1. Introduction

1.1 Project Aims and objectives

The principle aim of this 4th year group project is to design and develop an autonomous flying platform. The flying platform must be capable of monitoring its inertial motion characteristics and thus provide the necessary correction conditions to enable stable flight at a distance of 1 meter from the ground. Stable flight can be considered achieved when the mean difference, over a specified time, between the angles of the platform in pitch and roll, with the horizontal is zero, and any deviation from this is below 10 degrees. A secondary aim of the project takes into account the difficult nature of the task. The project has been worked on for a number of years, and it has proved a considerable task to fully develop a fully functioning flying platform. Thus, in the interest of future projects, the work carried out during this project will be guided towards producing a system that can readily be further developed by subsequent project groups. To make this a reality the project will be documented as closely and as accurately as possible, thus providing subsequent groups with all the knowledge required to continue the development of this system.

1.2 Project Brief

Although the main requirement of project was to design and build a flying platform that could perform in the way specified in section 1.1, there were several other specific design requirements that needed to be considered. These design requirements, along with the main aim of the project, were given to us in the Design Brief. The first of these design requirements was that the main bulk of the thrust for the platform should be generated using a ducted fan driven by a small Internal Combustion engine. The second requirement was that the flying platform designed should be a self-contained unit, with all the necessary components for flight being mounted on the platforms structure, including the power supply. In order to make the flying platform a potentially useful device, if and when it has been fully developed, the design brief also stated that it should be capable of carrying a payload of no less than 1 kg and should have a minimum flight time of 20 minutes.

With these requirements in mind a Product Design Specification, which is located in appendix A, was drawn up. This document specifies in detail all the objectives for the project.

2. Background Research

Although to the general public the concept of a flying platform is not at present well known, the development of such vehicles has been quietly progressing for a number of years. The term flying platform is loosely used to describe a class of vehicle whose common design features are that they are relatively small (for instance, in comparison to a helicopter), capable of vertical lift off and have the ability to hover. One of the fundamental reasons for the ongoing development of such vehicles, in spite of the vast design problems associated with them, is there incredible versatility. There is a vast number of application for which they could be used from military reconnaissance [1] to civilian rescue [2]. The development of such vehicle systems has progressed in three well-defined types, MAVs, UAVs and AUAVs. The first of these, the Manned Aerial Vehicle, has been in development for the longest, since the 1950's. A MAV is, as the name suggests, a vehicle that is capable of carrying and essentially being controlled by a human pilot. The second type of vehicle, the Unmanned Aerial Vehicle, does not carry a pilot, but the vehicle is still controlled by a human via remote control. The third type, the type to which the flying platform of this project can be considered, the Autonomous Unmanned Aerial Vehicle, is the most high tech of the three and the one that most current research projects are focussing on. AUAVs function completely independently; both the stability and position are controlled by an onboard navigation system. The operational processes are also controlled via some form of onboard computer, thus the entire system is self-sufficient. The massive advantage of this is that the vehicle can be sent into hostile areas that would be dangerous for humans to enter or where radio signals can't easily be relayed. The fact that the vehicle functions as an independent unit does however make the task of designing a 100% reliable vehicle considerable.

From the documentation of the research carried out by the previous years group into current AUAV solutions [3], it was apparent that the general design of such systems consists of four fundamental areas. These areas are the methods of thrust generation and power generation, the control and navigation of the vehicle and the actual structural design. It is however evident, by the varying levels of success achieved by previous solutions, that in order to successfully develop a flying platform system these areas must be considered closely in relation to one another, as well as separate problems.

3. Project Organisation

3.1 Team structure

The 2004 flying platform project group consists of 9 members, whose specialist skills are split between electronic engineering, mechanical engineering and engineering management. It was decided early on in the project that each member of the group should be allocated some specific area of the platform design. However, due to the complex nature of the platform and the fact the different design areas are dependant on one another, these allocations were only to be used as initial guidelines and as the project progressed these were changed and adapted to suit the situation. To ensure that all the design requirements of the platform were considered, four smaller groups were formed, one for each of the fundamental design areas highlighted by the background research; thrust generation, power generation, control systems and structure. Each of these groups had an appointed chairman, thus aiding the communication between the groups.

3.2 Management

It was decided by the group that a single member should undertake the management of the flying platform project. This member acted as the chairman in all the meetings that the group had together and coordinated the chairman of the subject specific groups. The chairman was also given the responsibility of producing the initial, projected timeline for the project as well as to keep a close track of the groups progress and amending the timeline as appropriate. Two group meetings were held a week, one with the project supervisors present and one without. These meetings were used for general discussion concerning the progress of the project, task allocation and any problems being experienced as well as providing a set time for communication between the sub-groups. It was decided that in order to ensure that the project progressed at a steady rate, fixed deadlines were set for each of the tasks allocated in the meetings. The chairman was held responsible for ensuring that either the team member concerned completed the task or a new deadline was negotiated.

4. Platform Overview

After carrying out background research into existing solutions for flying platforms and then carefully considering the design specification it was decided by the group that the platform was to be based on the previous years design. The results of last years testing showed that it was a viable design by achieving moderate success in the tethered flights. Obviously with a revised design brief there had to be some modification to the design, but there were also several changes made in order to refine and improve the system. The general concept of the platform remained essentially the same. A five-fan system was used, the central ducted fan providing the main bulk of the thrust and four surrounding ducted fans to provide the remainder of the thrust and maintain the platforms stability. It was decided by the group that the four outer fans used in last years project should be used on the flying platform. This decision was based on two factors, firstly the previous group had success using them for an identical application, thus providing a solid development base for the current project to begin, and secondly to keep the cost of the project to a minimum. The central fan was changed however, instead of using a fifth electric fan, a ducted fan powered by a small IC engine was chosen. Although this increases the overall weight of the platform, it was thought that the extra thrust produced would easily compensate for this and provide excess thrust for carrying a power source and a payload.

It was also decided that instead of attempting to use batteries, which could not be mounted on the platform, an on board genset should be implemented to provide power for the outer fans and control systems. This genset consists of an IC engine, similar to that powering the central fan, and a generator. Using these IC engines added a significant number of peripheral components to the platform, not only the IC engines them selves. Both require exhaust systems and fuel tanks, thus the structure had to be modified to allow mounting of these. Along with the modifications made to facilitate these extra components the actual shape of the design was changed to aid control of the platform. The previous years project used a single plane design [4], in order to simplify the mathematical model. Although this does simplify the modelling, it makes the actual control of the platform more difficult. With this in mind the design of the structure was modified so that the centre of gravity lies below the plane of the stability fans, thus aiding controllability.

The platforms control system comprises of two sections: stability control and height control. The platform is kept stable by controlling the thrust output of the outer fans. The fans are controlled as two sets of diagonally opposing pairs. This sets the pitch and roll axis to be along the diagonal lines linking these fans. In order to make corrections around the pitch and roll axis the relevant fans provide the necessary thrust differential i.e. one of the pair has its thrust increased and the other has its thrust reduced. This method was employed because it provides the fastest correction response; it also helps to keep the power consumption fairly constant. The outer fans also control the height of the platform. Initially it was thought that the thrust of the central fan could be used to control the height, but this was deemed unpractical due to the difficulty in accurately controlling the IC engine. There is another possible axis in which a control system could have been implemented, known as the yaw axis. This axis is normal to and through the centre of the plane on which the pitch and roll axis lie. It was decided by the group that as this is not of major significance in the initial development of a flying platform that this could be ignored thus simplifying the control system.

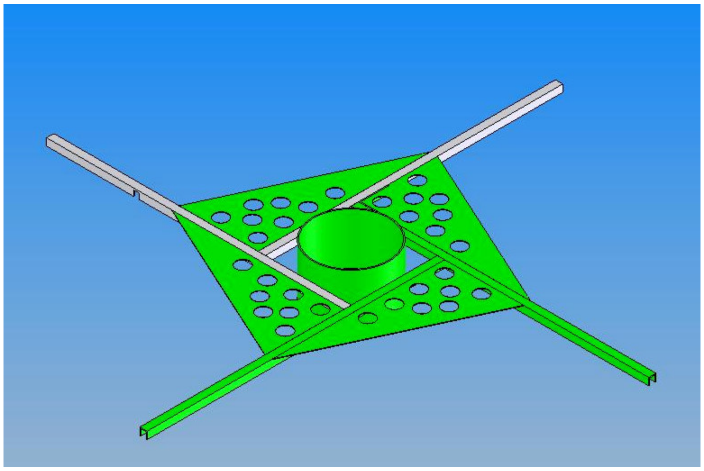


Figure 1
Outline of the basic structure [5]
Required components mounted beneath platform thus making centre of gravity lie below the plane of the stability fans.

5. Control System

The control systems designed for the stability and height control are based on the same control theory, with a negative feedback control loop being utilised in both cases. A negative feedback control loop basically uses some sensor to take a measurement of the parameter to be controlled and then compares this value with the required value of the parameter. The control system then processes any difference between these values, it then drives some actuator to try and rectify the system until the measured parameter reaches the same value as is required. The system continually loops thus maintaining the desired value for the parameter during the operation of the system. The controllers used to process the difference signal use some combination of Proportional (P), Integral (I) and Differential (D) set up to a specific differential equation, which is determined by the transfer function of the process. The differential equation is also used to set other parameters such as the system overshoot and damping. Control systems can be designed using either analogue or digital techniques. After carrying out research into both varieties, and discussion with DR G.A. Lester it was decided by the group that an analogue control system should be implemented for the flying platform[1].

[1] A comparison of analogue and digital control systems can be found in Appendix B.

The platform is deemed to be stable if it remains in a horizontal orientation. For this to be the case the angle of tilt around the pitch and roll axis of the platform must be zero. The control system in this case uses a PID controller to control the thrust of each fan pair in order to minimise these angles. In order for the negative feedback loop to be implemented, the sensors required by the system need to measure the pitch and roll of the platform.

The requirement for height control stated within the design brief is that the platform should be able to hover at a steady 1 metre above the ground. The control system in this case uses a PD controller to adjust the thrust of the outer four fans. In order for the negative feedback loop to be implemented, the sensors required by the system need to measure the distance of the platform of the ground.

6. Inertial Measurement System

The inertial measurement system used within a flying platform generally serves two purposes. The first is to provide information on the motion (accelerations and velocities) and attitude of the vehicle (vehicles pitch, roll and yaw) thus giving the control system the feedback signals required for heading correction and stability control. The second is to provide positional information on the platform. This allows the platforms position either be tracked and recorded or used with in a control system so as to be altered. The IMS contains a number of inertial sensors along with some processing circuitry so as to provide complete information.

The IMS implemented in the flying platform is required to provide both attitude information, for the stability control, and positional information, for the height control. There is a vast number of sensor and processing combinations that can be used to provide this information but generally a system comprising a number of gyros, accelerometers and inclinometers will has been adopted by most designs. With this in mind and the fact that the previous group had some success using a similar system it was decided that this approach should be used for the flying platform being developed in this project.

7 Sensor Research

7.1 Accelerometers

Accelerometers are used to provide the required information concerning the translatory movement of the flying platform. Most modern accelerometers are single degree of freedom sensors that give an output proportional to the acceleration in a single axis. In the case of the flying platform it is not the actual acceleration of the platform that is required, it is the position of the platform relative to some fixed starting point. The accelerometer can be used to provide this because it is possible to derive this information from the accelerometer output. The change in position over a specified time, along the specified accelerometer axis can be calculated by twice integrating the signal output.

There are a number of different types of accelerometer on the market, which vary in both method of sensing and specification. The most appropriate type for the flying platform would be one of the variations of a MEMS (Micro-Electro-mechanical-

Sensors) accelerometer. These are produced using similar techniques to that of integrated circuits. This gives them the great advantage of being small, lightweight, relatively cheap as well as being robust and reliable [6]. There are several key features that need to be considered when selecting an accelerometer. These include the resolution of the device, the range of measurable accelerations and the sensor bias drift. Although the resolution and range of measurement are important factors contributing to the choice of an accelerometer, for this particular application, the sensor bias drift (or sensor bias stability) is the most critical [7]. The sensor bias is the amount by which the output signal is offset from zero volts when the sensor is not accelerating, causing the output to have an error. Using a trimming circuit to null the offset can compensate for this error. However this bias has a tendency to drift, thus causing an error in the accelerometer output that is not compensated for by the set voltage offset compensation voltage. The process of twice integrating the output, to determine position only compounds this problem. If the accelerometers output has drifted by a voltage D_a the error in position will increase proportionally to the square of time [8]:

$$\text{Acc} = D_a \qquad (1)$$

$$\text{Velocity} = \int \text{Acc} = \int D_a = D_a\, t \qquad (2)$$

$$\text{Position} = \int \text{Velocity} = \int D_a\, t = \tfrac{1}{2} D_a\, t^2 \qquad (3)$$

For the application of the flying platform this is very significant. The control system will compare the output of accelerometer to a known value at which the platform should be at 1 metre. If the output of the accelerometer drifts the control system will continually try to correct the position, even thought the platform has not actually moved. This false height correction will make the platform gradually drift up or down, out of the users control.

There is another very significant source of error that must be considered. This is the error that occurs when the orientation of the accelerometer is changed from that of being parallel with its intended axis. Theses errors can be attributed to the principles of which accelerometers operate.

[2]Although an accelerometer determines the acceleration of a body they do not directly measure the acceleration; they in fact measure the difference between acceleration and gravitation. Consider a system by which a mass, m, is suspended from a bar by a spring in a gravitational field g. The spring will be extended by force mg. If the bar is accelerating upwards with acceleration a, a force, ma, will increase the length of the spring. The total deflection of the spring is caused by a combination of the gravitational force and the force due to acceleration, thus the deflection of the spring represents the difference between the forces

$$mg - ma \qquad (4)$$

[2] The explanation of accelerometer theory is taken directly from the Research Project Report [10] submitted earlier in the project.

where g and a are both considered positive in the downward direction. Since the system uses a constant mass the quantity measured is the difference between gravity and acceleration.

$$f = g - a \qquad (5)$$

This is known as the specific force. This relationship holds for components of gravitation [9]. Thus if an accelerometer is accelerated in a vertical direction the acceleration reading obtained will be dependant on the angle of the sensing axis relative to that of the vertical direction. If the accelerometers axis is parallel with the vertical, the gravitational force and force due to acceleration each only have a single component that acts along the length of the spring, thus making the spring extend by the full amount. If the axis of the accelerometer is at an angle the force must be resolved into components. The component of forces acting along the length of the spring will have been smaller than that of the case with a vertical sense axis, thus the measured specific force will be reduced, hence giving a reduced reading of acceleration, even though the actual acceleration of the body is the same. It is of great importance that this error must therefore either be eliminated or compensated for in some manner.

7.2 Rate Gyros

Rate Gyros are used to provide the rate of rotation around the pitch, roll and yaw axis. This rate of rotation can be then be processed to provide the angle by which the platform has rotated. This information is primarily used for to provide the stability control system with the signal required for tilt correction, however the correction factor necessary for the accelerometers can also be derived from this.

There is a wide variety of Rate Gyros on the market including Ring Laser Gyros (RLG) [11] and a variety of MEMS devices. Although the RLG provides very good accuracy and general specifications, the advantages of the reduced size, weight and cost, as well as the robust nature and higher immunity to vibration of the MEMS device suggests that these would be the more suitable for the flying platform. As with most accelerometers rate gyros are single degree of freedom devices, which therefore provide information about the rotation in only one axis.

As for the accelerometers one the key features to be considered when selecting a rate gyro is that of the gyro drift. The angle of revolution of the platform is derived from the output of the rate gyro by a single integration, thus the returning result sees an extra term due to the gyro drift that increases proportionally with time. Thus drift produces an error in the angle measured. This error causes the actual value for when the platform is horizontal to become non-zero. The control system will still however compare this signal with zero; thus this offset will make the platform remain at some tilt angle about the axis for which the gyro is measuring about.

7.3 Inertial Measurement Unit:

An Inertial Measurement Unit is a device that has sensors capable of measuring the inertial movement of a body in all six degrees of freedom. Most modern IMU use a combination of gyros and accelerometers to provide the measurement, thus the errors relating to the individual devices such as drift and orientation remain. Although the device does not eliminate these errors it still has a number of clear advantages over using separate sensors. The primary advantage of the IMU over the use of six individual single degree of freedom devices is that the sensors are within very close proximity of one another. This helps define the exact location for which measurements are being taken about. The fact the sensors are kept within close proximity within an enclosed volume also helps to keep the temperature stable. In both the cases of the gyro and the accelerometer bias drift can be temperature dependant, thus a stable temperature will reduce the amount the bias changes by. If this is not enough, however, information regarding the temperature of all the sensors, to be used in some temperature compensation system, can be more easily obtained. Another significant advantage of the IMU is that the sensor axes are likely to be perfectly orientated with one another. This is important because any uncompensated error in orientation will produce an initial error in the control of the platform that will always prevent the system from functioning as desired. For example if three accelerometers are used within the IMU in order to determine the accelerations in the x, y and z axis, if they are not set perfectly orthogonal to one another unwanted components of gravity will cause errors in the outputs.

It is not uncommon for IMU to have some extra sensors such as Inclinometers. These devices can be fabricated either as an individual sensor or by using two accelerometers and some processing circuitry. Either way the sensors measure the angle of rotation around a single axis. They are generally included to provide information on the body when it is stationary, usually to calibrate some control system. It is inadvisable to use them to provide signals for the stability control system because there output is sensitive to translational movement.

7.4 Error Correction Methods:

Although the errors caused by sensor drift are important and should be minimised as far as possible the most significant error that needs to be compensated for is the error resulting from accelerometer orientation, as described in section 7.1. There are two methods that can be implemented to provide the necessary correction. The first method uses a mechanical system to adjust position of the sensor array so as to keep the orientation of the accelerometers in inertial space the same, thus removing the error entirely. This is known as a gimballed system. The second, more modern method is to track the orientations of the accelerometers and to apply correction algorithms to the output signals, this is known as a strap-down system.

In general both of these correction systems are used where inertial measurements need to be made in all six degree of freedom thus in this description an IMU is used to provide the sensor array, it is however possible to use a number of individual sensors instead.

7.4.1 Gimballed System

In a gimballed system three accelerometers are mounted orthogonal to one another on a platform. This platform is in turn mounted on a set of three gimbals, each driven by a servomotor. This gimbal and motor arrangement allows the platform to be rotated in any angle about the pitch, roll and yaw axis. Also mounted on the platform is a set of three rate gyroscopes, each with their axis set orthogonal and so they measure the rate of rotation about the pitch, roll and yaw axis. The output of each rate gyroscope is used to drive its respective gimbal. As the body rotates, the gyroscopes measure the movement and send signals to the servos, which are null seeking. The servos drive the gimbals so as to counteract the movement of the platform, thus maintaining the orientation of the accelerometers in inertial space.

This method is effective in eliminating the errors caused by variation in accelerometer orientation but it does have some major drawbacks, especially when being considered for the flying platform. The greatest drawback is a result of the gimballed system having a large number of mechanical parts. This has two consequences; firstly it makes the design, construction and maintenance of the system very complicated and secondly, and more significantly it tends to make the systems large in size and fairly heavy. This second point is very important when considering the system for the application of this project, a flying platform that is limited in both thrust and size.

7.4.2 Strap-down System

A strap-down system attaches the array of sensors or IMU directly to the vehicle or body being measured. Removing the mechanical aspect of the gimbals and servo system makes them far lighter and more compact, however this does now mean the accelerometers will follow the exact path, which the vehicle follows. Consequently their orientation in inertial space will be constantly varying, thus introducing the previously described errors. This problem is solved by using rate gyroscopes to passively track the orientation of the accelerometers in inertial space. The tracking signals are then processed by some specified algorithm that creates a correcting factor for the accelerometer reading. This does introduce the need for some form of on board processing unit powerful enough to perform the computations required fairly quickly, thus increasing the size and weight of the system. However, with the availability of small and lightweight, but powerful processors this does not present a vast problem. This type of system is more ideally suited to an application such as a flying platform because of the reduced size and weight.

8 Inertial Measurement System Design

The primary requirement for the IMS of the flying platform is to output the signals required by the control system, as specified in section 6. In order to provide these signals a minimum of 3 sensors is required. This consists of two rate gyroscopes, from which the pitch and roll angles can be determined and an accelerometer from which the height can be determined. This was the approach was used by the groups in previous years to some success and thus was considered by the group. However, after some discussion and negotiation with BAE systems, carried out by Dr G.A. Lester and Dr M.A. Jenkins, it was agreed that they would provide us with a prototype, military grade Inertial Measurement Unit. The IMU provided by BAE provides a sensor array capable of inertial measurements in all six degrees of freedom. Although this is more than required for our application at present, this will allow for further development in the future, which is a clear advantage. Also the fact that the device uses very high quality sensors, which would normally be out of our price range, is small in size and has a relatively low weight, led the group into deciding to implement this device into the design of the flying platform.

8.1 SilMU0X® Inertial Measurement Unit

Picture 1
SilMU0X® Inertial Measurement Unit

The SilMU0X® Inertial Measurement Unit, as shown in picture 1, provides inertial measurements in terms of angular rate and linear accelerations in three orthogonal axis [12]. Three MEMS rate gyroscopes are used to provide the rate of angular rotation and three MEMS accelerometers are used to provide measurement of the linear accelerations. The IMU also contains two pairs of MEMS accelerometers set up as inclinometers that provide the angle from vertical of the pitch and roll axis. The IMU also provides some degree of tilt error compensation for the accelerometers. This compensation is not mentioned in either data sheet [12][13] thus the exact nature of this compensation had to be acquired by some correspondence with Tony Moy at BAE systems. The relevant emails can be found in appendix K. The IMU provides compensation for angular variations about the pitch axis.

The specifications of the sensors within the IMU are more than sufficient for the application of the flying platform. The rate gyroscopes are capable of measuring angular velocities of up to ±50°/s. The accelerometers are capable of measuring accelerations up to ±15g, however the measurements are only accurately calibrated over the range ± 1g. The roll inclinometer is capable of accurate measurement over the range ±15 ° and the pitch inclinometer is capable of accurate measurement over the range ±53 °. These specifications are all quoted in the data sheets [12] as being worst case. Unfortunately due to the device being a military prototype, full specification documentation could not be obtained.

The signals are outputted from the IMU in a digital format, using a serial data stream. The Serial Data Message [13] consists of eleven, 24-bit words, each one containing one of the angular rate, linear acceleration or inclinometer measurements. Of the three data words that are not used for the sensors, one is a null word and the other two give information concerning the self-test of the device and its temperature. In order to distinguish between the sensors the data word is split into a Header field and a Data field, as shown in Table 1. The Header field consists of the 8 least significant bits of the data word. The 4 LSB of the header field identifies which of the sensors the data relates to, the other 4 bits (Health and BIT) in the Header field are not used by this prototype version of the IMU. The 16 Bit Data field contains the inertial data for the device specified by the identifier, formatted in two’s complement form.

Header Field								Data Field															
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	29	20	21	22	23
Identifier				Health and BIT				Data															
LSB							MSB	LSB															MSB

Table 1
SilMU0X® IMU serial data message format

The serial data message is transmitted in conjunction with two timing signals: a 1.25 MHz clock signal, outputted on the clock lines and a synchronisation signal, outputted on the sync lines. The clock signal consists of a 24-pulse burst that directly coincides with the 24-bit data message. In effect a clock pulse is generated for each bit transferred in the Serial Data Message, thus there are no clock pulses when data is not being outputted by the IMU. The synchronisation signal is provided to mark the end of each Serial Data Message. A 400 ns pulse occurs on the sync line at the falling edge of the 24th clock cycle in each burst. The timing diagram supplied by BAE systems is shown in figure 2

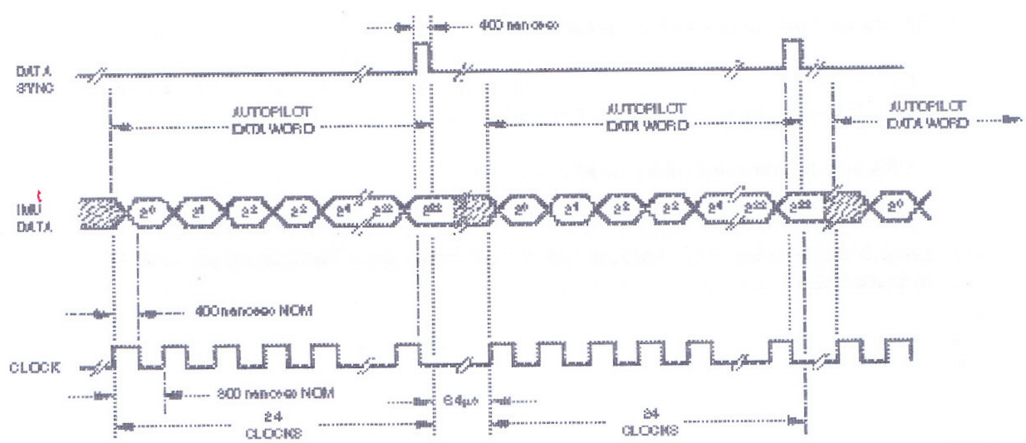


Figure 2
SilMU0X® IMU Data and control line
timing diagram.

The IMU Clock, Data and Sync output signal are all encoded using the RS422 standard. Each of the IMU outputs signals are transmitted using a differential pair transmission line. This consists of each output signal having a Hi Line and a Lo Line. The output signal in TTL form is obtained by decoding the signals on these lines. The RS422 standard states that for the Hi line, 5 V equates to logic 1 and 0 V equates to logic 0 and for the Lo line, 5V equates to logic 0 and 0V equates to logic 1.

The IMU requires a supply of 8 Vdc of which the ripple voltage up to 12 KHz must not exceed 150 mV and from 12 KHz to 400 MHz must not exceed 20mV. The average power consumption of the IMU is 5 VA, however the supply must be able to supply a peak power of 12 VA for 5 ms and 7 VA for a further 100 ms so as to allow start up of the device.

8.2 Signal Processing

There are a number of signal processing stages that have to be carried out in order to convert the serial data stream into the signal required by the stability and height control systems. The first stage of signal processing requires the serial data stream to be broken up so that the measurements taken by each individual sensor can be converted to an analogue voltage. The second stage of processing requires the measured signals to be converted into the form required by the control system. Designing and building an IMU decoder circuit achieved the first stage. The solution for the second stage was somewhat dependant on which sensors were to be used. For the stability control system it was decided that the pitch and roll angles should be derived from the output of the Rate Gyros rather than directly taken from the inclinometer reading. The reason for this is that it was felt that there would be oscillation in the x and y plane of the platform due to engine vibrations. Inclinometers are sensitive to translation movement thus these oscillations would cause errors in measurement. In order to accurately produce the pitch and roll angle from the rate gyro a circuit that performed bias compensation and a single stage of integration was designed and built. There was only one sensor type that could be used for the determination of the position for the height control, the accelerometers. To provide the required signal from the accelerometer measurement a circuit that provided two integrating stages and some sensor bias compensation was designed and built. The final circuit designs and design processes used for both the Gyro and Accelerometer signal processing are documented in section 8.9.

8.3 IMU Decoder

The IMU decoder has three main design requirements. The first is to provide some method of converting the measurement data in the Serial Data Stream into analogue voltage. The second is to identify which sensor provided the data that has been converted. The third is to provide a designated decoder output for each sensor that can hold the analogue voltage between the times when the data is being refreshed. This is of particular importance because the analogue control system will be continuously using the sensor signal in the feedback loop. This is actually one of the disadvantages of using this IMU compared to individual sensors. The sensor readings of the IMU give the values that are taken as samples at a specific time. This means that between the times when the samples for each sensor are taken the output could actually be inaccurate. Most individual sensors, such as the ADXRS300 gyro used by the previous years project, give a continuous analogue output thus this problem does not exist. However, the sampling rate of the SilMU0X® is 50 Hz, fast enough to make the effects due to this problem negligible. The fourth design requirement is to make the analogue outputs have a range of ± 10 V. The group decided on this range because it was felt that such a range gives the decoder circuit good versatility. This requirement, however, is set by the components chosen within the design rather than by design itself.

There are two distinct types of circuit that could be designed to fulfil the requirements. The first is a microprocessor-based system, which uses a piece of software to decode and convert the sensor data. The second is a purely hardware based system that uses logic gates and analogue circuitry to perform the necessary functions. Given that this circuit will provide the measurements for all the control systems, any failure by this system would cause complete loss of control of the platform. The hardware system has one clear advantage over the software-based system in this respect. If the hardware system has been designed and built correctly and has been thoroughly tested, providing it remains in good condition (no solder joints become loose) the circuit will function correctly every time. In the case of the microprocessor system there is a chance the system could crash, because of poorly written software, and thus stop working in flight even though it worked during testing. It was therefore decided by the group that rather than risk designing a microprocessor system, for which we did not feel confident about writing reliable software, a hardware system should be designed.

8.3.1 Design Procedure

The first point of the design to be considered was how the information in the header field and the information in the data field could be accessed at the same time. It was clear to see that to enable the analogue level to be read on a sensor specific decoder output the header field would need to be used to select the output device on which the level would be stored.

It was decided that the most efficient method of achieving this was to convert the serial data into parallel data. This is implemented in the decoder circuit by creating a 24-bit parallel output shift register. The serial data stream is clocked in using the system clock, after 24 clock pulses the clock line remains low for 6.4 µs, as shown in the timing diagram in section 8.1. This means that the each bit value of the 24-bit data word will remain on its respective output on the shift register until the system clock starts to pulse again, thus the data has been converted from serial to parallel data. This means that the remainder of the circuit has got 6.4 µs to convert the data and select the appropriate output to hold the data on. The 24 bit shift register was fabricated from three 8 Bit shift registers by connecting them together as shown in figure 3. The header field data (bits 0-7) is held on the outputs Q0 (MSB)-Q7 (LSB) of shift register 3. The data field data split between the shift register 1 and shift register 2. Shift Register 1 holds bits 16-23, with the MSB of the data field being held on Q0 and Shift Register 2 holds bits 8-15, with the LSB of the data field being held on Q7.

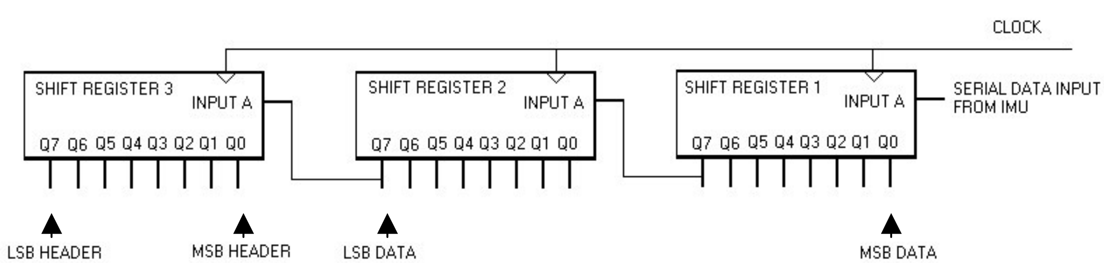


Figure 3
24-Bit shift register

The next factor considered in the design was the method used to select which decoder output the sensor data would be assigned to. As mentioned in section 8.1 the identity of the sensor from which the data came from is determined by the binary number made up of the 4 LSB of the 24-bit data word. Thus in order to select the correct decoder output device on which to store the sensor signal, some system by which this identifier could be converted into a controlling signal specifically designated for that device is required. The ideal solution to this problem was to implement a 4-16 converter. This device is effectively a 4-input/16-output binary to decimal converter. The binary number is inputted via four parallel inputs and the device is then strobed (enabled) by some signal to start the conversion. Once the conversion is complete only one of the 16-output lines goes high. The output line that goes high corresponds directly to the binary number that was inputted and at any one time only the selected output will be high. This means that for each different identifier a specific line will be high and no other, thus providing a unique control line that can be used to select the decoder output device.

Once all the data has been clocked onto the shift registers the identifier is held on outputs Q7-Q4 of the third 8-bit shift register. Thus to provide conversion of the identifier the 4-16 decoder inputs are connected directly to these outputs. The signal used to strobe the device was initially the clock but this was later changed to be the sync. Once the device has been strobed the selected output will remain high until the device is strobed again.

At this stage we had a circuit that could change the data from serial to parallel, temporarily hold this data so that the header field and data field can be operated on separately and decode the header field so as to create a sensor specific control signal. The next stage to be considered was the method how the digital data is converted to the required analogue voltage level, and how this level could be held between refresh cycles.

The first part of this stage was relatively straightforward; in order to convert the parallel data being held on the first two shifts registers, a parallel input Digital to Analogue converter (DAC) had to be implemented into the circuit. How many were to be used and what they would be used for was determined in the second part of this design stage. In order to provide a specific decoder output for each of the IMU sensors, 8 separate devices capable of acquiring and then holding the analogue levels are required. To ensure that the outputs hold only the information corresponding to their assigned sensor, the output device used must be capable of being controlled by the 4-16 decoder outputs. This problem was considered and two possible solutions were conceived.

The first solution entails using a separate DAC for each sensor output. This would involve the parallel data being inputted to every DAC and the write line of each DAC being controlled by one of the 4-16 decoder outputs. Even though every DAC present has the data sitting on its inputs, the only DAC to perform a conversion, and therefore output an analogue voltage level, is the device whose 4-16 decoder output goes high. Since this is determined by the binary identifier inputted into the 4-16 decoder inputs, this creates a specific analogue output for each sensor within the IMU. The DAC will only carry out a conversion when the write line is enabled, thus once written to, unless it is purposely reset, the output of the DAC will not change until it is again write enabled. Providing the DAC write line is disabled before the data on the inputs changes the analogue voltage output will be held constant between refresh cycles as required.

The second solution uses only a single DAC to provide the conversion and a number of Sample and Hold devices for the decoder sensor outputs. The DAC performs the conversions for all the sensors and then the output is applied to each Sample and Hold device, which then acts as the sensor output for the IMU decoder. A sample and hold device is an IC that samples the voltage across its input when the device is enabled, when disabled the device holds this value on the device output until its enabled again. This means although the DAC output is connected to every Sample and Hold input, the only device that samples the DAC output is the one that is enabled. Thus by using the 4-16 decoder outputs to control when each sample and hold device is activated a specific output device can be selected for each specific identifier and thus each sensor within the IMU.

Both of these methods were considered but it was decided by the group that the second method was the one to be used. This decision was based solely on the cost of producing the circuit. Although both of the methods fulfil the requirement the first method is far more expensive to implement than the second. The reason for this is due to the large number of DAC required by the first method. To make sure that the outputs from the decoder are as accurate as possible it was decided that the resolution of the data should remain as high as possible. In order to achieve this the full sixteen bits of the sensor data needs to be converted. This requires that 16-Bit DAC's be used; these however are fairly expensive, the cheapest suitable device being £18. To maintain accuracy for every sensor output, the first system requires eight of these devices to be used whereas the second only requires one. Although the second system requires eight sample and hold devices to create the outputs for the decoder, these are far cheaper than the DAC, starting from about £2. Using the second method therefore vastly reducing the cost of the circuit whilst maintaining the same performance.

The final stage of the circuit design was to determine what control signals were necessary and their relevant timing. In order to do this the signals were theoretically followed through the design. Although some of these have been stated previously they will be mentioned again so as to make it easier to follow through the complete system.

The first stage of decoding that requires a control signal is the serial to parallel conversion. This simply requires the clock signal to be inputted to the clock input of the shift register. The shift registers used were set up so as to clock the data in on the positive clock edge.

In the next stage of the circuit two operations must occur almost simultaneously. These are the decoding of the identifier and the digital to analogue conversion of the sensor data. As it is critical that both these operations do not start before all the data is held on the shift registers, the control signal used for both these is derived from the sync line. This is due to the fact that the sync line produces a pulse directly after the 24 clock pulses (theoretically when all the data should be clocked into the registers). The 4-16 decoder makes the conversion on the negative edge of the sync pulse [14]. The DAC requires a minimum write pulse width of 60ns [15]. The sync pulse is 400ns so this did not need altering, however the DAC is active low, thus the sync line (which is pulsed from low to high) required inverting. This was achieved by routing the sync line through a two input Nand gate that has its inputs tied together.

At this point the identifier decoding has been executed and the Digital to Analogue conversion process has been started thus the next stage it to select and activate the correct sample and hold device so as to store the converted data. The sample and hold devices are controlled by a specific control input. The device is active low thus in order to take a sample this control line is sent low. The sample and hold devices require a specified data acquisition time, which can be set by the inclusion of an external capacitor. It was decided that the sample and hold device should have acquired the analogue voltage and be holding the level before new data is clocked into the shift registers. As shown by the IMU timing diagram (figure 2, section 8.1) the length of time between the sync pulse and new data being clocked in was 6.4 µs, thus the control pulse which determines the sampling period should be less than this. In order to control the length of the sampling pulse whilst ensuring that the correct sample and hold device is selected for the corresponding sensor, at the correct time a combination of two control signals are used. The 4-16 decoder outputs were used to fulfil the sample and hold selection criteria and a signal derived from the sync pulse was used to set the sampling pulse length. A monostable was used to increase the length of the sync pulse to 4.7µs. This extended sync signal is then used in combination with each output of the 4-16 decoder via two input Nand gates. The output of each of these nand gates goes to the control input of the corresponding Sample and Hold output device. The sample and hold device samples only when both the Sync pulse and the 4-16 output are high, as shown by table 2 (SH is active low). Since only one of the 4-16 outputs goes high at a time, only one of the sample and hold devices can be activated, and since the sync pulse is 4.7µs, the selected device will only sample for 4.7 µs. Also, because the pulse length-determining signal is derived from the sync, the time when the signals combine to produce a low control signal is directly after the sync pulse. This therefore fulfils the criteria that the Sample and Hold device will have acquired and will be holding the voltage level before any new data is clocked into the system. The timing diagram for this signal is shown in figure 4.

Sync line	4-16 output	Control Signal
Low	Low	High
Low	High	High
High	Low	High
High	High	Low

Table 2
Sample and hold control line truth table

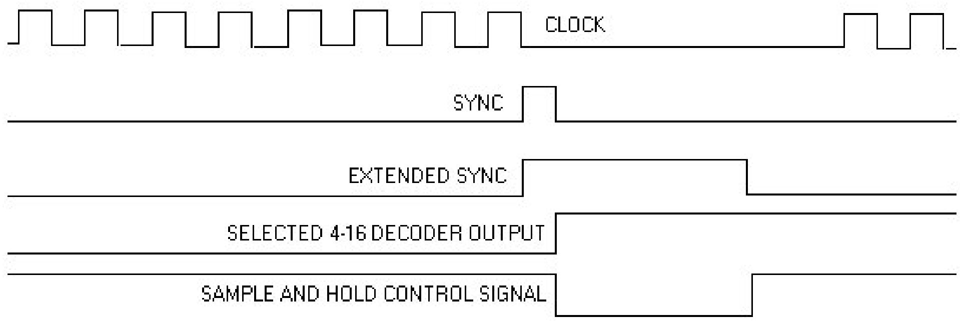


Figure 4
Timing diagram of sample and hold control signal

Note: The signal on the selected 4-16 decoder output line will go low at the next sync pulse and then remain low until the identifier that this line corresponds to, is once again decoded.

With the basic design for the circuit completed the next stage was to select the required components.

8.3.2 Component Selection

The components of the circuit that were considered most critical to the decoders operation are those that have a direct effect on the accuracy of the analogue sensor outputs i.e. the Digital to Analogue converter and the Sample and Hold IC. For this reason these devices were carefully researched before a decision was made as to which one was used. Although the specifications and operation of the other components was important, the choice of these was not so thoroughly researched. This section describes the specification required for each component and provides details of the component chosen and the reasons for the choice as well as detailing any extra peripheral circuitry used specific to the component.

Digital to Analogue Converter

The primary requirement of the Digital to Analogue converter was that it should be able to convert the 16-Bits of parallel sensor data, which is in twos complement format, into an analogue voltage. Twos complement format is a binary format that allows both positive and negative numbers to be represented by the data. This is essential for the IMU decoder because in order for the direction as well as the magnitude of any rotations or accelerations to be known the IMU outputs the sensor data in this format. For example in the case of the rate gyros, a clockwise rotation about the gyros axis will produce a negative reading and an anticlockwise rotation about the same axis will give a positive reading. The other requirements of the device are that it should posses a relatively fast conversion time and that the range of analogue output levels should be ±10 V. The first of these requirements is due to the fact that the data on the DAC inputs is only valid for each sensor for a limited period of time (period when the clock has stopped). This means that to ensure the analogue level stored on to the relevant output device is accurate it must finish the conversion before this time window has elapsed. In fact the Sample and Hold devices where the analogue voltage is eventually stored have a minimum acquisition time. Thus the DAC conversion must be completed well before this time window has elapsed, so as to also leave the sample and hold device enough time to accurately acquire and store the voltage.

The DAC used in the IMU decoder is the DAC712, made by Burr-Brown®. This device is a 16-bit, parallel input DAC that converts data formatted in the twos complement form. The device has a ±10V output range, which is regulated by an internal, temperature compensated, 10V regulator [16]. The main timing constraint on the DAC was the write pulse length was greater than 60ns. The sync pulse is used to write enable the DAC in the IMU decoder design, this pulse is 400 ns long, thus this timing constraint was fulfilled.

To ensure that the DAC operates in the mode that we require the DAC necessary pin connections were carefully considered. The main point considered on the DAC set up was that of the Input latches. The DAC inputs have a dual latch system and the device can be set so as any combination of these latches can be used to input the data. For the use of the DAC in the IMU decoder circuit, the latches did not need to be used, thus the DAC was set up so as to make the latches transparent. To do this, pins 11 and 12, were connected to ground so as to hold them low and pin 9 was connected to the 5 V supply rail so as to hold it high. Information concerning the connection of every pin is shown on the full decoder circuit diagram as shown in Appendix C.

The DAC also required some peripheral circuitry to function to its full capability. The DAC output can be finely trimmed so as the maximum positive and negative outputs can be set to exactly 10V. The circuits that were used to do this are specified in [16] and shown below in figure 5, appendix D.

In order to trim the DAC output the Offset circuit was adjusted first. The code that produces the maximum negative output voltage (8000_{HEX}) was applied to the DAC inputs and potentiometer in the Offset circuit was adjusted until the output of the DAC was at –10V. After this step was complete the Gain circuit was adjusted. The code that produces the maximum positive output voltage ($7FFF_{HEX}$) was applied to the DAC inputs and potentiometer in the Gain circuit was adjusted until the output of the DAC was at +10V. Both these steps were carried out using a digital voltmeter.

Sample and Hold IC

The primary requirements of the Sample and Hold IC were that it should be able to sample and hold voltages varying from –10 V to +10 V and have a fast acquisition time. The acquisition time is the time for which the potential across the storage capacitor reaches that of the potential applied to the input. The decoder design requires the device to sample and return to hold mode within the period that the IMU clock has stopped. The control signal for the sample and hold goes low for 4.7µs, but this starts with the positive edge of the sync thus the time allowed for acquisition is shortened, due to the DAC requiring a short time to make the conversion. As this conversion time is not clearly defined in the DAC data sheet it was decided that the fastest possible IC, that the budget allowed, should be used. Other factors considered in the choice of Sample and Hold IC included the devices hold step error and the droop rate. The holds step error is the voltage offset that occurs when the device is switched from sample mode to hold mode. The droop rate is the amount by which the output voltage of the device drops whilst in hold mode. Obviously both of these factors are important because they will have an effect on the accuracy of the decoder's sensor outputs.

The sample and Hold device used is the HA5320, made by Harris Semiconductor. This device is a high-speed device whose acquisition time can be set to be less than 1μs. The maximum voltage that can be held on the output is limited by the supply used. The maximum value recommended for this is ±20 V thus the device can provide the ±10V output range required. The maximum hold step error for this device is 1 mV and the maximum droop rate is 80 mV/s. The IC works by storing the output voltage onto an internal storage capacitor, however an external storage capacitor can be added to the system so as to provide better droop rate and hold step characteristics. The inclusion of this external capacitor does however come at the expense of an increased acquisition time. In the case of the IMU decoder it is essential that the hold step error and droop rate performance are maximised, thus an external hold capacitor was included in the system.

In order to calculate the value of the capacitor that provides acceptable performance characteristics, the devices performance curves were used, which can be found in appendix E. The value initially chosen was 330 pF. This increases the acquisition time, for an output accurate to ±0.01% of the input voltage, to approximately 3 μs, thus keeping it within the circuits time constraints. The droop rate and hold step were theoretically reduced to about 20mV/s and 0.3 mV. The input of the device is refreshed at 50 Hz, thus the time for which the output is held is about 20 ms. With a droop rate of 20mV/s the output will be reduced by a maximum of 0.4 mV before it is refreshed. This was deemed acceptable for purpose of the flying platform. The hold capacitor is connected between pins 7 and 11 as shown on the full decoder circuit diagram in appendix C. Another capacitor, known as the noise bandwidth capacitor, whose value is 0.1 of the external hold capacitor (68 pf) is connected from pin 8 to ground as suggested in the device data sheet [17].

As with the DAC there is some peripheral circuitry associated with the Sample and Hold IC. In order to null the offset caused by the hold step error a 10 K pot is connected between pins 3 and 4, whose wiper connection is connected to the –15 V supply rail. The potentiometer allows the output to be adjusted by ±15 mV.

4-16 Converter

The 4-16 line decoder used is the CD4514BC, made by Fairchild Semiconductor. The output of this device is active high i.e. the presence of a specific binary number on the inputs is indicated by the corresponding output going high. The four bit binary number is inputted via inputs A, B, C and D, with D as the MSB. The truth table specifying the relationship between the data inputs and selected output can be found in appendix F. The device also has an active high inhibit function, when active all outputs are held low regardless of the input and strobe conditions. This is disabled for our application by connecting the Inhibit pin, pin 23, to ground.

Shift Register

The shift registers used is the 74164A, made by National Semiconductor. This is an 8-Bit Serial-In, Parallel-Out shift register that enters serial data synchronous with the rising edge of the clock input. The data is inputted through an internal two input AND gate, via pins 1 and 2. To by pass this input condition pin 2 is tied to the 5 V supply rail, thus remaining permanently high. The device also has a reset function, which is activated by a low signal, in order to disable this the relevant pin, pin 9, was also tied to the 5 V supply rail.

To ensure that the DAC received the parallel data correctly and 4-16 received the correct binary value for each identifier, special care was taken to ensure that the inputs of the DAC and the 4-16 decoder were connected to the correct outputs of the shift register. The input/output connections are shown below in figure 6.

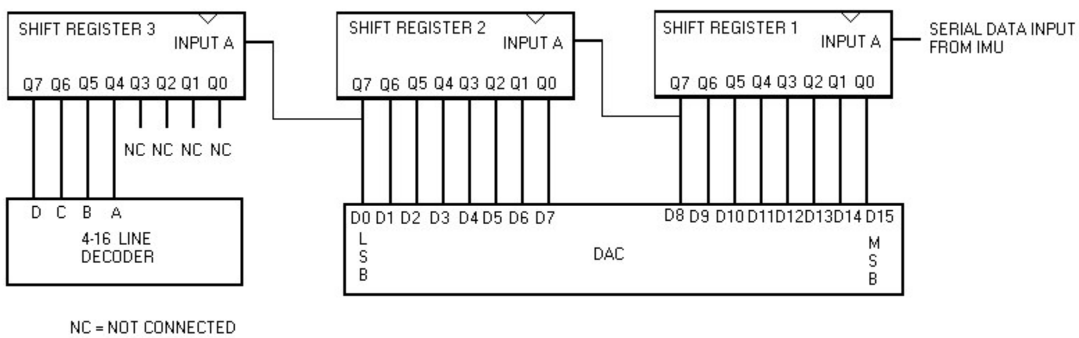


Figure 6
Input and output connections of DAC and
4-16 line decoder

Monostable

The monostable used to create the extended sync pulse is the CD4538 IC. The device produces a pulse whose width is determined by the values of two external components consisting of a resistor and a capacitor. The pulse width is determined by equation 6.

$$\text{Pulse width} = 0.7RC \quad \text{seconds} \quad (6)$$

The pulse width required for the IMU decoder is 4.7 μs, thus a resistor of 6.8 KΩ and a capacitor of 1 nF were used. Information on how these are connected can be found on the full IMU decoder circuit diagram in appendix C.

The device can be used in four different modes as specified in the device data sheet, which can be found in Appendix G. The mode required by the IMU decoder is the positive edge triggered, non-retrigerable mode. In this mode the output pulse will start on the positive edge of the input pulse (sync pulse) and it must go low before it can be triggered again, thus guaranteeing a pulse of the required width. In order to set the monostable to this mode the TR- input, pin 5, was connected to ground and the reset pin, pin 3, was connected to the positive supply rail. The sync pulse was inputted to the TR+ pin, pin 4, and the output taken from the Q output pin, pin6.

NAND gates

The two input NAND gates used are the 74HCT00E IC. These had no specific set up requirements or peripheral circuitry apart from when they are used as inverters; in this case the two inputs are tied together.

8.3.3 IMU Decoder Circuit Construction

The details of the stages and processes undertaken in the construction of the IMU decoder can be found in [18].

8.4 IMU Decoder, Initial Testing

In order to ensure that the IMU decoder was functioning correctly, before inputs were taken from the actual IMU, a series of test circuits designed to emulate the IMU were built and used. The IMU is effectively on loan from BAE systems, thus care to maintain it in good working condition is of great importance.

8.4.1 Manual Input test device

The Manual Input test device is a simple system comprising of three switches that enabled the user to manually produce the clock, sync and data signals. The circuit designed to produce the clock pulse is shown in figure 7.1, appendix N. The CD4538 monostable is used to remove any switch bounce, this is necessary because the shift registers clock inputs are edge triggered. The output pulse width is set to be 0.7 seconds by the combination of the 1MΩ resistor and 1nF capacitor. The sync pulse is generated using an identical circuit. The circuit that generates the data stream is shown in figure 8.1, appendix N.

The test circuit is operated by connecting the outputs of the test circuit to the corresponding inputs of the IMU decoder. Data is inputted one bit at a time by setting the data output to a 1 (switch closed) or a 0 (switch open) and then pressing the clock circuits push switch. This sends a single clock pulse into the shift registers thus storing the data value onto the first output of the shift register. The data value can be altered as required and then a second clock pulse can be sent to the shift register. This moves the first data bit to the second output and stores the new bit on the first output. This procedure is repeated 24 times thus putting a bit of data on each of the 24 outputs of the shift register. The first bit of data entered is the LSB of the data message. The sync button is then depressed in order to send a sync pulse into the circuit, thus starting the decoding of the data. The decoder outputs are then checked to see if the correct output voltage appears on the correct output pin.

Testing

Two test strings were used, one that should produce a voltage of +10V on the selected output and one that should produce a voltage of –10V on the selected output.

+10V Test string: $X_1X_2X_3X_4$ 0000 1111 1111 1111 1110

-10V Test string: $X_1X_2X_3X_4$ 0000 0000 0000 0000 0001

X_1, X_2, X_3, X_4 are the identifier bits which vary depending on which output pin the voltage level is to be stored at. A list of the identifier code words and what output pin they should select is shown in table 3.

Decoder Output pin	X_1	X_2	X_3	X_4
1	1	0	0	1
2	1	0	1	1
3	1	1	0	1
4	0	1	0	1
5	0	0	1	1
6	0	1	1	1
7	1	1	1	0
8	0	0	0	1

Table 3
Identifier code word and pin allocation

Tests were carried out for each Decoder pin by replacing X_1, X_2, X_3, X_4 with the corresponding data bits (as shown in table 3) and the resulting string being entered into the decoders serial data input.

Every test carried out using this method was successful and thus it was concluded that the decoder circuit was functioning correctly when run at low speed. However, to ensure that the timing of the circuit was correct, and that it would function properly with the IMU data and control signals, a full speed test method was required.

8.4.2 IMU Emulator

In order to test the circuit under the conditions, as it would have to operate under with the IMU, a circuit that precisely emulates the IMU was designed and constructed. The IMU emulator uses a PIC micro-controller and the relevant software to produce data, clock and sync signals that match that of the IMU outputs. The IMU emulator was programmed so as to produce a different voltage on each of the IMU decoder's outputs. The voltage that should appear on each output pin, providing the IMU decoder is functioning correctly, is shown in table 4. A full description of the IMU emulator hardware and software designs can be found in [19].

Decoder Output pin	Output Voltage
1	2.5
2	5
3	7.5
4	-5
5	-7.5
6	-2.5
7	+10
8	-10

Table 4
Required outputs from IMU decoder for
Emulator testing success

8.4.3 IMU Emulator testing

In order to test the IMU emulator, the data and control line outputs of the IMU emulator were connected to the corresponding inputs of the IMU decoder. The voltage at each of the IMU decoder's outputs was then compared with its expected value. The result from this test was that every output pin had the correct corresponding voltage, as shown in table 4. From this result it was concluded that the IMU decoders timing characteristics are correct and that the circuit is functioning as designed.

8.5 IMU Decoder testing using SilMU0X®

To enable the SilMU0X® to be used with the IMU decoder an RS422 decoder had to built in to the front end of the decoder. The reason why this was not built into the IMU decoder design was that it was initially thought that the various IMU outputs required by the IMU decoder could be taken solely from the Clock High, Sync High and Data High lines. The reason this is deemed feasible is that the High line of an RS422 differential pair is effectively a TTL compatible output, with a logic 1 represented by 5V and a logic 0 represented by 0 V. It was only decided after the decoder had been built, with the aid of some discussion with Dr J.M Horwood, that it would in fact be better to decode the differential lines for each signal rather than simply using the High line.

8.5.1 RS422 Decoder circuit

The RS422 decoder circuit simply consists of a single component, a Texas Instruments MC3486 RS422 line receiver. This single chip contains 4 separate RS422 differential pair decoders thus it is capable of decoding all three of the required control signals. The circuit used is shown in figure 7.

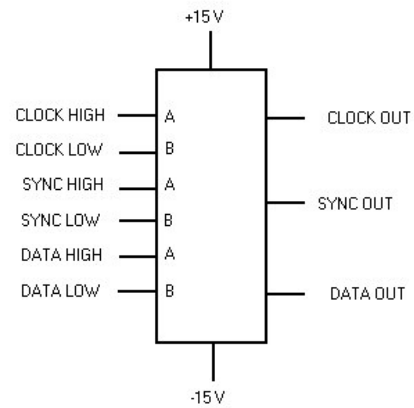
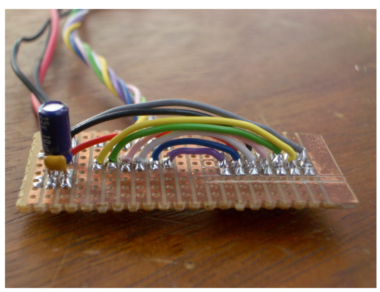


Figure 7
RS422 line receiver circuit

8.5.2 SilMU0X® IMU Connector

Before testing using the SilMU0X® IMU could be carried out a suitable pin connector had to be constructed. The reason for this is that the SilMU0X® IMU is designed to be used in a system whereby the IMU is soldered directly to a printed circuit board, thus no connector that enables flying leads to be attached to the input/output pins is commercially available. The connector produced is shown in picture 2.



Picture 2
IMU connector

The connector provides a method of obtaining the necessary Data and Control line outputs from the IMU, as well as providing the necessary supply voltages from an external power source. The pins that required connections and the colours of wires used to make the connections are shown in table 5. The complete pin configuration and pin out diagram for the SilMU0X® IMU can be found in appendix H.

Pin Number	Pin Function	Wire colour
2	+8 V dc supply	Red
3	System Ground	Black
7	Case Ground	Grey
8	Data High output	Purple
9	Data Low output	Blue
10	Clock Hi output	White
11	Clock Low output	Pink
12	Sync Hi output	Green
13	Sync Low output	Yellow

Table 5
IMU connector wiring and pin allocation

8.5.3 Initial Testing

The initial testing of the IMU decoder was split into two stages. The first stage involved looking at the Data and Control signals being generated by the IMU. This was carried out to ensure that these signal were in the correct form as specified by the IMU data sheets [12] [13]. To ensure that the RS422 decoder circuit was working correctly each output of the circuit was compared with the corresponding high line of the signal coming directly form the IMU. The output of the RS422 decoder for each control/data signal should be exactly the same as each signals corresponding high line. This proved to be the case for all the signals, the only difference being that the decoded version of the signal was noticeably less noisy. The control signals viewed from the output of the RS422 decoder were then compared to those specified in the data sheets. The clock, sync and data signals were all found to be correct.
The second stage involved testing the IMU decoder with the SilMU0X® IMU. The inputs to the IMU decoder were taken from the RS422 decoder outputs. The various sensor outputs were then individually monitored by the use of an oscilloscope. To determine whether the decoder circuit was functioning properly, the IMU's motion or orientation was changed in a way that would produce a signal by the sensor whose decoder output was being monitored. For example in order to test the x-axis gyro the IMU was rotated about the x-axis. The expected output of each sensor was known for each movement thus it could be determined whether the decoder was working or not. The results of this initial testing are shown in table 6, appendix M.

8.5.4 Conclusion

The results obtained from the initial testing showed that the IMU decoder was not working with the IMU. We have, however, already ascertained that the decoder circuit does function correctly, through the manual input and emulator testing stages. Given that the only difference between the tests is the device that inputs the data, it was considered likely that the problem must be somehow associated with this. There were three probable causes of the problem; the first is that the system inputs are suffering from noise, and thus causing false triggering as well as the inputted data being corrupt. The second is that the data signals from the IMU are not exactly as we thoughts, thus causing the decoder circuit design to be in error. The third, which was considered very unlikely, was that the actual data outputted from the IMU was incorrect.

8.6 Decoder debugging

The debugging of the IMU decoder occurred in two stages. The first stage was to try and reduce the noise within the system. This consisted of adding decoupling capacitors at regular intervals along the power supply lines of the decoder circuit. This included the IMU connector and RS422 decoder circuit. To ensure that the circuits were effectively decoupled, two different types of capacitors were used at each decoupling point. This pair consisted of a 100nF disc ceramic capacitor, used to reduce small, high frequency spikes, and a 10 μF electrolytic capacitor, used to reduce the lower frequency, larger current spikes. Six of these pairs were introduced to both the 5V and ±15 V supply rails on the IMU decoder board itself, and then one pair on each the IMU connector and RS422 circuit. The decoder circuit was then once again tested with the SilMU0X® IMU, although the noise on the ground plane had been significantly reduced the decoder outputs remained as before, thus the problem had not been solved.

From this, and the fact that the IMU decoder circuit is known to function, it was considered that the problem must be due to the serial data either being inputted incorrectly, due to circuit design, or the data being incorrect itself. In order to determine the exact problem some diagnostic tests were carried out on the IMU decoder circuit. One such test used an oscilloscope to check whether the 4-16 decoder was decoding the correct identifier code. If the 4-16 decoder was functioning correctly the output lines corresponding to each identifier should have a pulse on them every 20 ms, as the data for each sensor is refreshed. The results from the test are shown in table 7

4-16 output line	Pulse present
S7	YES
S8	YES
S9	NO
S10	YES
S11	NO
S12	YES
S13	NO
S14	NO

Table 7
A table showing the results from the 4-16 decoder output test

A pulse should have been identified on each of the 4-16 decoder outputs S7 to S14. As can be seen from the results in table 7 this was not the case. This indicates that the 4-16 decoder was not decoding the identifiers correctly. Since it was known from the emulator testing the 4-16 decoder did in fact function properly, it was determined that the problem must be associated with the actual identifier data being inputted. In order to determine the exact cause of the problem it was necessary to find out exactly what data was being inputted to the 4-16 decoder, to do this several tests using a data analyser were performed.

8.6.1 Identifier data testing

In order to discover exactly what data was being inputted to the 4-16 decoder, the data input lines were individually monitored using a Sony 308 data analyser. This device can sample, store and present 8 parallel lines of data on an LCD screen. The data analyser also has a function that converts the lines of sampled data in to an equivalent binary or hexadecimal number. The instance at which each data bit is captured is determined by some triggering condition, externally set by the user.

8.6.2 Test method 1

To obtain the identifier word being inputted to the 4-16 decoder inputs the 308 data analyser was used in parallel timing mode, with inputs 0 to 3 connected to inputs A to D of the 4-16 decoder. The order of these connections (0 to A, 1 to B etc) is critical to enable the correct hex or binary conversion to be carried out; input 0 of the data analyser is considered the MSB. The other necessary connections were that of the ground wire to the system ground and that of the trigger line. The data sampler was set up so as to sample only at the time when the identifier code should be on the 4-16 inputs. In order to do this the trigger line was connected to the sync pulse. The sync pulse firstly signifies that all the serial data has been clocked onto the shift registers and secondly starts the 4-16 conversion, thus the data on the 4-16 inputs at this time is the data that is decoded. It was expected that the results would show a repeating pattern of 11 different identifier codes which should match the transmit order specified in table 8.

Transmit order	1	2	3	4	5	6	7	8	9	10	11
Identifier (hex)	9	7	A	8	B	0	C	F	D	E	1

Table 8
IMU identifier transmit order

Test 1 Results

The results from this test are shown in both hexadecimal and binary format in table 9.

Repeating pattern (Hex)	E	4	0	6	0	8	E	A	C	2	0
LSB (bin)	0	0	0	0	0	0	0	0	0	0	0
	1	0	0	1	0	0	1	1	0	1	0
	1	1	0	1	0	0	1	0	1	0	0
MSB (bin)	1	0	0	0	0	1	1	1	1	0	0

Table 9
Repeating pattern of identifier codes obtained in test 1

As can be seen from comparison of the specified results in table 8 and the observed result from table 9, the identifier word being inputted to the 4-16 decoder at the time of conversion is wrong, thus the correct output chip is not being selected. Although it is useful to definitively prove this, we had already established this from the results of the decoder output tests. In fact the most critical observation made from the study of this data is that the LSB of each identifier word is 0. This is significant because it suggests that the data is not being clocked on to the shift registers correctly or the first bit of data (bit 0) is missing. To discover exactly what is happening as the data is clocked through the shift registers a second test was performed.

8.6.3 Test Method 2

The method used for the second test is identical to the first but with a different trigger condition. In this case, rather than triggering from the sync line the system is triggered by the clock line. This means that the data can be viewed as it moves through the shift registers, directly after every clock pulse. If the system were functioning correctly, the data for the identifier word should be seen on the 4-16 data inputs directly after the 24th clock pulse of each cycle.

Clock Cycle	1	2	3	4	5	6	7	8	9	10	11
Sampling clock pulse											
1	9	7	A	8	B	0	C	F	D	E	1
24	E	4	0	6	0	8	E	A	C	2	0

Test 2 results

The complete results can be found in appendix I, however the significant results from this test are shown in below in table 10. The sampling clock pulse refers to the position of the clock pulse within the 24 pulse cycle i.e. the first clock pulse of each new cycle is number 1 and the last is number 24.

Table 10
Repeating pattern of data seen on 4-16 inputs
sampled after every clock pulse.

The significant of these results is considerable. They firstly show again that the repeating pattern on the 4-16 decoder inputs is not correct after the 24th clock cycle, but secondly, and more importantly, they show that after the first clock pulse of the next cycle, the identifier data on 4-16 input pins is what it should have been on the 24th pulse of the previous cycle (as shown in red). The outcome of this is that the data being clocked through the system is correct but for some reason it is delayed, thus not reaching the correct positions on the shift register by the time the conversion starts.

8.7 IMU decoder circuit solution

The results of the second test proved that the data being generated by the SilMU0X® IMU was correct and the problem with the system is in fact due to a design flaw of the

IMU decoder. With this in mind the timing diagram was once again consulted. It was observed from this that each data bit does not arrive until after the rising edge of its corresponding clock pulse. The shift registers on the IMU decoder circuit are rising edge triggered, thus the serial data message moves one place along on the rising edge of each clock pulse. The 24th bit of data arrives after the positive edge of the 24th clock pulse thus is not clocked onto the shift register.

The solution to this problem was very simple, as shown in the timing diagram in figure 8, if the clock signal is inverted the falling edge becomes the rising edge and vice versa. This has the effect of effectively delaying the clock pulse by half a time period, long enough for the 24th bit of data to arrive before the final rising edge of the 24th clock pulse. To implement this in the IMU decoder circuit the clock signal used to input the data message to the shift registers was inverted by using one of the spare two input NAND gates already on the circuit board (there was a spare gate due to the NAND gate IC on the board being a quad gate device). To operate as an inverter the NAND gates inputs are tied together. The circuit diagram of the final circuit can be found in appendix C.

Once the revision had been made to the IMU decoder circuit it was tested using the test procedure stated in section 8.53. The results gained from this test conformed to the expected results, as shown in table 6, Appendix M. From this it was concluded that the IMU decoder was functioning as required, decoding and converting the serial data message into 8 sensor specific analogue outputs.

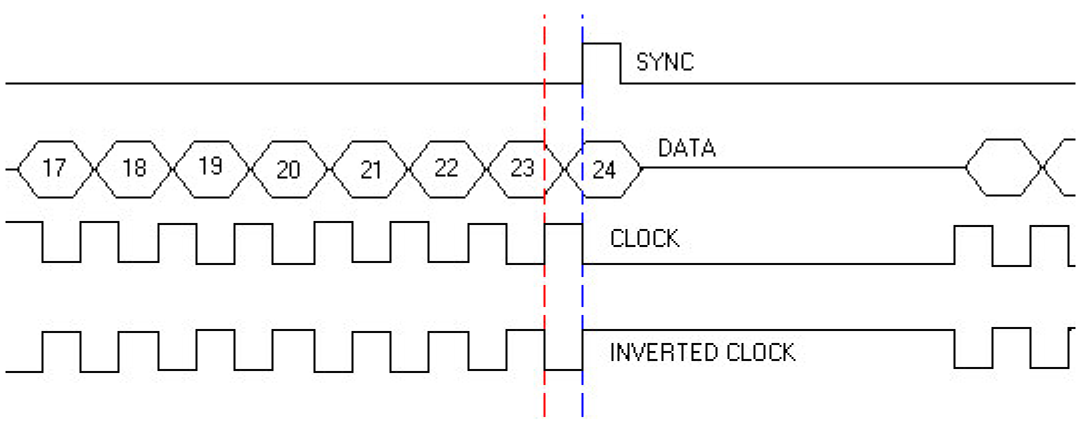


Figure 8
IMU control signal timing diagram

8.8 Signal Processing circuit design

The signal processing circuits used to convert the IMU decoder sensor output signal into those required by control system consisted of two parts, a sensor bias compensation circuit and a integration stage. The number of integration stages required was determined by the sensor signal to be processed. The processing circuit for the output signal of the rate gyros requires a single stage of integration where as for the output of the accelerometer, two stages of integration are required. Although each circuit requires a different number of stages, the basic integrator circuit used is the same. In the case of the accelerometer, where two stages of integration are required, two of these basic circuits are used in series.

8.8.1 Basic Integrator Circuit

The integrator circuit used is a standard op-amp integrator, using an OP97 precision op-amp. The circuit diagram is shown in figure 9.

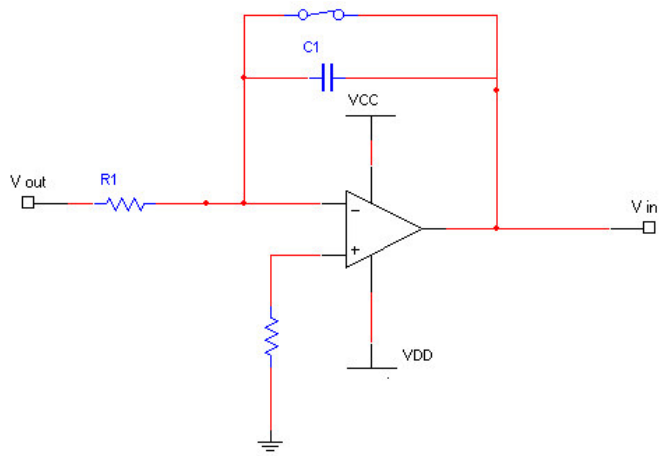


Figure 9.
Circuit diagram for standard op-amp integrator

The output voltage of the circuit behaves as described by equation 7, thus the output is the integral of the input voltage multiplied by the gain of the circuit, 1/RC.

$V_{out} = (1/RC) \int V_{in}\, dt + \text{constant}$ (7) [20]

In order to reset the integrator at the beginning of each flight a push switch across the storage capacitor is included. When the switch is closed the capacitor is discharged and the output returns to zero volts. This is important because it enables the inertial measurements to be referenced to a known starting point.

8.8.2 OP97 Precision op-amp

The op-amp choice for the integrator circuits was considered very important. The integrators are providing the control system with all its required information, thus accuracy is paramount. As mentioned in section 7.1, any error caused by voltage offset at the integrators inputs will increase, at the integrators output, proportionally with time for a single stage of integration and proportional to the square of time for a double stage of integration. One of the possible sources of error is the offset voltage inherent to op-amp inputs. There are two solutions that can be used to minimise this problem, the first is to use an op-amp with a very low V_{os} and the second is to use some form of trimming circuit that can null the offset caused by V_{os} to zero. However, the V_{os} of op-amps fluctuate with the temperature of the device, so even if the op-amp has it V_{os} trimmed perfectly to zero at the beginning, if the temperature changes, so does the V_{os}, thus causing a small offset to remain uncompensated for. It is the variation of V_{os} with temperature that dictates the choice of op-amp; obviously in order to reduce errors as far as possible an op-amp with a very low V_{os} drift over temperature is required. The OP97 has a V_{os} drift with temperature of less than 0.6μV per degree, and was thus considered to be acceptable for the application intended. Another useful function of this op-amp is that it has an internal trimming circuit, thus allowing the op-amp to be trimmed by the inclusion of a single external component, a 100K potentiometer. This was connected between pins 1 and 8 of the op-amp IC, with the wiper connected to +15 V, as suggested by [21].

8.8.3 Basic bias compensation circuit

The basic design of the bias compensation circuit for each processing circuit is also the same. The bias compensation circuits are used to null the offset from the zero reference point of the sensor outputs, when the IMU is stationary and in its starting orientation (z-axis parallel with vertical), caused by sensor bias. The zero reference point is 0V for all the sensors apart from the z-accelerometer. This is because when in the starting orientation the z-accelerometer is measuring a downward acceleration of 9.8 m/s^2, due to gravity, thus the offset caused by the sensor bias is equal to the difference between the sensors output and the voltage expected for an acceleration of this magnitude and direction.

The circuit, as shown in figure 10, is a potential divider whose output voltage can be adjusted using the potentiometer. The voltage across the potential divider is kept at a constant 5V by a 5V voltage regulator. This is of key importance because if the total voltage across the circuit varies so does the output voltage, thus causing a small offset from 0V to remain.

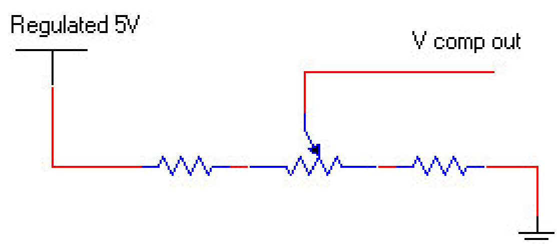


Figure 10
Sensor bias compensation circuit

In order to design compensation circuits that accurately null the bias for each sensor, the approximate bias for each sensor was determined experimentally. In order to determine the bias of the rate gyros, the corresponding outputs of the IMU decoder were measured when the IMU was stationary and in its starting orientation. The bias point of the z-accelerometer was, measured by orientating the IMU so that the z-axis was perpendicular to vertical. This stops the z-axis accelerometer measuring any component of gravity thus ensuring that the voltage measured at the corresponding output is solely due to the sensor bias. The results form these tests are shown in table 11.

Sensor	Bias mV
x axis gyro	-85
y axis gyro	-78
Z axis accelerometer	-80

Table 11
Sensor bias values

8.8.4 Rate Gyro Integrator and bias compensation Circuit

The circuit diagram for the rate gyro integrator and bias compensation circuit is shown in figure 11, Appendix J. The values for the resistor, R1, and capacitor, C1, were chosen so as to give the circuit a gain of 1. It was suggested in [18] that the capacitor type most suited for use in integrator circuits are large polyester capacitors, because of their good charge and discharge properties. Thus a 2.2µF polyester capacitor is used in the circuit. In order to produce the required gain of 1 in combination with this capacitor a 470 KΩ resistor is used.

The bias points of both the x-axis and y-axis gyros were found to be –85 mV and –78 mV respectively, thus the bias compensation circuit for each gyro processing circuit are identical. The output voltage of the compensation circuit can be varied from 9 mV to 96 mV by adjusting the potentiometer. The output of the bias circuit is connected to the inverting input of the op-amp via a 470 KΩ resistor so as to ensure the gain of the circuit for this input is the same as for the sensor input.

Although the control system requires both the y-axis and x-axis gyroscope outputs to be processed by the above circuit, because the circuits were identical it was decided that only one should be built. This could then be used to convert either of the outputs as necessary for testing. When it is required that the IMS circuits are to be used on the flying platform a second, duplicate circuit can be constructed.

8.8.5 Accelerometer Integrator and bias compensation Circuit

The circuit diagram for the z-axis accelerometer integrator and bias compensation circuit is shown in figure 12, Appendix J. The component values were selected in a similar manner to the gyro circuit, using a combination of a 22µF capacitor and a 47 KΩ resistor to provide a gain of 1 for each integrator stage of the circuit. The bias voltage of the accelerometer was found to be 80 mV, thus an identical circuit to the gyro bias compensation circuit was used to compensate this. The output of this bias circuit is connected to the inverting input of the op-amp via a 47 KΩ resistor so as to ensure the gain of the circuit for this input is the same as for the sensor input.

8.8.6 Initial Integrator and bias compensation circuit testing

The initial test procedures for the integrator and bias compensation circuits were very simple. The testing of the integrator stage was carried out in two stages. The first stage of the integrator testing consisted of applying a known signal into the integrator inputs and then monitoring the output. The input signal used was a square wave of amplitude 1 V peak to peak. The output produced from the single integrator circuit was a triangle wave of the same amplitude and the output of the dual integrator circuit was a sine wave of the same amplitude. Both these results conform to that of the expected behaviour of integrator circuits, thus it was concluded that they functioned correctly. The second stage was used to test the V_{os} offset trim circuit. The output of the integrator circuit was viewed with no input to the integrator, thus the only input that the circuit is seeing is that due to V_{os}. The output of the integrator was seen to slowly drift; the 100KΩ potentiometer in the trimming circuit was adjusted until the output stopped drifting, it is at this we know point at V_{os} has been nulled (for the given temperature).

The testing of the sensor bias compensation circuits was carried out simply by monitoring the voltage out put of the circuit using a voltmeter whilst adjusting the potentiometer from its minimum to maximum settings. The voltage range of each bias compensation circuits were found to be slightly different due to component variations but they all provided the voltage range required in order to compensate for the sensor bias.

With the construction and successful testing of all the individual sections of the IMS complete, the next stage of the project was to test the whole system together.

8.9 Inertial Measurement System Testing

There were several aims for the testing of the complete Inertial Measurement System, the first was to provide accurate calibration of the output signals to be used in the control system. It was of paramount importance to determine these as they need to be accounted for in the theoretical control model and thus in the actual control circuitry. The figures required were the voltage step per degree of rotation for the pitch and roll angle signal and the voltage step per meter of vertical translation for the height control signal. The second aim of the testing was to determine exactly what compensation had been applied to the signals internally within the IMU.

8.9.1 Test Rig

In order to provide reliable test results a test rig was designed and built which enabled the orientation to be accurately varied. The test rig, as shown in picture 3, enables the IMU orientation, in terms of pitch and roll angles, to be varied and accurately measured in relation to its zero orientation (z-axis parallel with vertical). To simplify the gimbal design it was decided to only be able to vary either of the angles at a time. The axis of variation can be swapped by changing the pivot points of the IMU holder. Another advantage of the test rig, apart from being able to set the exact angle of rotation of the IMU, is the fact that the test rig accurately holds the IMU in the orientation set. This allows multiple measurements to be taken without the worry of the IMU gradually changing orientation over time. The full design and construction details can be found in [22].

Picture 3
IMU test rig

8.9.2 Test Methods and expected results

Although the primary aim of the testing is to determine accurate calibration figures for the angle and position outputs of the processing circuitry some initial testing had to be carried out on the unprocessed sensor outputs from the IMU decoder. The aim of these initial tests is to show if the sensor outputs are behaving, in terms of sensor bias and stationary measurement output, as expected, thus enabling this to be accounted for in the calibration calculations. The results from these initial tests also provide data that can be analysed to determine what, if any, error correction is being used on the output signals. Another aim of the testing is to determine the maximum theoretical flight times. The tests were carried out in two stages, the first stage consisted of all the relevant gyro testing and the second consisted of the accelerometer testing. The reason for the tests being conducted in this order was that if there were any compensation applied to the accelerometer outputs, it would be derived from the gyro output. Thus if the gyro outputs are found to be erroneous it would prepare us for possible peculiarities in the accelerometer results.

Gyro bias variation

The bias variation test was used to determine whether the sensor bias of the rate gyros is dependent on how their sensing axis is varied in pitch and roll. Due to the way the MEMS rate gyros operate, which is described in [10], it is expected that providing there has been no compensation applied to the device the sensor bias should remain constant, independent of the orientation of its sense axis. In order to test this the orientation of the IMU was varied and the relevant output of the IMU decoder (which represents the actual sensor measurement) was then measured with the IMU stationary. Tests were conducted by individually varying the pitch and roll angles of the IMU, from -30^{o} to 30^{o} (- sign indicates anticlockwise rotation about specified axis), using the test rig (section 8.9.1).

Stability control signal calibration

The stability control signal calibration tests measure the output of the gyro integrator and bias compensation circuit, which represents the angle through which the specified rate gyro has been rotated, for a range of different size rotations. The tests were carried out for each gyro by rotating the IMU, from a specified zero position, in the specific sense axis of each sensor over a range of $\pm 20^{0}$ (- sign indicates an anticlockwise rotation). This range chosen can be limited to $\pm 20^{0}$ because the maximum tilt in terms of pitch and roll, which the platform could recover from, is less than this in either direction of rotation. The test rig was once again used to accurately vary and hold the angle of rotation with the angle of rotation. The zero position, 0^{0} on the test rig protractor, was set to be the point at which the gyro integrator and bias compensation circuit was reset, using the reset switch. In order to give accurate results, with minimum drift, the sensor bias was nulled using the bias compensation circuit before each test. The test rig was once again used to accurately vary and hold the angle of rotation with the angle of rotation.

The expected results of these test was that for each gyro a rotation in one direction would provide a positive voltage, which steadily increases until the gyro stops rotating. At this point the voltage will be held. If the gyro is then rotated back in the opposite direction the output will become less positive, eventually returning to zero when the gyro returns to the starting point. The same occurs with a rotation starting in the opposite direction to the first case, but the voltage output will be negative rather than positive.

Maximum theoretical Flight times

The maximum theoretical flight times for the flying platform are determined by the errors in the control signals produced by sensor and V_{os} drift and the integrating action of the processing circuits (providing the platform is carrying enough fuel). In order to calculate the maximum flight times a limit must firstly be set on what drift is deemed acceptable and then the drift of the processing circuit output must be measured. In the case of the flying platform its was considered that the angle offset from the horizontal, caused by drift, should be no more than 5^0 and the height offset from 1m, the required hover height, should be no more than .2m. In order to test the drift of each processing circuit the outputs were measured with the input from the IMU being that of when the IMU is stationary. This means the only signals being integrated are the error signals.

Accelerometer Output variation

The tests for the accelerometers output variation were carried out in order to determine how the accelerometer outputs varied with a change in orientation of the sensors sense axis in terms of pitch and roll, whilst the IMU is stationary. The reason for this test being necessary is that although the IMU might appear to be stationary it is actually accelerating towards the centre of the earth at 9.8 ms^{-2}, due to gravity. Thus the accelerometer output will output a voltage that represents this acceleration. As discussed in section 7.1, if the accelerometers sense axis is at some angle to this acceleration, the output from the accelerometer will be a component of the vertically downward acceleration. Thus as the sense axis of each accelerometer is varied in pitch and roll, the size of this component changes depending on the size of the angle between the platform and vertical. In order to test this the orientation of the IMU was varied and the relevant output of the IMU decoder (which represents the actual sensor measurement) was then measured with the IMU stationary. Tests were conducted by individually varying the pitch and roll angles of the IMU, from -90^o to 90^o (- sign indicates anticlockwise rotation about specified axis), using the test rig (section 8.9.1).

The results expected for this are dependant on which accelerometer is being tested and what compensation has been used. In order to calculate some expected results it was assumed that there was no compensation. The X-axis accelerometer output was expected to remain unchanged when the roll angle was varied, since a roll rotation is a rotation around the x-axis, but to change when the IMU pitch was varied. This output was expected to be at a maximum at $\pm 90^0$, as this is when the sense axis of the accelerometer under test is parallel to the vertical. A similar result is expected for the Y-axis accelerometer, the only difference being that the output will remain constant for a variation in pitch and change for a variation in roll. The z-axis accelerometer output was expected to change equally with both variation in pitch and roll and for its maximum value to be when the pitch and roll angles are 0^o, and for its minimum value (0V +bias) to be when the pitch and roll angles are at $\pm 90^0$.

Height control signal calibration

The height control signal calibration tests measure the output of the accelerometer integrator and bias compensation circuit, which represents the distance and vertical direction through which the specified IMU has been translated, for a range of different size translations. The test involved moving the IMU up or down to a specified position and then measuring the voltage output of the z-axis accelerometer processing circuit. The magnitude and direction of the translation was 1m vertically upwards as this is the required height for the flying platform system to hover. In order to get accurate results the output voltage of the accelerometer due to gravity had to be nulled. This was done by inputting another voltage into the dual-integrator circuit, which was of the same magnitude, but of opposing polarity to this voltage output. The sensor bias was also nulled; using the bias compensation circuit, to ensure this did not introduce an error.

8.9.3 Results

The results for the tests described in section 9.9.2 can be found in tabular form in Appendix L.

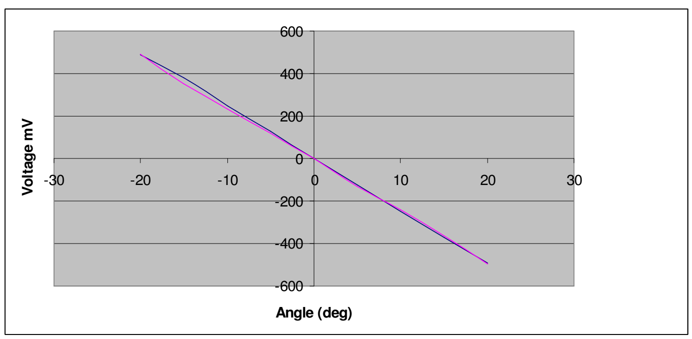
8.9.4 Testing and Results Analysis

The first point of interest comes directly from the results of the gyro bias variation tests. As can be seen from tables 14,15,16 and 17 in Appendix L, the output of the Y and Z-axis gyros remained pretty much constant throughout any variation of the pitch and roll angles of the IMU, where there was fluctuation it was by no more than by 4 mV. The constant voltage output that was measured in these tests was the sensor bias and thus these devices were behaving as expected. The bias points for both these were also fairly similar, -78 for the y-axis gyro and –81 for the z-axis gyro, thus again suggesting that these are accurate results. The x-axis gyro, however, did not behave as expected. As can be seen in tables 12 and 13, in appendix L, for variations in both the pitch and roll of the IMU, the bias point also varied. There are a number of possible reasons for this. The first is that the actual sensors may be malfunctioning, thus producing erroneous results, the second is that there may be some form of compensation on this gyro output and the third is the possibility of some cross coupling with another sensor, such as an inclinometer. From the information obtained from Tony Moy [23], we gathered that there was some form of pitch compensation but not roll compensation, since the results show that these output anomalies occur for both pitch and roll variation, it is presumed that it is not caused by the compensation. However the information regarding this compensation was very much incomplete thus it can’t be ruled out entirely. The effect of these output variations is quite considerable. If the bias point is changing with the motion of the IMU the bias can only be nulled when the IMU is in a fixed position. Since the IMU will never be in a fixed position in flight and the effect of the bias point not being fully nulled is to cause errors at the output of the integrator to rapidly increase, this gyro cannot be used in the control system, at least with out some far more advanced bias compensation circuitry.

Since the x-axis gyroscope was giving anomalous results the stability control signal calibration test could not be performed on this device. As soon as the IMU was varied in pitch or roll the resulting offset, due to the bias point changing caused the integrator output to saturate. However, the results of this test for the Y and Z-axis gyros were more successful. As can be seen from graph 1, the outputs varied in a linear fashion, thus making them suitable for use in the control system. The calibration figures for each device are shown in table 27.

Sensor	mV/degree
Y-Axis gyro	245
Z-Axis gyro	246

Table 27
Table showing the calibration figures for the stability control signals



Graph 1
Graph showing how the Y-axis gyro (blue line) and Z axis gyro processing circuit output varied with angle of rotation.

The results for the gyro integrator drift test were also fairly encouraging. Even though the x-axis gyroscope was giving irregular results in the previous tests, it could still be used in the drift test because the IMU was to remain in the same orientation. The results for this test can be seen in table 20, Appendix L. The drift rate used to determine the theoretical flight time (in terms of gyro errors) is the maximum drift rate recorded. The reason for this is that this provides a worst-case scenario and the flight time should always be this or better. The largest drift recorded was recorded on the y-axis gyro processing circuit output, the output drifted by 90mV/min with a zero IMU input. This equates to a time, for which the stability system maintains the orientation of the platform within the acceptable limits, of about 13 minutes. This seems to be a reasonable time, however the flight time will be determined more by the drift of the accelerometer processing circuit due to the double integration stage.

The results gained from the accelerometer testing stage, shown in tables 21-26, in Appendix L, were fairly promising. The results of the X and Y-axis accelerometer tests were as expected. The X-axis accelerometer’s output only varied when the roll angle of the IMU was adjusted and the Y-axis accelerometer's output varied only when the pitch angle of the IMU was adjusted. Some further analysis could also be carried out on these results to firstly confirm the accelerometers are behaving correctly and secondly to gauge if any compensation has been applied to them. The acceleration the sensors are measuring is the component of gravity acting along the sensors sensing axis, thus if we know the voltage that represents an acceleration of g acting along the sense axis, the bias of the sensor and the angle at which the sense axis has to the vertical the expected results can be calculated. The first step was to find the sensor bias, so this could be taken subtracted from the results, thus leaving the output voltage solely due to the gravitational acceleration. The bias point of the X and Y-axis accelerometers is the output voltage when no component of gravity is acting on the sense axis i.e. when the accelerometers are perfectly horizontal. The voltage output when an acceleration of g is acting on the sense axis is given when the accelerometers senses axis is vertical thus the results which represent this are the results for rotations of $\pm 90^0$. Tables 28 and 29, in appendix L, show the voltages measured for each angle tested and then the expected value, which is obtained by calculating the component of gravity that should be acting on the accelerometers sense axis. Table 28 shows this for the X-axis accelerometers variation in pitch and table 29 shows this for the Y-axis accelerometers variation in roll. The formula used to calculate the expected values is shown by equation 8, in appendix L. As can be seen from tables 28 and 29, the measured results are very close to the calculated, expected results. This indicates two points, the first is that the X and Y accelerometers are functioning correctly and the second is that their outputs are not compensated in any way.

The results from the z-axis accelerometer, as shown in tables 25 and 26 in appendix L, were not quite as expected. Although the output of the accelerometer varied as expected when the IMU was varied about the roll axis, the results from the pitch variation test did not. As can be seen in table 25, when the IMU was varied about the pitch axis the outputs recorded did not match the trends seen for any of the other accelerometer tests. The fact that this occurs for variation in the pitch and not the roll is interesting because it indicates that this may be due to some compensation, which was described as only acting for pitch errors [23]. If this were the case, however, the compensation would be expected to null the effect that rotation has on the accelerometer axis. Thus the expected output voltage would remain to be that of when the sense axis is parallel with the acceleration due to gravity, regardless of whether this is actually the case. This suggests that if the sensor outputs are compensated, it has been carried out in an unfamiliar way or there may have been some cross coupling between the sensors. The fact that the accelerometer output acts as is should with roll variation suggests that the first of these explanations is more likely. To ensure that the accelerometer was behaving correctly with variations in the roll axis, a similar analysis was carried out as for the X and Y accelerometers. Once again the sensor bias and the output voltage that represents an acceleration equal to g along the sense axis were obtained. The output voltage purely due to acceleration was then calculated for each angle (measured acceleration – sensor bias) and this was compared to the predicted results. The results for this analysis are shown in table 30 in appendix L along with the equation used to calculate the predicted result, equation 9. The results from this shows that the z-accelerometer acts as expected for angle variations about the roll axis and that the signal has no compensation applied to it in terms of this.

Unfortunately the calibration figure of the position control signal could not be calculated. In order to ensure that the input voltage of the dual integrator circuit is zero when the platform is on the ground, so as to allow position to be measured from a known reference point, the sensor output voltage caused by the acceleration due to gravity must be nulled. As this voltage varies with the pitch and roll angle of the IMU, the voltage required to null this offset changes. Unless the nulling system used can vary the voltage accordingly, any accidental tilt that occurs when the IMU is being lifted vertically upwards, result in the input to the processing circuits having an offset. This offset, as described in section 7.1 and 7.2, will make the integrator output drift rapidly thus resulting in an erroneous position signal. This makes it very difficult to obtain an accurate voltage that corresponds to a specified height. This problem could be resolved by introducing externally provided pitch and roll compensation to the signal, so as to counteract the effect of tilt, and thus keeping the required nulling voltage to be the same, however due to the fact that the accelerometer seems to be internally compensated in an unknown way makes this task very difficult to achieve.

In summary it has been found that the Y and Z-axis gyros and the X and Y-axis accelerometers are functioning correctly and with no compensation applied to them, thus enabling inertial measurements to be taken, in a form that is fully understood, which can be readily processed by the control system. The X-axis gyro and Z-axis accelerometer, however seem likely to have some form of compensation applied to them, or some error in the measurement, that prevents, at this time from them being used to provide accurate inertial measurements that can be used by the control system of the flying platform.

9. Conclusion and recommendation for further work

In conclusion to the design and development of a flying platform it can be said that the project as a whole was a very challenging, but rewarding task and the experience gained from this will be of much use in the future. Unfortunately, due to time restraints, the flying platform design was not taken through into the construction stage, thus preventing any actual flight-testing. Obviously this would have been a preferable stage to reach because although each section of the platform has been tested individually, it is a step further to get them interacting and functioning correctly within one another. A flight test also provides an instant idea whether the approach in this years project is deemed suitable and thus giving an indication on whether subsequent project groups should try to further develop this system. The fact that flight tests were not achieved, however, does in no way mean the project was unsuccessful. The design brief for this project was slightly different from previous years in the fact that the platform had to contain its own power supply and the use of an internal combustion engine to drive the main thrust producing fan. These two factors alone make the design of the system more demanding, development of both these areas had to be started from the very beginning, with no previous work to give guidance, this inevitable meant mistakes were made. The fact that solutions to both the thrust and power generation systems are very near completion, with encouraging test results for both will provide a solid foundation from which to continue development. Another differing factor between this flying platform design and previous groups work was the use of the IMU to provide the necessary inertial measurement.

Although the development and testing of the required processing circuitry was successful, in that the IMU sensor signals were decoded and manipulated to give some of the required control signals, in order for the system to be integrated with the flying platforms control system extensive work and development is still required. The most obvious problem with the system in its current state of development is the two sensors that are not providing expected measurements, thus preventing all the required control signals from being generated. This problem can be avoided by using the IMU in a different orientation, however this is undesirable. If the IMU is orientated so as the z and y-axis gyros, which both perform as required, are used to measure the pitch and roll of the device and the x axis accelerometer is used to measure vertical acceleration, all the required control signal can be generated. The reason this is undesirable it will prevent the system from ever being controlled in all six-degree of freedom whilst using this IMU, thus limiting the future development path for the flying platform. The other major problem with the system is the signal correction system. In order to generate accurate control signals the sensor measurements must be compensated for the effects of tilt errors. In the case of this project two factors prevented the development of such a correction system, the first was due to a lack of time and the second was the nature of the IMU. It appeared that two of the sensor outputs had some form of internal correction applied to them, the fact that we could not find exactly what this consisted of, by testing or research, makes the development of an external compensation circuit very difficult, if not impossible.

Although the IMU has initially caused some problems, the superior accuracy and performance of the sensors, seen form the successful results, and the unit's compact size are sufficient advantages for the continued development of this system to be recommended. With this and the problems experienced in mind it is suggested that any subsequent groups act on the following proposals. The first task the new group must undertake, to provide any chance of success, is to find out exactly how the sensors signals are processed between the inertial measurements being taken and the serial data output. In order to successfully do this is the group musty liase closely, if possible, with the engineers at BAE systems. The reason for this is that the IMU was originally designed and built for a specific purpose, thus the signals generated have more than likely been modified to suit this, thus the only documentation of this will be held by BAE. The second, providing the first is achieved, is to carefully consider IMU interface. This year it was built using a hardware system, and although this performed its purpose adequately, in retrospect a microprocessor-based system would be preferable. The advantage of this is that correction could be applied to the signals by fast running, programmed algorithms, before they are converted into analogue outputs. This is likely to be more accurate than using approximation type correction on the analogue signal. The third proposal is that some other method for generating the height control signal is considered. The reason for this is the nature of the processing circuit used to manipulate the acceleration signal is too sensitive to errors, the double integration stage means that any tiny offset on the input will make the output become invalid very quickly.

Although a platform did not fly this year, the project has provided a sturdy foundation from which the development a flying platform system can be continued, thus in these terms it can be considered a success.