resistor be used to limit the max current into V+. (See *Figure 3* in Functional Description Section 6.0)

Note 4: When the input voltage (V_{IN}) at any pin exceeds the power supply rails ($V_{IN} < V^-$ or $V_{IN} > V^+$) the absolute value of current at that pin should be limited to 5 mA or less. The 20 mA package input current limits the number of pins that can exceed the power supply boundaries with a 5 mA current limit to four.

Note 5: Human body model, 100 pF discharged through a 1.5 kΩ resistor.

Note 6: Total unadjusted error includes offset, full-scale, linearity, and multiplexer errors.

Note 7: Cannot be tested for ADC0832.

Note 8: For $V_{IN}(-) \geq V_{IN}(+)$ the digital output code will be 0000 0000. Two on-chip diodes are tied to each analog input (see Block Diagram) which will forward conduct for analog input voltages one diode drop below ground or one diode drop greater than the V_{CC} supply. Be careful, during testing at low V_{CC} levels (4.5V), as high level analog inputs (5V) can cause this input diode to conduct—especially at elevated temperatures, and cause errors for analog inputs near full-scale. The spec allows 50 mV forward bias of either diode. This means that as long as the analog V_{IN} or V_{REF} does not exceed the supply voltage by more than 50 mV, the output code will be correct. To achieve an absolute 0 V_{DC} to 5 V_{DC} input voltage range will therefore require a minimum supply voltage of 4.950 V_{DC} over temperature variations, initial tolerance and loading.

Note 9: Leakage current is measured with the clock not switching.

Note 10: A 40% to 60% clock duty cycle range insures proper operation at all clock frequencies. In the case that an available clock has a duty cycle outside of these limits, the minimum, time the clock is high or the minimum time the clock is low must be at least 1 µs. The maximum time the clock can be high is 60 µs. The clock can be stopped when low so long as the analog input voltage remains stable.

Note 11: Since data, MSB first, is the output of the comparator used in the successive approximation loop, an additional delay is built in (see Block Diagram) to allow for comparator response time.

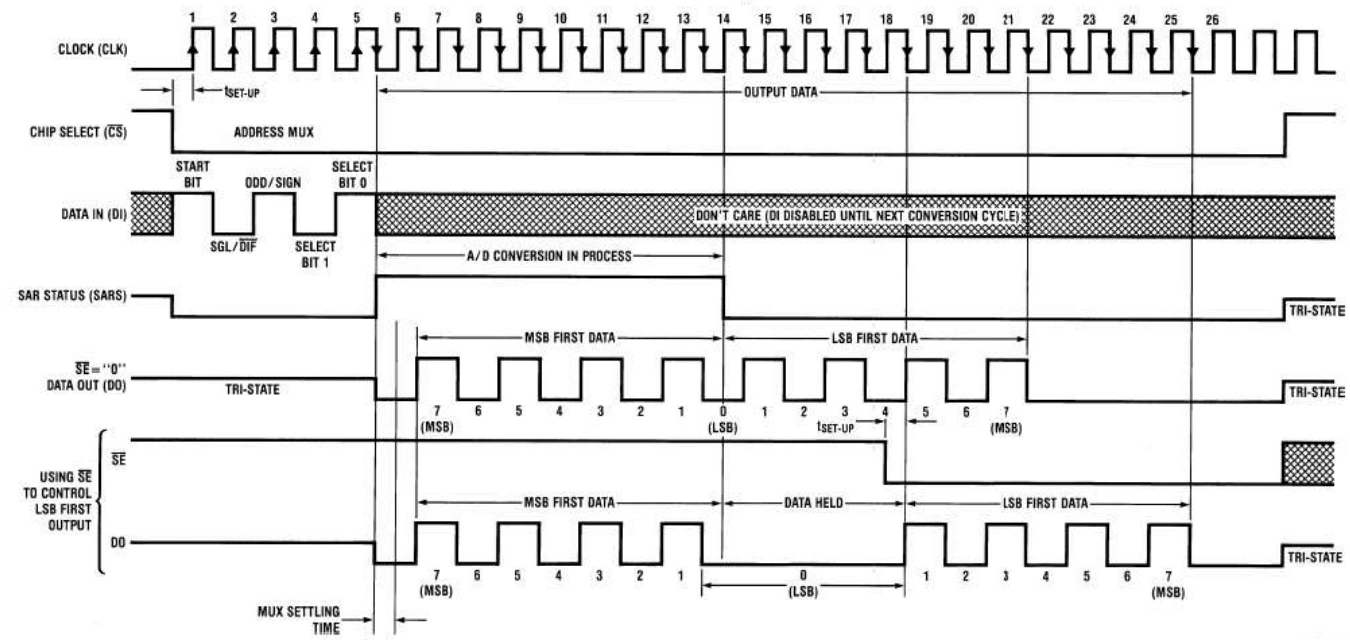
Note 12: Typicals are at 25°C and represent most likely parametric norm.

Note 13: Tested limits are guaranteed to National's AOQL (Average Outgoing Quality Level).

Note 14: Guaranteed but not 100% production tested. These limits are not used to calculate outgoing quality levels.

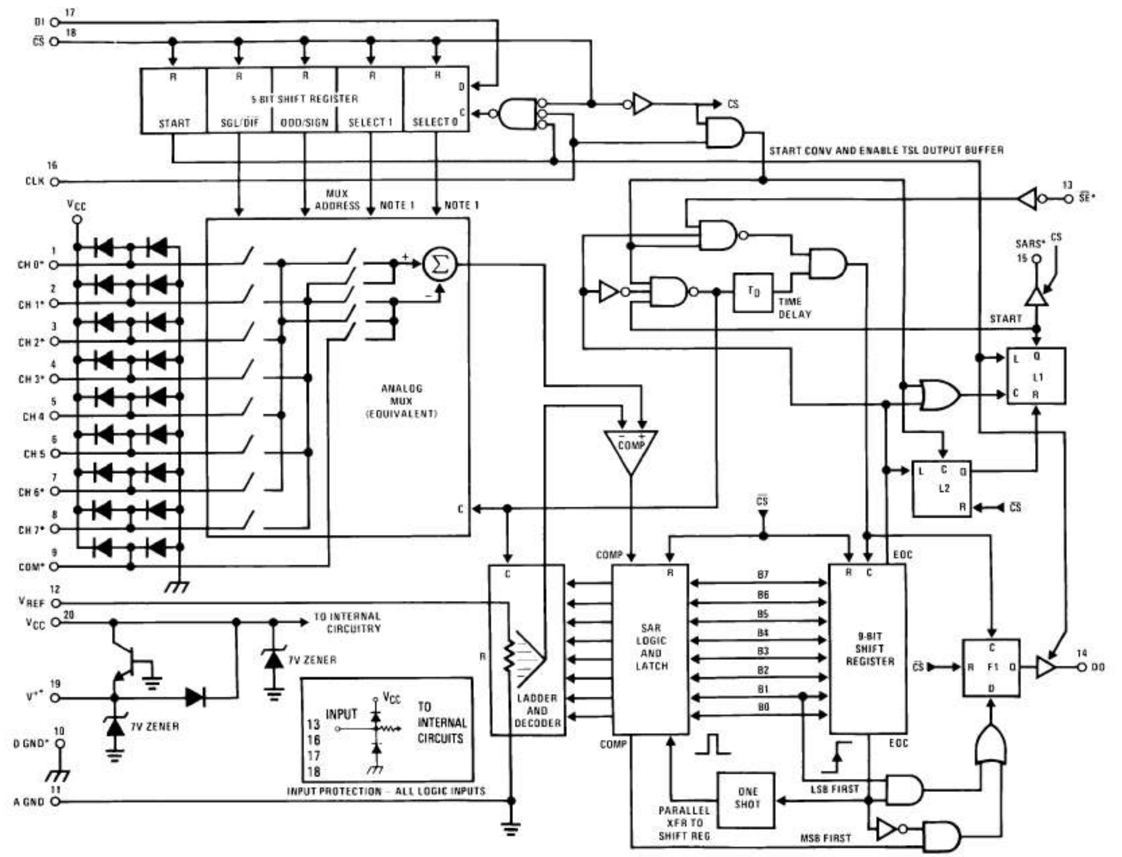
Timing Diagrams (Continued)

ADC0838 Timing



*Make sure clock edge #18 clocks in the LSB before $\overline{SE}$ is taken low

ADC0838 Functional Block Diagram



*Some of these functions/pins are not available with other options.

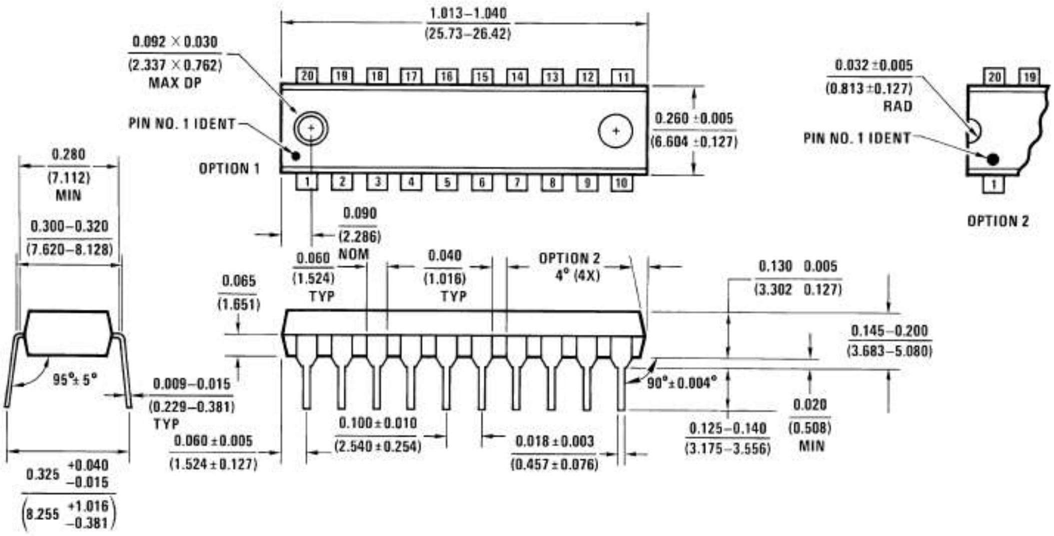
Note 1: For the ADC0834, D1 is input directly to the D input of SELECT 1. SELECT 0 is forced to a "1". For the ADC0832, DI is input directly to the DI input of ODD/SIGN. SELECT 0 is forced to a "0" and SELECT 1 is forced to a "1".

Functional Description (Continued)

TABLE 2. MUX Addressing: ADC0838

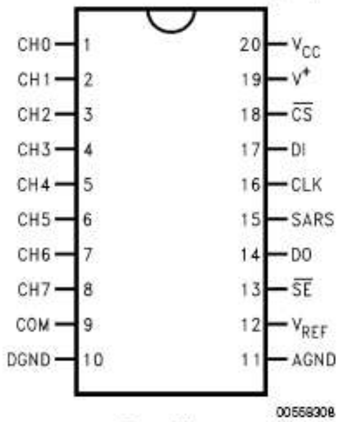
Single-Ended MUX Mode

MUX Address				Analog Single-Ended Channel #								
SGL/ $\overline{DIF}$	ODD/ SIGN	SELECT 1	0	0	1	2	3	4	5	6	7	COM
1	0	0	0	+								−
1	0	0	1			+						−
1	0	1	0					+				−
1	0	1	1							+		−
1	1	0	0		+							−
1	1	0	1				+					−
1	1	1	0						+			−
1	1	1	1								+	−



Connection Diagrams

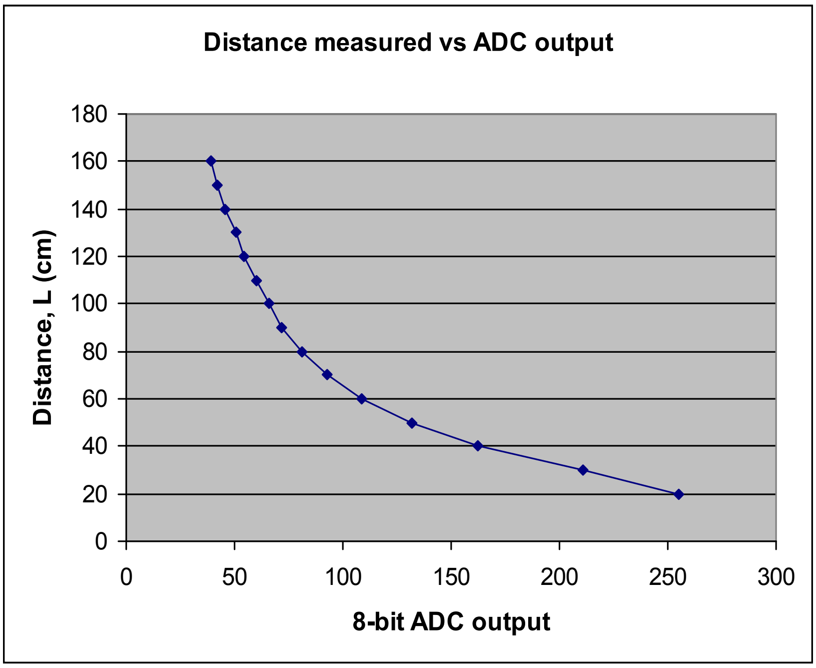
ADC0838 8-Channel Mux
Small Outline/Dual-In-Line Package (WM and N)



Top View

APPENDIX F

Calibration of Sharp IR GP2Y0A02YK:



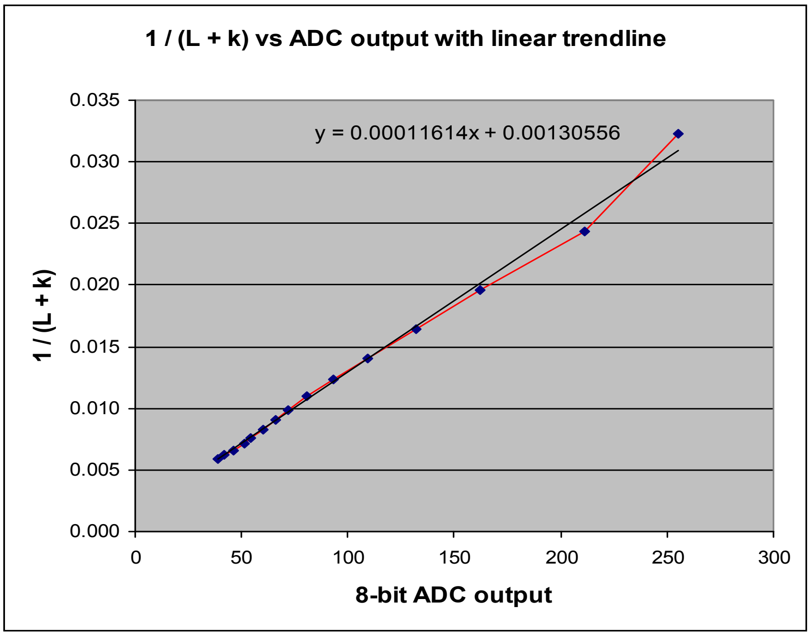


Figure 5.10: Calibration curves of Sharp GP2Y0A02YK IR sensor

After calibration, the non-linear relationship of the distance measured and the ADC's 8-bit output has been linearized. According to the recommendation by Acroname, two calibration constants, m' and b', can be obtained from the slope and intercept values as indicated by the trend line's equation. The third constant, k is a user-input constant which can be changed to adjust the proximity of the values obtained from the linear equation with the actual measurement in order to produce the most accurate calculation from the trend line equation. The ideal condition is when then linear trend line (Black) coincides with the raw data line (Red). Thus, value of k is adjusted until the linearization is as close to the ideal condition as possible.

The calibration equation follows the linear equation format $y = mx + c$:

$$1 / (L + K) = m * (\text{ADC output}) + c$$

After some manipulation, Distance, $L = (m' / (\text{output} + b')) – k$

where $m'=1/m$ and $b'=c/m$

Table 5.1 below shows the raw data obtained from experiment that will be used for calibration. Table 5.2 shows the calculated measurements after linearization. The red columns are actual distances and the ADC output obtained that were keyed-in by author. As can be seen from the results, after calibration an accuracy of +/- 1 to 3cm (static measurement) can be obtained.

Table 5.1: Raw data for Sharp GP2Y0A02YK calibration

Raw Data	
ADC output	**1 / (R + k)**
255	0.0323
211	0.0244
162	0.0196
132	0.0164
109	0.0141
93	0.0123
81	0.0110
72	0.0099
66	0.0090
60	0.0083
54	0.0076
51	0.0071
46	0.0066
42	0.0062
39	0.0058

Table 5.2: Calibration data for Sharp GP2Y0A02YK

Linearization Calculation			
ADC output	**Actual Distance**	**Calc D**	**Float D**
255	20	21	21.34
211	30	27	27.74
162	40	38	38.70
132	50	49	49.11
109	60	60	60.61
93	70	71	71.60
81	80	82	82.35
72	90	92	92.44
66	100	100	100.48
60	110	110	109.87
54	120	121	120.98
51	130	127	127.34
46	140	140	139.43
42	150	151	150.73
39	160	161	160.38

APPENDIX G

IR Sensor Evaluations:

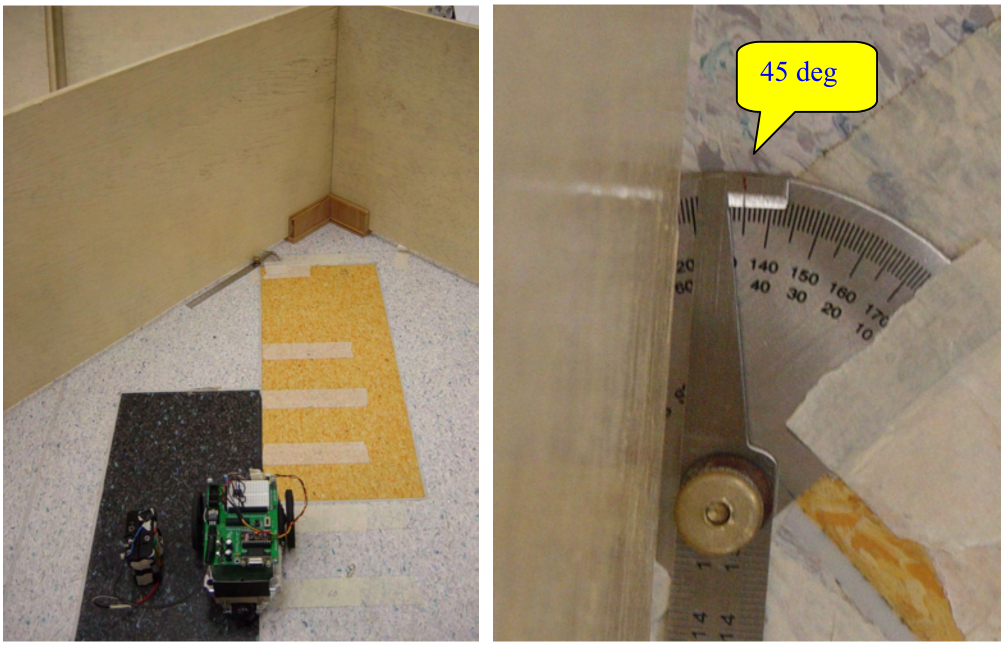


Figure 5.12: Experimental setup to for Non-Perpendicular sensing condition

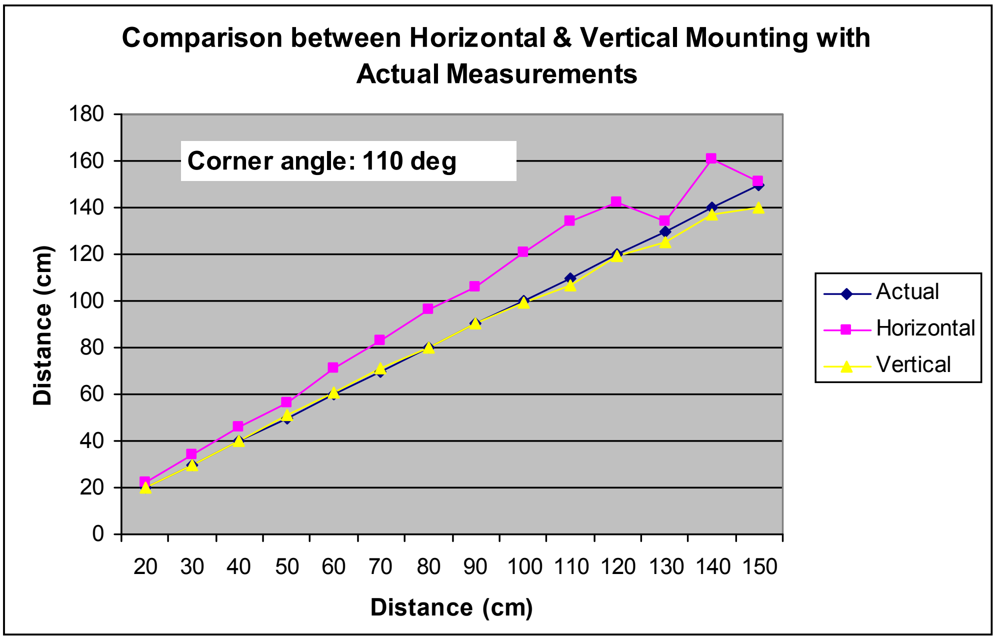
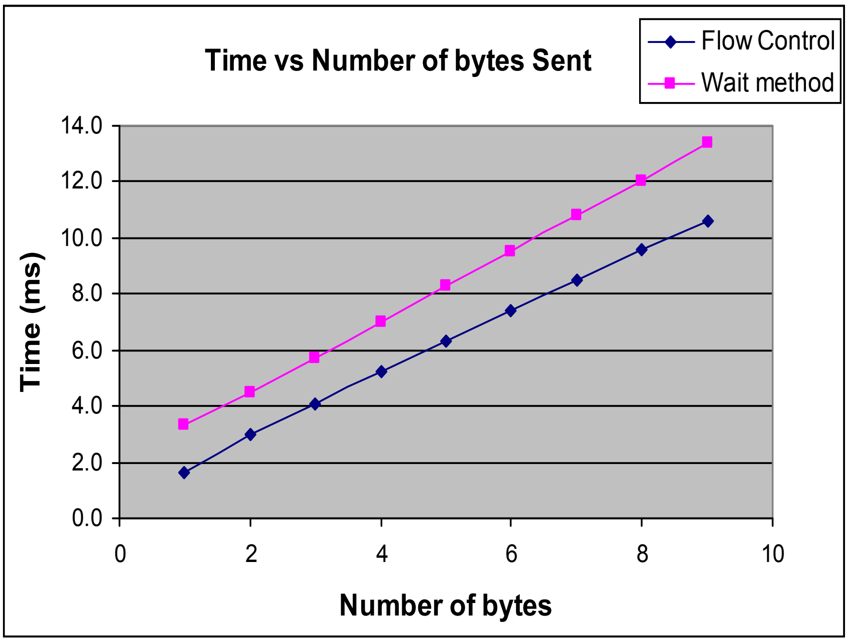


Figure 5.14: Measurement at corner angle of 110^0

APPENDIX H

Serial Communication Tests Results:



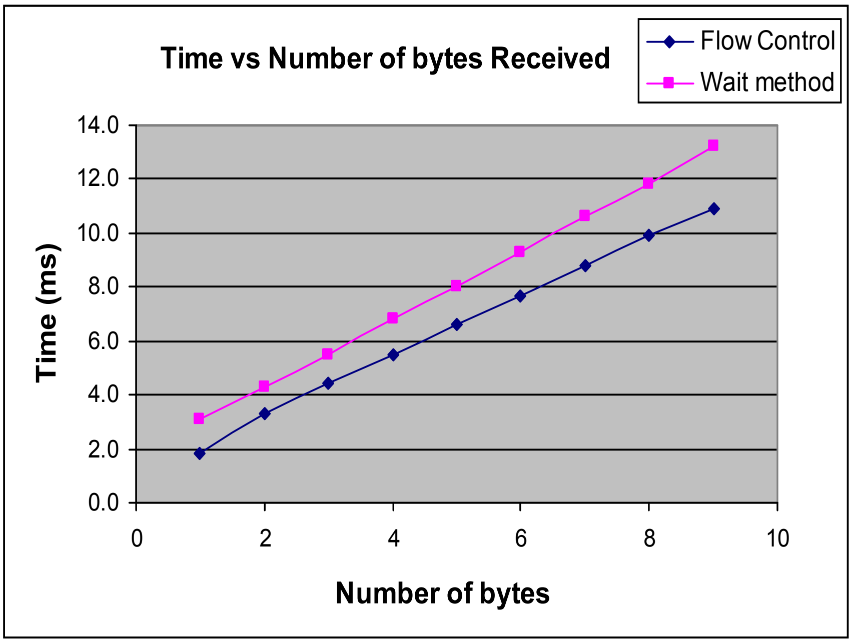


Figure 6.1: Time vs Number of bytes sent/received by Flow Control method and Wait method

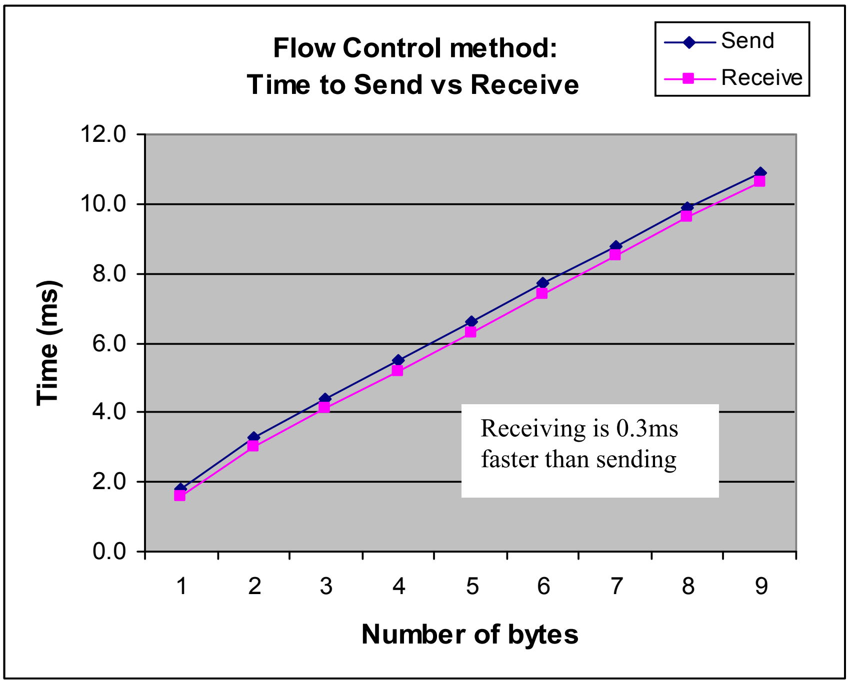


Figure 6.2 (a): Comparison of time used to send/receive by Flow Control Method

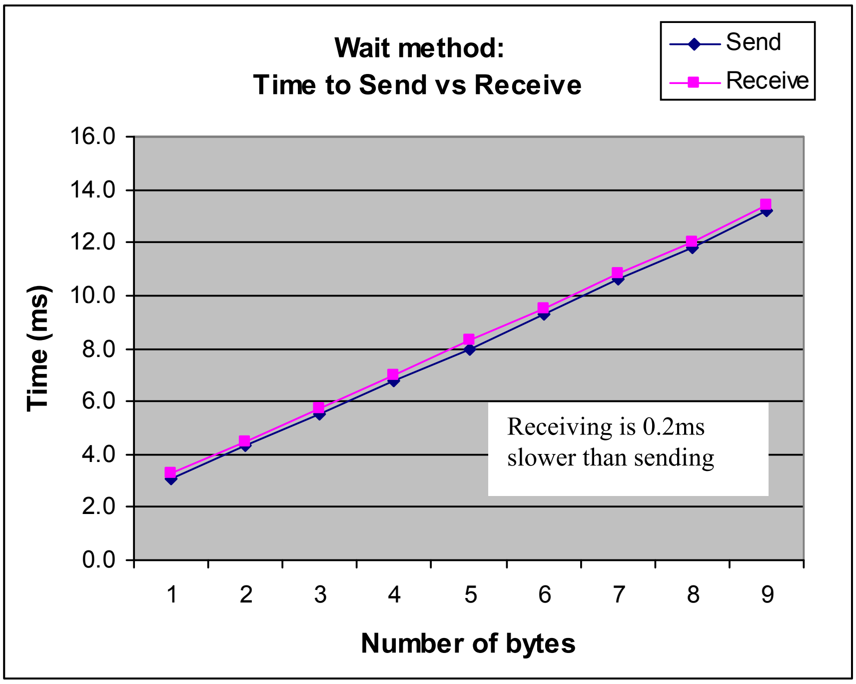


Figure 6.2 (b): Comparison of time used to send/receive by Wait Method

APPENDIX I

PWM Pulse Analysis:

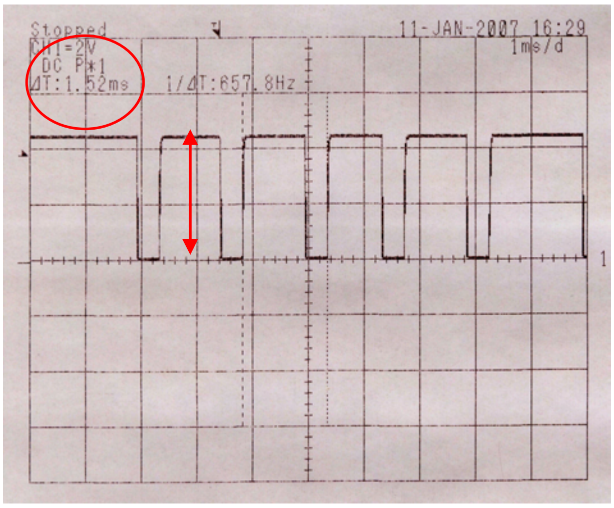


Figure 6.3 (a):

Neutral pulse width = 1.52ms

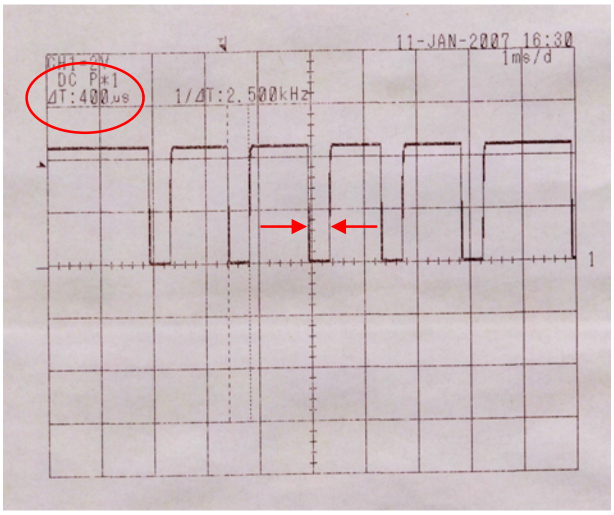


Figure 6.3 (b):

Constant separation = 400µs

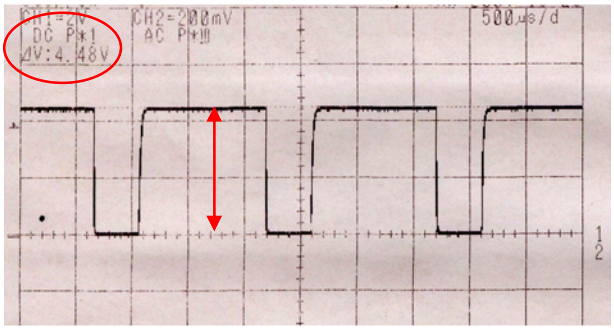


Figure 6.3 (c):

Magnitude of each signal is 4.48V

APPENDIX J

Programming Source Codes:

1) On-board CAS:

```
' {$STAMP BS2pe}
' {$PBASIC 2.5}

'----- [ Stamp-Baud rate Select ] -----------------------------------------------

#SELECT $STAMP
#CASE BS2, BS2PE
    baud_1200  CON  17197
    baud_2400  CON  16780
    baud_4800  CON  16572
    baud_9600  CON  16468
#CASE BS2SX
    baud_1200  CON  18447
    baud_2400  CON  17405
    baud_4800  CON  16884
    baud_9600  CON  16624
#ENDSELECT

'----- [ Pin Assignment ] -----------------------------------------------------

Dout           PIN   9        ' Data Out
SCLK           PIN   10       ' Serial Clock for ADC0838
Din            PIN   11       ' Data In
CS             PIN   12       ' Chip Select

X_output       PIN   13
Y_output       PIN   15

transmit_out   PIN   1        ' Transceiver data output pin
transmit_in    PIN   0
```

```
'----- [ Variables ] -------------------------------------------------------------

  ' IR sensor variables
ADResult1     VAR  Byte   ' Raw ADC reading channel 1
ADResult2     VAR  Byte   ' Raw ADC reading channel 2
ADResult3     VAR  Byte   ' Raw ADC reading channel 3
ADResult4     VAR  Byte   ' Raw ADC reading channel 4
ADResult5     VAR  Byte   ' Raw ADC reading channel 5
distance1     VAR  Byte   ' Distance 1
distance2     VAR  Byte   ' Distance 2
distance3     VAR  Byte   ' Distance 3
distance4     VAR  Byte   ' Distance 4
distance5     VAR  Byte   ' Distance 5

  ' Tilt sensor variables
X             VAR  Word
Y             VAR  Word

'-----[ IR Transform Function Constants ]-----------------------------------

m             CON  8611
b             CON  11
k             CON  11

'----- [ Initialization ] -------------------------------------------------------

HIGH CS
LOW Din
OUTPUT transmit_out

SERIN transmit_in, baud_9600, [WAIT("0")]       'Wait to receive sync byte
                                                'from ground stamp1

'----- [ Main routine ] ---------------------------------------------------------

DO
 'IR distance measurement

 LOW CS                              'RawData_ADC0838
 SHIFTOUT Din, SCLK, MSBFIRST, [%11000\5]
 SHIFTIN  Dout, SCLK, MSBPRE, [ADResult1\9]
 HIGH CS
```

```
  LOW CS
  SHIFTOUT Din, SCLK, MSBFIRST, [%11100\5]
  SHIFTIN  Dout, SCLK, MSBPRE, [ADResult2\9]
  HIGH CS

  LOW CS
  SHIFTOUT Din, SCLK, MSBFIRST, [%11001\5]
  SHIFTIN  Dout, SCLK, MSBPRE, [ADResult3\9]
  HIGH CS

  LOW CS
  SHIFTOUT Din, SCLK, MSBFIRST, [%11101\5]
  SHIFTIN  Dout, SCLK, MSBPRE, [ADResult4\9]
  HIGH CS

  LOW CS
  SHIFTOUT Din, SCLK, MSBFIRST, [%11010\5]
  SHIFTIN  Dout, SCLK, MSBPRE, [ADResult5\9]
  HIGH CS

  distance1 = (m /(ADResult1 + b)) - k  MAX 200
  distance2 = (m /(ADResult2 + b)) - k  MAX 200
  distance3 = (m /(ADResult3 + b)) - k  MAX 200
  distance4 = (m /(ADResult4 + b)) - k  MAX 200
  distance5 = (m /(ADResult5 + b)) - k  MAX 200

  'Tilt measurement

  PULSIN X_output, 1, X
  PULSIN Y_output, 1, Y
  X = (X MIN 0 MAX 1020) - 0 ** 16384 - 127
  Y = (Y MIN 0 MAX 1020) - 0 ** 16384 - 127

   SEROUT transmit_out, baud_9600, ["1", distance1, distance2, distance3,
   distance4, X.HIGHBYTE, X.LOWBYTE, Y.HIGHBYTE, Y.LOWBYTE,
   distance5]

LOOP
```

2) Ground Station 1 (Control Decision):

```
' {$STAMP BS2}
' {$PBASIC 2.5}

'----- [ Stamp-Baud rate Select ] -----------------------------------------------

#SELECT $STAMP
#CASE BS2, BS2PE
      baud_1200  CON  17197
      baud_2400  CON  16780
      baud_4800  CON  16572
      baud_9600  CON  16468
#CASE BS2SX
      baud_1200  CON  18447
      baud_2400  CON  17405
      baud_4800  CON  16884
      baud_9600  CON  16624
#ENDSELECT

'----- [ Pin Assignment ] -----------------------------------------------------

'PIN 0 is reserved for Flow Control
seroutput    PIN  1          'Wire-connect this pin to receiver stamp
serinput     PIN  9
transmit_in  PIN  8          'Transceiver data input pin
transmit_out PIN  13

'----- [ Variables ] ------------------------------------------------------------

distance1  VAR   Byte        'IR sensors data
distance2  VAR   Byte
distance3  VAR   Byte
distance4  VAR   Byte
distance5  VAR   Byte

X          VAR   Word        'Tilt sensor data
Y          VAR   Word

chin1      VAR   Byte        'Variables for storing control commands
chin2      VAR   Byte
chin4      VAR   Byte
```

```
chin1_n   CON  109       'roll trimming
chin2_n   CON  136       'pitch trimming
chin4_n   CON  154       'yaw trimming

chin3     CON  190       'throttle trimming

'----- [ Initialization ] -------------------------------------------------------

INPUT transmit_in
OUTPUT transmit_out
OUTPUT seroutput
INPUT serinput

SERIN serinput\0, baud_9600, [WAIT("0")]      'Wait to receive sync byte from
                                              'ground stamp2
SEROUT transmit_out, baud_9600, ["0"]         'Sync with on-board stamp

'----- [ Main routine ] ---------------------------------------------------------

DO
  'Part I: Obstacle Avoidance ---------------------------------------------------

  FOR counter = 1 TO 30

  'serial in sensor data
    SERIN transmit_in, baud_9600, [WAIT("1"), distance4, distance1, distance2,
distance3, X.HIGHBYTE, X.LOWBYTE, Y.HIGHBYTE, Y.LOWBYTE,
distance5]

  'default pulse width
    chin1 = chin1_n
    chin2 = chin2_n
    chin4 = chin4_n
```

```
'Obstacle avoidance control
  IF (distance1 < 120) THEN      'Obstacle in front
    GOSUB backward
  ENDIF
  IF (distance3 < 120) THEN      'Obstacle behind
    GOSUB forward
  ENDIF
  IF distance1 < 120 AND distance3 < 120 THEN
    chin2 = chin2_n             'Obstacle in front & behind: FREEZE!
  ENDIF
  IF distance2 < 120 THEN       'Obstacle on left
    GOSUB right
  ENDIF
  IF distance4 < 120 THEN       'Obstacle on right
    GOSUB left
  ENDIF
  IF distance2 < 120 AND distance4 < 120 THEN
    chin1 = chin1_n             'Obstacle on right & left: FREEZE!
  ENDIF
  IF (distance1 > 120 AND distance2 > 120 AND distance3 > 120 AND
distance4 > 120) THEN
    chin2 = chin2_n + 10        'If no obstacle detected, move forward
  ENDIF

  SEROUT seroutput\0, baud_9600, [chin1, chin2, chin3, chin4]

 NEXT

'Part II: Stabilization -------------------------------------------------------

 FOR counter = 1 TO 15

    SERIN transmit_in, baud_9600, [WAIT("1"), distance4, distance3, distance2,
    distance1, X.HIGHBYTE, X.LOWBYTE, Y.HIGHBYTE, Y.LOWBYTE,
    distance5]

'default pulse width
  chin1 = chin1_n
  chin2 = chin2_n
  chin4 = chin4_n
```

```
 'Calibration for tilt sensor
  X = X - 4
  Y = Y + 2

  IF X.HIGHBYTE = 0 AND X.LOWBYTE >= 5 THEN
   chin1 = chin1_n + 50
  ENDIF

  IF X.HIGHBYTE <> 0 AND X.LOWBYTE <= 251 THEN
   chin1 = chin1_n - 50
  ENDIF

  IF Y.HIGHBYTE = 0 AND Y.LOWBYTE >= 5 THEN
   chin2 = chin2_n + 50
  ENDIF

  IF Y.HIGHBYTE <> 0 AND Y.LOWBYTE <= 251 THEN
   chin2 = chin2_n - 50
  ENDIF

  SEROUT seroutput\0, baud_9600, [chin1, chin2, chin3, chin4]

 NEXT

LOOP

'----- [ Subroutines ] ---------------------------------------------------------

forward:
 chin2 = chin2_n + 30   MAX 250
 RETURN

backward:
 chin2 = chin2_n - 30   MIN 0
 RETURN

left:
 chin1 = chin1_n + 30   MAX 250
 RETURN

right:
 chin1 = chin1_n - 30   MIN 0
 RETURN
```

3) Ground Station 2 (Signal Generation):

```
' {$STAMP BS2sx}
' {$PBASIC 2.5}

'----- [ Pin Assignment ] ----------------------------------------------

'PIN 0 is reserved for Flow Control
serinput   PIN   1       'Wire-connect this pin to transmitter stamp
trainer      PIN   2       'Wire-connect this pin to trainer port
unusedpin  PIN   3      'An unused pin
seroutput  PIN   12

'----- [ Stamp-Baud rate Select ] ----------------------------------------

#SELECT $STAMP
#CASE BS2, BS2PE
  baud_1200  CON  17197
  baud_2400  CON  16780
  baud_4800  CON  16572
  baud_9600  CON  16468
#CASE BS2SX
  baud_1200  CON  18447
  baud_2400  CON  17405
  baud_4800  CON  16884
  baud_9600  CON  16624
#ENDSELECT

'----- [ Constants ] ------------------------------------------------------

delay   CON   260        'pulsout to an unused pin for this amount of time
                         'will cause approx 0.4ms delay
ch5     CON   2100       'unit: 0.8us = 1.68ms for Thermal Intelligence(OFF)
ch6     CON   1400       'unit: 0.8us = 1.12ms (neutral)
ch7     CON   1400       'unit: 0.8us = 1.12ms (neutral)

'----- [ Variables ] ------------------------------------------------------

ch1     VAR   Word       'Variables for pulse width of individual pulse
ch2     VAR   Word
ch3     VAR   Word
ch4     VAR   Word
```

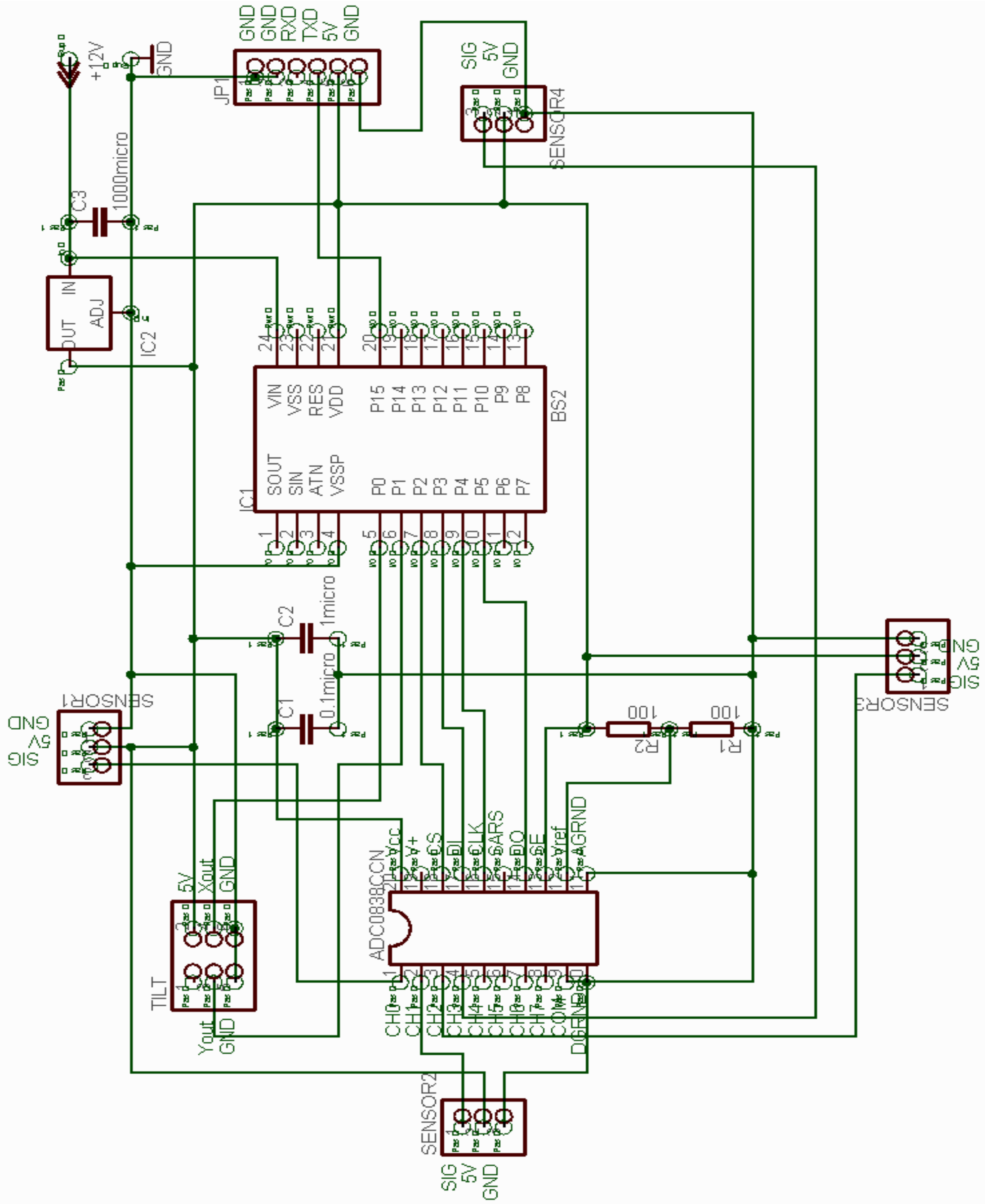
```
prev1   VAR   Word
prev2   VAR   Word
prev3   VAR   Word
prev4   VAR   Word

chin1   VAR   Byte        'Variables for storing data input via serial
chin2   VAR   Byte
chin3   VAR   Byte
chin4   VAR   Byte

'----- [ Initialization ] --------------------------------------------------

OUTPUT seroutput
INPUT serinput
DIR2=1                 'set PIN 2 as output
OUT2=0                 'Pin 2 is noninverted, 1 for inverted

SEROUT seroutput\0, baud_9600, ["0"]      'Sync with ground stamp1

'----- [ Main routine ] ---------------------------------------------------

again:
  TOGGLE trainer
  PAUSE 2

  'abort serin to timeout function if waiting time exceeds 12ms
  SERIN serinput\0, baud_9600, 30, timeout, [chin1, chin2, chin3, chin4]
  'check if serin data is invalid (garbage signal)
  IF chin1 > 250 OR chin2 > 250 THEN
    GOTO timeout
  ELSE
  'convert control input to corresponding pulse width
    ch1 = (993 + chin1)*10/8          ' roll
    ch2 = (993 + chin2)*10/8          ' pitch
    ch3 = (760 + (3*chin3))*10/8      ' throttle
    ch4 = (993 + chin4)*10/8          ' yaw
  ENDIF

  prev1 = ch1
  prev2 = ch2
  prev3 = ch3
  prev4 = ch4

  GOTO generate
```

```
timeout:               'generate a pulse similar to last generated in case of timeout
  ch1 = prev1          'to avoid causing uncontrolled behavior of the UAV
  ch2 = prev2
  ch3 = prev3
  ch4 = prev4
  GOTO generate

generate:
  OUT2=0
  PULSOUT unusedpin, delay

  'ch1
  PULSOUT trainer, ch1       'first pulse: roll
  PULSOUT unusedpin, delay
  'ch2
  PULSOUT trainer, ch2       'second pulse: pitch
  PULSOUT unusedpin, delay
  'ch3
  PULSOUT trainer, ch3       'third pulse: throttle
  PULSOUT unusedpin, delay
  'ch4
  PULSOUT trainer, ch4       'fourth pulse: yaw
  PULSOUT unusedpin, delay
  'ch5
  PULSOUT trainer, ch5       'fifth pulse: Thermal Intelligence
  PULSOUT unusedpin, delay
  'ch6
  PULSOUT trainer, ch6       'sixth pulse: unused
  PULSOUT unusedpin, delay
  'ch7
  PULSOUT trainer, ch7       'seventh pulse: unused
  PULSOUT unusedpin, delay

  TOGGLE trainer

  PAUSE 12

  OUT2=0
  PULSOUT unusedpin, delay

  'ch1
  PULSOUT trainer, ch1       'first pulse: roll
  PULSOUT unusedpin, delay
```

```
'ch2
PULSOUT trainer, ch2          'second pulse: pitch
PULSOUT unusedpin, delay
'ch3
PULSOUT trainer, ch3          'third pulse: throttle
PULSOUT unusedpin, delay
'ch4
PULSOUT trainer, ch4          'fourth pulse: yaw
PULSOUT unusedpin, delay
'ch5
PULSOUT trainer, ch5          'fifth pulse: Thermal Intelligence
PULSOUT unusedpin, delay
'ch6
PULSOUT trainer, ch6          'sixth pulse: unused
PULSOUT unusedpin, delay
'ch7
PULSOUT trainer, ch7          'seventh pulse: unused
PULSOUT unusedpin, 130

GOTO again                    'loop
```

APPENDIX K

PCB Design Diagram:



(Courtesy of Mr. Muhamad Azfar bin Ramli)

APPENDIX L

<u>Graphical Illustrations of Control Architecture:</u>

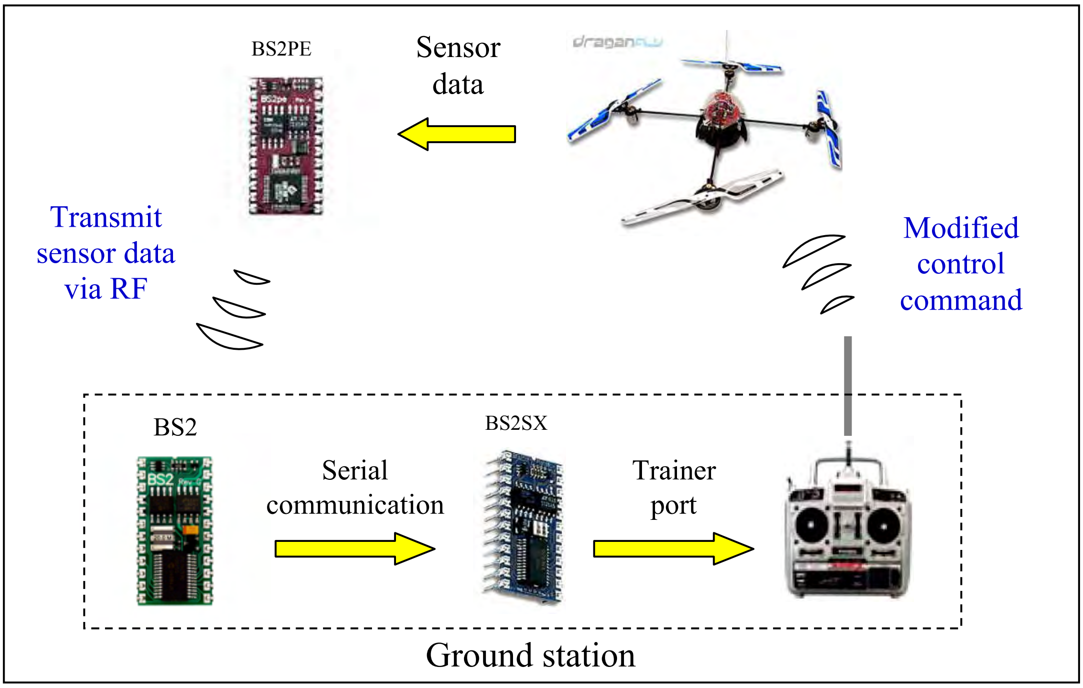


Figure 5.7: Graphical illustration of Control System Architecture

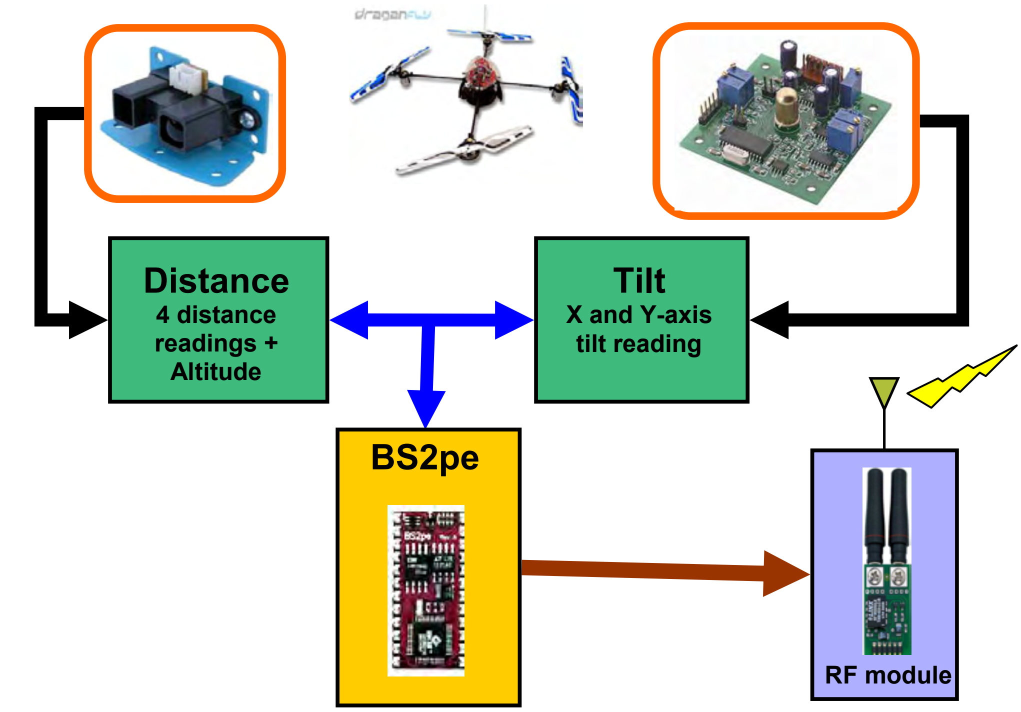


Figure 5.8: Graphical illustration of On-board Collision Avoidance System (CAS)

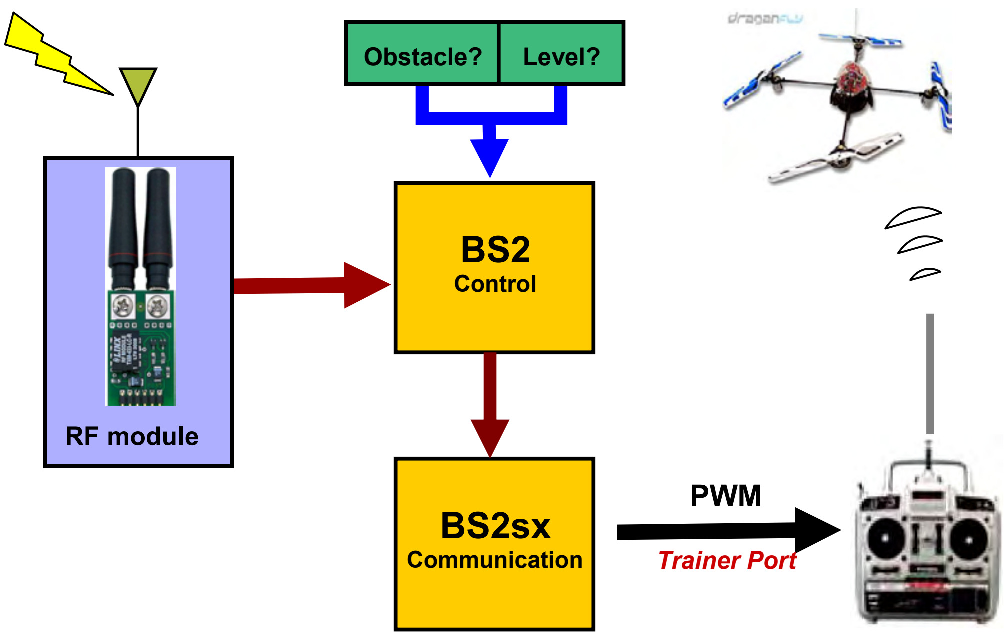


Figure 5.9: Graphical illustration of Ground Station