1.0 Introduction

Over the last twenty years there has been a steady growth in the study of hovering flight. There has been a steady increase in the improvement of this type of system from Manned Aerial Vehicles (MAV) to Unmanned Aerial Vehicles (UAV) and now with the rapid increase in modern technology the challenge of being able to design and construct a fully autonomous flying platform that would be able to hover without any human intervention is possible.

The design and development of a flying platform has been attempted over several years at the University of Exeter. Although each year has been able to add new in sights into the creation of a flying platform none as of yet have been successful.

2.0 Project Aim

The Aim of this final year project is to design and develop an autonomous flying platform that will be able to hover above the ground and can be capable of stable and static flight without any human interference. The platform must be fully autonomous and must carry all the systems required to enable it to keep a steady flight, this involves the onboard sensors and power sources. The platform must be able to deal with any outside interference and be able to correct itself and carry on remaining stable. It needs to be designed so as it can be used to provide a viable operation in its future use.

3.0 Background Research and Literature Review

The fascination of flight has captured the human mind for centuries. Since 1903 when the Wright brothers were able to make the first flight, man has endeavoured to push the use of flight further. Over the past century the presence of increased technology has allowed the aerial vehicle market to grow and develop. One of the main challenges that has been encountered during the development of the aerial vehicle market was that of vertical flight. Advances in machines like the Helicopter and the Harrier Jump Jet have allowed man to show increased versatility in the landing and taking off of aerial vehicles. To enable such advancement in flight technology, other technologies also had to improve. The main advancement was in control systems and the sensors that were used within the vehicle. Over the last few decades, there has been a drive towards further development into vertical flight which has resulted in a categorisation of aerial vehicles

3.1 Manned Aerial Vehicles

Manned Aerial Vehicle's (MAV) are defined as aerial vehicles that are designed to have a human pilot to control the vehicle. The Hiller is an example of an MAV [1]. The Hiller flying platform is shown pictured in *Figure 1*. The Hiller platform was based on a design by Charles Zimmerman [2]. To the amusement of his engineering peers, Zimmerman proved the theory that rotors on the top (i.e. helicopters) are inherently unstable. Zimmerman theorized that a person's natural balancing reflexes would suffice in controlling a small flying machine.

Figure 1: **Hiller Flying Platform**

Figure 2: **PAM 100B**

The PAM 100B [3], shown in *Figure 2*, looks like an interesting amalgam of different early flying platform designs. It is built around a simple tubular frame with skids, about 3 meters (10 feet) across, fitted with twin two-cycle, four-cylinder Hirth F-30 piston engines with 145 kW (195 HP) each, with each driving a 2.8 meter (9 foot 8 inch) rotor, with the twin rotors arranged fore and aft. The platform can in principle be safely landed on a single engine.

There are other MAV's such as the Hummingbird and the De Lackner Flying Platform [4] which all require a pilot onboard so as to control the vehicle. Due to the fact that the MAV's need to carry a pilot they are therefore limited in there size. They are generally built with the pilot based above the rotor so as to supply greater thrust and more stability; the sizes can range from 3–6 metres in diameter.

3.2 Unmanned Aerial Vehicles

Unmanned Aerial Vehicle's (UAV) do not require any human presence on board the actual platform but they are still needed in the operation of the system. UAV's are controlled via a remote ground station; an example of this type of system is a remote control plane or helicopter as they are controlled from the ground. An Example of a UAV that has been developed is the Dragon Warrior or the Cypher II, show in *Figure 3* [5]. This UAV is capable of vertical take off and landing. It utilises a twin four blade design inside a duct which is quite similar to the Hiller platform.

Figure 3: **Cypher II**

The Cypher is one of the smallest (6.5 feet in diameter) and best known UAV. The Cypher II carries all its own flight systems and can be pre-programmed with the flight destinations; the craft is however continually connected to a remote ground station. Built-in computers direct its movements and actions on the way to, over and from its target. Cypher's have hover capability, three hour flight endurance, and top speed of 70 knots enabling flights out to 25 Km [6]. It is possible for Cyphers to be fitted with video cameras, Infra-Red cameras, chemical detectors, manometers, radio and satellite links, microphones to relay pre-recorded announcements, and non-lethal payloads (tear gas and/or smoke canisters, steel spikes to puncture tires or printed propaganda). This type of UAV is one of the more advanced and brings the gap between UAV's and Autonomous Unmanned Aerial Vehicle's (AUAV) closer. However some external input is still required so as to allow them to complete the tasks.

3.3 Autonomous Unmanned Aerial Vehicles

AUAV's are completely self sufficient and require no human pilot on board, any human control or in a remote ground station, or continual flight data updates. A large portion of the designs for AUAV's are based around the helicopter design, because this type of design has already had most of the aerodynamic and stability problems solved. An example of this is the Marvin [7]. The main of the problem that occurs with other types of design is the control problem and the ability of allowing the software to interface correctly.

One of the more advanced developments in autonomous flying platforms is the development of the Hoverbot. The Hoverbot is a fully autonomous flying platform and is capable of vertical take-off and landing without a launcher, it is also capable of hovering stationary at one location [8]. The Hoverbot uses four rotor heads and four electric motors, making it very quiet, easy-to-deploy. The resulting control system is a very complex, highly non-linear Multiple-Input Multiple-Output (MIMO) system, in which all input signals affect all output signals.

3.4 Applications

The demand for the use of AUAV's has increased greatly and is used in a wide variety of areas. Fixed wing, UAV's have been in service with the military and for civilian metrological services for years, but these types of UAV depends on remote ground stations and usually mobile launching platforms.

Although to date most of the resent development in UAV's has been lead by the defence industry, there are still a number of civilian applications that can utilise UAVs. There are possible applications in areas such as Agriculture, Communication relay, Law Enforcement, Aerial Photography and Mapping, and scientific and environmental research [9].

3.5 Previous Years Projects

In 2001 the flying platform was based on two ducted fans mounted in parallel and was powered by a 2.2kW Internal Combustion (IC) engine via toothed belts. The design of the platform was relatively large and was constructed from aluminium alloy and glass fibre re-enforced plastic (GFRP).A height sensor was developed based on a modulated light sensing circuit. The problem of the stability control was not tackled but a recommendation for the use of controlled vanes was suggested in order to solve the problem. The platform was tested under tethered tests but there was no control and therefore the platform demonstrated erratic behaviour [10].

In 2002 the platform design was based on a central fan to give the primary thrust for the lift of the platform. Around which was placed four smaller secondary fans for the control of the platform. All of the fans were electrically powered as it was suggested that it would be an easy and an accurate way to control the platform. There was a scale model produced from a 3-ply wood section which was designed so that the secondary fans would be set at an inclined angle to the vertical, this was chosen as it was expected to increase the inherent stability of the platform. A height control system was developed using a PID control method. Accelerometers were used for the sensing sector of the platform. There was very little work done to the stability control system of the platform, but the accelerometer was investigated as a probable for use in the stability control. The platform failed to actually fly due to time constraints and a lack of thrust from the fans [11].

In 2003 the design of the platform was similar to the previous year in that there were five fans that would all be powered using electric motors. The main difference was that the configuration of the outside fans was being mounted on a level configuration. The main structure was constructed from aluminium light alloy. The main focus of the project was the stability control of the platform; this involved the development of the sensors which were to define the input into the system. The group used a PID controller to stabilise the platform and a PD controller to control the height of the platform. The platform was able to exhibit a tethered test [12].

3.6 Overview of Flying Platforms

From studying the previous year's reports and from research into other flying vehicles there are some useful concepts and ideas that could be used to further the development of the Flying Platform in 2004.

It is shown that the management of the power systems is very important not only in being able to supply enough power to allow the fans to produce enough thrust but also so as there is some left over to power the control systems. It is shown that the use of electrical power on the control fans is a more effective and efficient way to control the stability of the system as these generally have a faster and more accurate response time than an IC driven unit.

The controls of these platforms was either performed by a human pilot or ground station, for the more autonomous types, control was designed using sensor systems, along with a digital or microprocessor controller such as the one demonstrated in the Hoverbot [8]. The actual control system can be built using either a microprocessor or by the use of analogue algorithms but both need to have an advanced sensor array as the input to allow better control. All of the platforms found employ the use of accelerometers and gyroscopes to give the required input to the control systems.

The structures of the platforms vary depending on the type of autonomous vehicle they were designing. There are three main choices of structure for a UAV, a helicopter based design, one singular duct with vanes, and one central ducted fan with four external fans for the control of the system.

4.0 Product Design Specification

Flying Platform PDS 2003/2004	
Performance	1. Must hover approximately 1 m above the ground. 2. Flight duration to be approximately 20 minutes. 3. Must remain Stable. 4. Must provide viable operating platform. 5. Must be able to carry a payload of up to 5 kg. 6. Must have the capability to have the On/Off controlled by remote.
Environment	1. Must be capable of operating in a temperature range of -10°C to 50°C. 2. Must be capable of operating in humid conditions and to be water resistant when operating in light rain. 3. Must be operated in minimal air flow disturbances i.e. minimal wind speeds.
Maintenance	1. Onboard battery must be easily attainable for possible replacement, and recharging. 2. Fuel tank for internal combustion engine must also be easily accessible for refuelling. 3. Oil checks on the IC engine will also have to be regularly carried out, as well as checks on the coolant levels.
Life in Service	1. Products life in service is to be approximately 5 years.
Development Cost	1. A budget of £1000 has been assigned to this project.
Size	1. The flying platforms dimensions to be the same as the dimensions specified in the previous groups report.
Weight	1. Yet to be determined but should be designed for minimum weight possible. Estimated weight including payload is approx 10 kg.
Materials	1. Materials used must have a high mechanical tolerance, and must have as lower density as possible.
Quality and Reliability	1. Product must be extremely reliable; failure of product may have fatal effects.
Constraints	1. Must not be a helicopter based design

Table 1: Product Design Specification

From the research carried out along with the way that previous years had undertaken the project, and the Product Design Specification (PDS) that was designated to the group, shown in *Table 1*, the main section that was requiring focus was the fact that the platform did not have any onboard power supply that would be able to last the length of the required journey. Also, improvements to the sensors and the control of the platform would need to be considered. The PDS was set to be fairly vague so as to give a larger scope when making decisions on how to make the project succeed.

It was decided that the platform should be based on the previous years project with one centralised fan and four secondary fans in a cross formation to perform the control systems. The central fan is to produce the majority of the lift for the platform and the outside fans are to be electric as they would allow a faster response. It was also thought that this type of design would enable an easier control system to be developed and it was a simplistic mechanical system [13].

5.0 Project Management

5.1 Group Structure

The project was allocated to nine MEng students of varying disciplines with assistance from two university lectures as supervisors. The Group was made up of Four Engineering and Management students, One Electronic Engineering Student, and Four Mechanical Engineering Students. The group designated a Chairperson (Liam Dushynsky), a Secretary (James Mackenzie-Burrows) and a Treasurer (Kevin Lowis). Along with these appointments there were also nominated leaders of each section so as to keep them moving smoothly, Propulsion (Richard Holbrook), Control (Kevin Lowis), Power Systems (Alex Tombling) and Structure (Chris Poczka).

5.2 Organisation

Due to the improved way which the previous year had been able to run the organisation of the project a similar approach was taken. It was decided that there would be two minuted meetings each week, one of these would be a formal meeting where the two supervisors would be present. It was felt that each of the meetings should be minuted to give a professional approach and to allow absent member to know what had been discussed, the minutes were taken by the secretary. There were also informal meetings held between each of the groups as and when they were required. A PERT chart [14], *Appendix 1*, was created so as to allow each member to understand what and when tasks needed to be completed. This was revised when required and was put through a Critical Path Analysis (CPA) by the chairperson [15]. It was also decided by the group to set up a section of web space where pieces of information relevant to the progression of the project could be stored so as it could allow other group members to access this information easily therefore saving time.

5.3 Task Assignment

As stated previously the group was split into four different groups with some of the member being present in more than one as there expertise would be required. The allocation is shown in *Table 2*.

Name	Section	Primary Area
Liam Dushynsky	Control, Power systems, Propulsion	Electronics, Management
Richard Forder	Control	Electronics
Richard Holbrook	Power Systems, Propulsion	Mechanical
Rebecca Hughes	Control	Control, Mechanical
Kevin Lowis	Control	Control, Electronics, Management
James Mackenzie-Burrows	Power Systems, Propulsion	Electrical, Management
Jody Muelaner	Propulsion	Mechanical
Chris Poczka	Structure, Propulsion	Mechanical
Alex Tombling	Control, Power systems, Propulsion	Electronics, Mechanical

Table 2: Allocation of Sections

This was not a strict allocation of the group members and was subsequent to change when extra resources were required. There was quite a lot of overlap when it came to the testing of sections such as the Generator and propulsion. There was a limited knowledge of electronics and ducted fan design within the group so in many sections there was a significant demand for extra research.

5.4 Finance

There was an initial budget given to the group of £500 which was open for change dependent on the progress of the project. It was discovered that this amount had to be added to, due to the cost of some of the larger items that were required. The final budget negotiated was £1,550. A set of balance sheets were drawn up at pre-set dates through out the project so as to allow the group to have knowledge as to the projects finances.

A system was devised to allow the purchase of products to be properly put forward to the treasurer along with proposal forms for more expensive items. The proposal for purchase of more expensive items was put forward at meetings for the approval of the group. The majority of the purchases were made through the Engineering Department accounts; the project was also given a separate account with the Exeter University Engineering Stores which was settled on completion of the project. A complete Finance report is included in *Appendix 2*.

6.0 Flying Platform Design

After extensive research into power systems it was decided that batteries would not be suitable as the power required would mean that the battery would need to be quite heavy meaning the platform would never actually be able to get off the ground [16]. It was decided that to have the best chance of an onboard power supply we would need to have a generator to produce the required power. A small two-stroke 4 HP IC engine was purchased to drive a Plattenburg brushless motor so as to get the require 36 volts and 110 Amps out of the system [17]. With the addition of the extra weight, more thrust would be needed could only supply 4 kilos if they were able to run at there optimum efficiency. Therefore an additional IC engine was required so as to supply the central fan with the extra lift in order to allow the platform to take off [18]. The four external fans that were purchased in the previous project will be used again as they seem the most suitable to control the platform.

The platform will use an Internal Measurement Unit (IMU) as the sensor to determine the tilt of the platform in both pitch and role along with the height of the system. This will then input into the control system. The control system will depend on the shape and weight distribution of the final platform. It was decided that the IC engine would be quite hard to control so the four external fans would be used to control both the height of the platform and its stability. The platform will be designed so as to allow the centre of mass to be below the central fan; this will allow the platform to have better inherent stability [19, 20]. The platform (that is to fly autonomously) not only has to be able to remain at a set height and position, but it also must be able to make sure it is stable in pitch, roll and yaw (*Figure 4*). It has been decided by the group that the main concentration should be on the pitch, and, the roll aspects and platform. The movement of yaw will not be considered as it was felt this was negligible to the main stability of the platform.

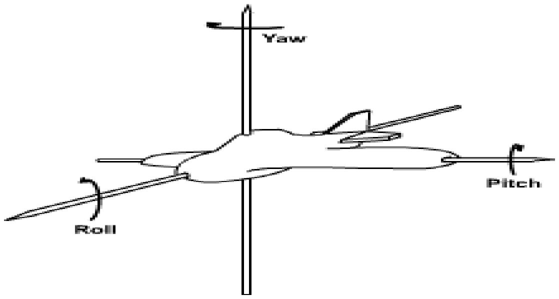


Figure 4: Pitch, Roll, and Yaw

Although both the height control and the stability control are to be controlled by the same external fans they can be broken down into two separate sections. Both sections required development through analytical modelling [21], control theory application, and physical controllers to enable the implementation of the theoretical models. *Appendix 3* illustrates both the system approach for the control of the platform and the control flow diagram.

From the control algorithms, the signal will need to be put through Pulse Wave Modulation (PWM) as otherwise the fans will not be able to react, this needs to be put into 1ms pulses at a rate of 50Hz, this will allow the increase and decrease in speed the Plattenburg motors [22]. The development of the IMU will be essential to the working of the control system and will need to be developed so as useful signal will be output. This will also need to include the development of a rectifying algorithm so it will allow each sensor to be compensated for the angle of tilt that will be exhibited in the other axes [23].

7.0 Control

7.1 General Control Theory

When looking at control theory there are two types of variables that change the control system. There is a controlled variable, which is the quantity that is measured and controlled. Or there is the manipulated variable, which is the quantity that is varied by the controller so as to affect the value of the controlled variable. Control therefore is the measuring of the controlled variable of the system and then applying the manipulated variable to the system in order to correct or limit deviation of the measured value from the desired value [24].

7.1.2 Control Systems

There are two main types of control system, an open-loop control system and a closed–loop control system (or Feedback control systems). An open-loop system is where the output has no affect upon the control action. A closed-loop system allows the difference between the input signal and the feedback signal are put through the controller so as to reduce the error and bring the output back within the desired limits. A closed-loop system is shown in *Figure 5*.

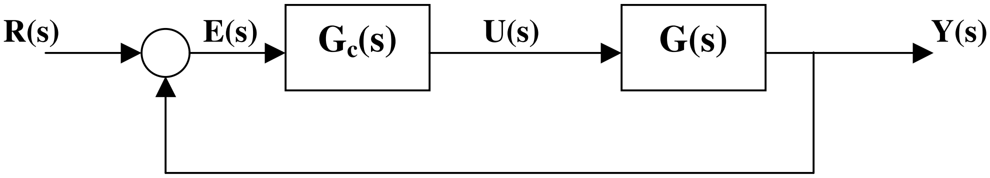


Figure 5: Closed-Loop Block Diagram

7.1.3 Platform Control

A Closed-loop control system will be used on the flying platform as it needs to take into account the movement from the sensors and try and keep it stable within set limits. A block diagram of the system is in *Appendix 3*.

A typical controller has three standard modes of operation: Proportional mode (P), Integral mode (I) and the Derivative mode (D). It was determined that each of these standard modes would be required, which meant that a PID controller would be necessary to control the system [25]. The basic PID controller follows the transfer function shown in *Equation I* [26].

$$G_c(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D s \tag{1}$$

Where

K_P = Proportional Mode
K_I = Integral Mode
K_D = Derivative Mode

The proportional mode in the control system adjusts the output signal in direct proportion to the input signal. A higher gain will give a response of higher magnitude, which will usually increase the rise time (t_r). The integral mode corrects any offset that may occur between the desired value and the process output automatically over time. This action effectively corrects the steady state error (e_{ss}). The derivative mode anticipates where the process is going by analysing the time rate of the system; this helps to reduce the overshoot of the system and acts like a damper.

7.2 Analogue or Digital Control

An important decision at the start of the project was whether to use analogue or digital electronics for the control system. It was necessary for this to be decided early as it would affect the way the control system was designed and built. It would also make a difference as to what and how sensors were to be used.

7.2.1 Analogue Control

This type of control uses continuous signals that take the form of voltage levels. An analogue controller is designed using standard control techniques. Laplace transformations are carried out on the mathematical model to give the transfer functions of the process. These can then be manipulated along with standard equations for control systems to enable design of a system that has its steady state error, percentage overshoot, damping and stability controlled. Calculating the required gains for the proportional, integral and derivative parts of the equations allows these parameters to be controlled. Analogue control can be implemented with the use of operational amplifier (op-amps) circuits. The advantages and disadvantages for analogue control are present in *Appendix 5*.

7.2.2 Digital Control

Digital systems operate in a similar way to the analogue system but instead of the PID controller being implemented by op-amp circuits, a microprocessor with the relevant software is installed. The error signal that the microprocessor operates on needs to be a discrete-time, digital signal. The control parameters of the system are set by the algorithm used by the program to create the correcting signal. The same mathematical model would be used, but with different transforms so as to obtain the transfer functions in order to take into account the discrete-time intervals of the signal, this new transform is known as the z-transform. As the digital signal doesn't work in actual time (as it takes some time to compute the control system), this can sometimes be a problem, but there are new software systems that can be implemented so as the microprocessor looks further ahead and pre-plans the control output so as to give quicker response times. These are Predictive PID controllers and they use fuzzy logic to plan the output. Further information into Predictive PID controller and fuzzy logic is shown in *Appendix 4*.

7.2.3 Overview

Research into other UAVs and AUAVs shows that most modern systems use digital control. This is generally due to the ease of change to the control value that this type of system is able to offer. The main obstacle with digital control is that a fundamentally accurate model would need to be developed and implemented in the control system. For a control system to be successful it needs to be able to adapt to change easily and allow a certain degree of freedom when setting the control values.

It was decided that analogue control would be the preferred choice due to the following reasons:

- The error signal would be continuous throughout allowing the platform to be continually monitored without being time dependent upon the control system. The flying platform is a fairly small structure, thus any movement around the axis being stabilised will be fast. Thus the control system trying to counteract this movement will also need to be inherently fast.

- The mathematical model for the flying platform will not be highly refined, thus in this development stage it would be far more useful to have manually tuneable gains to provide quick adjustment. This would take longer to implement in digital.

- An analogue system would be easier to design and construct given the limited period of time. As there was no experience of using digital programming and a basic knowledge of analogue systems it was thus decided this would be the best course of action.

8.0 Sensors

8.1 Sensor Research

The IMU unit that has been previously mentioned will be fundamental to the control system of the platform. The main components present in a regular IMU are Three Gyroscopes and Three Accelerometers. However in the IMU (which has been kindly donated by BAE Systems) there is also the addition of two inclinometers. The inclinometers are able to supply the system with the tilt that is produced by the platform in both the role and the pitch direction. The IMU provides the inertial measurements in terms of angular rate, angle increments, and linear acceleration and velocity increments in three orthogonal axes [27].

8.1.1 Gyroscopes

The gyroscopes that are present in the IMU are three BAE Systems silicon micro-machined rate gyroscopes. The type of technology which is used in the making of these Gyros is Micro-Electrical-Mechanical-Systems (MEMS). The two constructional technologies of MEMS are microelectronics and micromachining. Microelectronics, producing electronic circuitry on silicon chips, is a very well developed technology. Micromachining is the name for the techniques used to produce the structures and moving parts of micro-engineered devices [28]. The sensor ranges of the Gyroscopes are shown in *Table 3*.

Axes	Rate Gyroscope Range	Accelerometer Range
Roll (x)	± 50º/s	± 15g
Pitch (y)	± 50º/s	± 15g
Yaw (z)	± 50º/s	± 15g

Table 3: Sensor Ranges for IMU

8.1.2 Accelerometers

The accelerometers that are present in the IMU are three silicon accelerometers; this also uses the MEMS technology in order to make accurate reliable components. The sensor ranges for these components are shown in *Table 3*.

Along with the three accelerometers for measurement of linear acceleration there are also two commercial low g range accelerometers [29]. These provide the inclination of the platform in terms of the angle from the vertical, in both the pitch and the roll axes. This is the output that will be used to give the input into the stability control system so as the platform will be able to determine the scale at which the fans need to be powered in order to correct the displacement and keep it level.

8.2 IMU Interface

As it was decided that an analogue control system was to be implemented and the output of the IMU was a digital signal, an interface needed to be designed. This interface would need to split up the single digital control signal and outputs a separate voltage level for each of the sensors within the IMU.

To enable the splitting of the digital signal the data stream needs to be clocked into three shift registers. For each sensor a 24 bit data stream is sent out from the IMU. The first 4 digits in the stream are used to find out and set which sensor is being detected and where the rest of the information is to be sent. The last 16 bits of this data stream is then sent to a Digital to analogue converter (DAC) and is changed into a voltage level. This voltage level depending on the sensor outputs a voltage in relation to the motion of the IMU, for complete knowledge of this design see [30, 31]. The remaining 4 bits are not used in this system and have been disconnected.

As the inclinometers are to be used to supply the angle of tilt for the flying platform in pitch and roll this will be the signal that is analysed. The signal from the IMU gives out 0.05 mrads as its least significant bit [32], which when calculated means that the IMU was able to do a complete range of ± 93.87º fro the inclinometers. As the output of the system will be in relation to the output range of the DAC, which is ± 10 volts, then the voltage per degree is 0.1065 V/ º.

The final output from this system will be scaled so as to give an out put to the control system of ± 2.5 volts. This will also be the range of all the outputs from the IMU interface.

9.0 Electronic Implementation of Control Theory

9.1 Initial Control Parameters

The flying platform is mathematically modelled and is described using *Equation 2* [33]. This equation is modelled using the principle that this project will be a closed loop system, and the external fans will be used to control the stability.

$$\frac{Y(s)}{R(s)} = \frac{1}{Is^2 + ks + my(g + \omega^2 y)} \qquad (2)$$

Where
I = Moment of Inertia
k = Constant due to Drag
m = Mass
y = Distance of centre of mass below centre of lift
g = Gravity
a = Procession of Platform

This equation represents the G(s) function as can be seen in *Figure 5*. This equation determines the effective control parameters of the system, the time constant (TC), the percentage overshoot, steady state error, and the corresponding control values of K_P, K_I, and K_D. The natural frequency of the system was calculated to 5.324 Hz with a TC of 0.19 s [34].

It was decided that the stability system would be split into two discrete systems for both the pitch and the roll. This would enable the control system to be set as if it would be considering a single axis double fan model. This was decided upon because it would allow the control problem to be significantly simplified, which would be a great help due to the lack of experience in control theory. The control system would still take the other axis into consideration, as the IMU would be designed to incorporate a compensation algorithm within its circuitry [35]. The input to the control system would, be as discussed previously, ± 2.5 volts of the entire degree range of the inclinometer as shown in section 7.2. (Although it is thought that we would only really need to consider ± 15º as after this point the system would become unstable.) The output of this system is also required to be ± 2.5 volts.

It was decided that the control values (K_P, K_I, and K_D) would need to be designed so as they could be easily altered. The reason for this was due to changes in the mathematical model for the stability of the platform. Due to time constraints it was felt that a control system would need to be designed and built so as the control values could be changed or set once the platform was complete and all the variables had been accounted for e.g. precise components and the positioning of the mass.

9.2 Control Implementation

9.2.1 Operational Amplifiers

Analogue electronics can be used to represent the stages that appear in control problems e.g. Integrators and differentiators. The main component in the construction of these types of controllers is the operational amplifier (op-amp) which is frequently used in order to amplify signals in sensor circuits or in the use of filter design for compensation purposes [36]. A basic op-amp is shown below (*Figure 6*) where there is a single output and two inputs. The two inputs are respectively known as non-inverting (+) and inverting (-). The signs for these inputs do not indicate positive and negative signals.

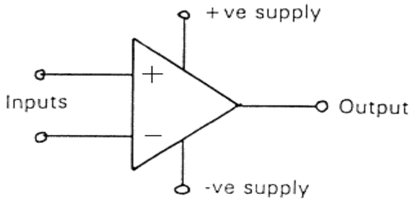


Figure 6: Operational Amplifier

Ideal op-amps have, a high open-loop gain, no current flows into the input terminals, an output voltage that is not affected by the load connected to the out terminal. However practical op-amps are not too dissimilar but some additional properties need to be considered. Some of the properties that need to be considered for practical op-amp are common mode gain, input voltage offset, and input bias currents. Each of these can produce an error in the final signal [37].

So far the op-amp has been discussed using an open-loop but in most practical scenarios a feedback loop is used. An op-amp is usually connected in some form of negative feedback link between the output and the inverting input terminal. This introduction of a negative feedback allows control of the closed-loop voltage gain so that the op-amp functions as a linear amplifier.

When an op-amp is used in this way the performance and output of the device is determined by the magnitude and type of components used externally to provide the require operation. Usually a combination of resistors and capacitors are used to produce varying op-amp circuits. Examples of these types of circuits that will be used when designing a control system will be shown if Section 9.2.2 – Section 9.2.6.

To enable the determination of a transfer function from the circuit, the impedance needs to be considered.

$$E_i(s) = Z_1(s)I(s)\,,\ E_o(s) = -\,Z_2(s)I(s) \tag{3, 4}$$

Therefore the transfer function is:

$$G(s) = \frac{E_o(s)}{E_i(s)} = \frac{Z_2(s)}{Z_1(s)} \tag{5}$$

This is calculated using *Figure 7*.

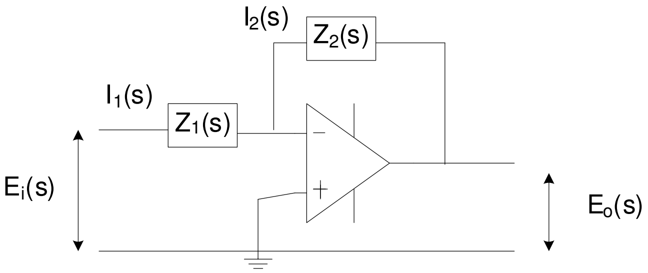


Figure 7: Op-amp Circuit Impedances

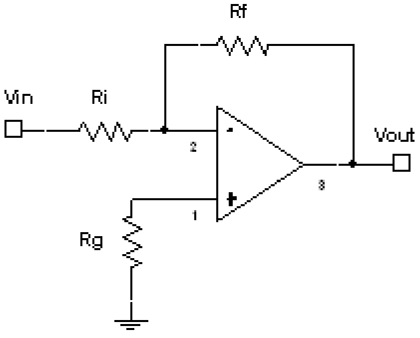
9.2.2 Inverting Amplifier [38]

The circuit shown in *Figure 8* gives a closed-loop gain of R_f/R_i. The positive terminal of the op-amp is grounded through a resistor Rg that is equal to the parallel combination of R_f and R_i this helps to minimise the offset error due to bias current. The resultant of this set up is that the output is inverted.

This circuit effectively fulfils the Proportional mode of a control system and with the placement of a variable resistor in the place of R_f it would enable a range of gains. The voltage and impedance rules for this circuit are shown in *Equations 6* and *7*.

$$Vout = -\frac{R_f}{R_i} Vin \qquad (6)$$

$$Z(s) = -\frac{R_f}{R_i} \qquad (7)$$



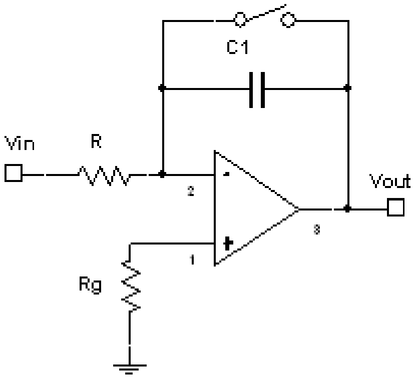


Figure 8: Inverting Amplifier *Figure 9: Integrating Amplifier*

9.2.3 Integrating Amplifier [39]

Replacing the feedback resistor from the inverting amplifier with a capacitor enables a circuit to be produced that has an output that is proportional to the integral with respect to time of the input signal. This circuit requires a switch so as to discharge the capacitor and set the initial conditions (the circuit is shown in *Figure 9*), to minimise the error bias due to bias current $R_g = R$. As this circuit performs, with respect to time, a time constant, RC, needs to be set. It is recommended that it should be set to the expected frequency of the actual platform, i.e. 0.19 [40]. The integrating amplifier exhibits a transfer function of 1/s, which will provide a circuit for the integral mode of the control system. The equations for this system are *Equation 8* and *9*.

$$V_{OUT} = \frac{1}{RC}\int V_{IN}\,dt \quad (8) \qquad Z(s) = -\frac{1}{RCs} \quad (9)$$

This circuit was tested and was found to exhibit drift so would need a high quality op-amp so as to stop or slow the drift.

9.2.4 Differentiating Amplifier [41]

For this circuit the resistor and the capacitor need to be interchanged. The circuit produces an output signal that is differentiated in respect to the time of the input signal, (shown in *Figure 10*). To minimise the error bias due to bias current $R_g = R$, the same as the integrator the time constant, RC, needs to be set to represent the expected frequency of the platform. The Differentiating amplifier exhibits a transfer function of s, which will provide a circuit for the differential mode of the control system. The equations for this system are seen in *Equations 10* and *11.*

$$V_{OUT} = -RC\frac{d(V_{IN})}{dt} \quad (10) \qquad Z(s) = RCs \quad (11)$$

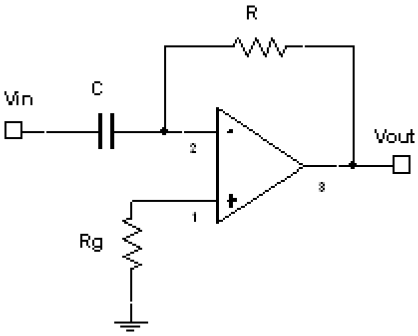


Figure 10: Differentiating Amplifier

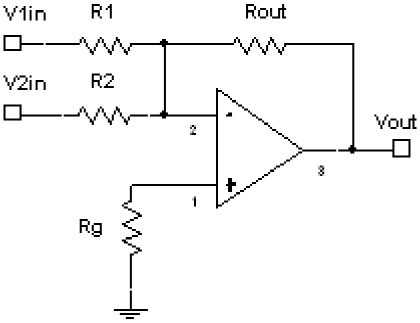


Figure 11: Summing Amplifier

9.2.5 Summing Amplifier [42]

The circuit shown in *Figure 11,* outputs an inverted signal that is equal to the sum of the various inputs. The gain of the circuit can be set using R_{out} and the resistor Rg should be set to the combination of the inputs (R_1 and R_2) and R_{out}. This circuit can be used as a summing junction in a control system as it allows the addition of voltages and currents. The equations of this circuit are *Equations 12* and *13.*

$$V_{OUT} = -R_{OUT}\left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right) \quad (12) \qquad Z(s) = \frac{R_{OUT}}{R} \quad (13)$$

9.2.6 Differential Amplifier [43]

This circuit is a subtracting circuit that allows the subtraction of two voltages. This circuit can be used as a subtracting junction in a control system; this is shown in *Figure 12*. The input impedances for the two inputs are not necessarily the same, the gain for either input is the ratio of R_1 and R_{OUT}, only if R1=R_2 and R_{OUT}=R_g. The Equations for this circuit are *Equation 14* and *15*.

$$V_{OUT} = \frac{R_{OUT}}{R_1}(V_2 - V_1) \tag{14}$$

$$Z(s) = \frac{R_{OUT}}{R_1} \tag{15}$$

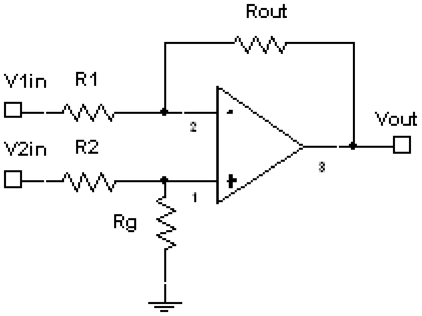


Figure 12: Differential Amplifier

10.0 Stability Control System

10.1 PID Controller

There are a variety of different PID controller circuits that can be put into control systems. The main recommendation in literature is a simple series PID circuit. These can range from having a parallel D+I mode with the P mode on the output, to a very simplistic series D+I with having the P mode as a complex function of the two. These types of controllers would operate as required but due to increased complexity, and the use of interacting values, when one control value is altered the others are also affected. This would create a problem for practical tuning of applications and would also require more analytical work to establish the electronic values so as to give the correct outcome. This type of scenario would not be useful to the project as it needs to be designed so as it can be easily varied. Therefore the most appropriate circuit would be a Parallel PID circuit as this can have the control value altered without affecting the values of the other two. This can be achieved by changing the resistor values which are going into each section, this could be achieved using potentiometers [44].

10.2 Parallel PI-D Controller

It was decided that a form of parallel PID circuit could be utilised most efficiently in this type of control problem. It was decided that the best form of control system would be a PI with D feedback loop (PI-D); this is illustrated in *Figure 13*. The approach of using this circuit enabled the individual components of the control circuit to be designed in separate modules and then connected together. This also enabled individual testing to commence, which allowed the correct outcomes from the separate systems to be known.

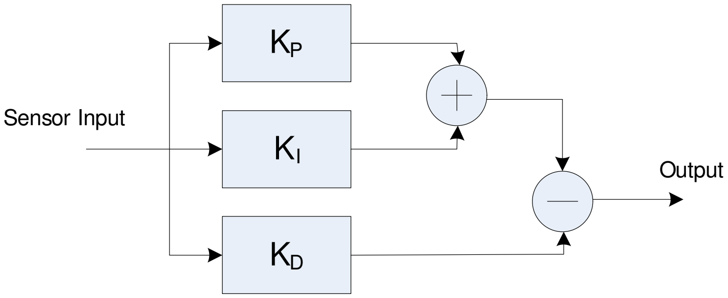


Figure 13: Parallel PI-D

The actual control values for the PI-D controller were not set at the point of design of the circuits, but it was suggested that each of the values should be designed so as to allow at least a control value from 0-10 on each controller [45].The transfer function for this system is slightly altered in comparison to the one mentioned previously in *Section 8.1.3*, as a subtraction now also has to be accounted for, the transfer function for this system is shown in *Equation 16*.

$$G_c(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} - K_D s$$

(16)

10.3 Components

The most crucial component of this system is the op-amps. Increased advancements in technology has allowed op-amps to improve greatly, bringing them closer to value of an ideal op-amp. It was decided that for the main op-amps a quad IC (Integrated chip) should be used so as to make the design more compact and thus lighter.
In the initial stages of the circuit development, LM324 Quad op-amps were used as these were readily available and would allow testing of circuitry before being replaced with the actual op-amps that were to be used. The TL064, (*Appendix 5*), was chosen to be the main op-amp as it was a good general-purpose op-amp. It offered low power consumption, low input bias and offset currents. This op-amp has a supply voltage level ± 18 V, a differential input voltage of ± 30 V and draws 200µA.

When the integrator was tested it was discovered that there was considerable drift in this element of the circuit. It was decided that a more precise op-amp would be required for the integrator so as to limit the drift. The OP-97 was chosen by looking at a range of op-amps and then calculating the error budget for them, (*Appendix 6*). The OP-97 is ideal for use in precision long-term integrators [46]. This type of op-amps offset voltage is ultra low at 25µV and it also has an offset current and offset bias of 30pA.

The capacitor that was chosen was tantalum electrolytic or ceramic. The resistors were chosen to be metal film both of which were readily available in a variety of values so they could be used as required. For the control variables it was decided that linear potentiometers would be used.

10.4 Setting Control Values

The control values K_P, K_I and K_D are derived from control theory. As discussed previously these are set as ratios of gains, thus if the ratio of gains remains constant the control values are effectively the same [47].

As each of the components of the PI-D Controller requires independent adjustment a variable resistor needs to be put into each of the circuits. In the proportional section there can be one designed into the feedback loop, but in the control of the integral and differential modes an additional part needs to be added onto the input of the system. The I and D modes have gains determined by two factors: the time constant and the input voltage. It was decided that the changing of the input voltage would be the controlling factor as it was more simplistic and had been demonstrated practically by the literature [48].

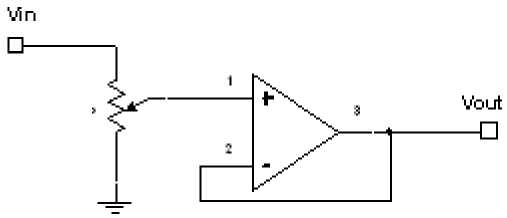


Figure 14: Practical Potentiometer

$$V_{OUT} = \frac{R_{SET}}{R} V_{IN} \quad (17)$$

$$Z(s) = \frac{R_{SET}}{R} \quad (18)$$

The variable circuit shown in *Figure 14,* will be placed onto the input of the I and D modes and will allow them to have the voltage level controlled between 0 and 100% of the input level. The Equations for this circuit are *Equations 17* and *18*. The potentiometers allow the control of the portions of the Integral and Differential modes contribute to the final output signal. It is suggested from literature that if this method is to be applied, the output needs to be buffered, (op-amp in *Figure 14*) this will stop the resistor affecting the impedance of the actual control section.

As the output voltage ranges from 0 to 100% of the input voltage it is impossible for the out put to have a gain greater than 1. This means that the control values need to be scaled so as to allow the ratio between gains to still be effective. Taking a set resistance point on the K_I and the K_D controllers and using this as effective 1 it would then enable a set voltage to be calculated. From this a gain could then be placed on the K_I and K_D controllers, the K_P controller would then be scaled up to the reference point.

The set resistance point was decided to be set at 10k as this would enable a complete range (as discussed in *Section 10.2*) of 0-10 for the control values. Dependent on the range of control values required the range could be increased or decreased, but the ratio of the gains must remain the same so as the control values will be correctly applied. The resistance values of the potentiometers can be determined from the control values using *Equations 19* and *20*. Appendix 6 shows the relationship between the resistance and the control values.

$$K_P = \frac{10R_{K_P}}{10k} \quad (19)$$

$$K_{IorD} = \frac{R_{K_{IorD}}}{10k} \quad (20)$$

10.4 Integrator

This type of circuit is affected the most by op-amps not exhibiting ideal behaviour. This is because the input offset voltage and bias current cause a continuous charging of the capacitor which is situated on the feedback loop, even when no input voltage is being passed through it. To make the integrator reset the switch needs to be pressed and this will then discharge the capacitor. Due to this problem the output of the integrator starts to drift and then eventually saturates. The solution to this problem is to trim the input offset voltage and bias current so as there is no effect from them. To Trim the OP-97 it is suggested that a 100kΩ potentiometer is placed between pins 1 and 8 as this will trim the circuit and limit the drift.

The integrator designed for use in this control system is shown in *Figure 15*. It shows both the integrator and the potentiometer for the setting of the control value. The equations for this circuit are *Equations 21* and *22*. These were calculated using equations 8, 9, 16 and 17.

$$V_{OUT} = -\frac{1}{R_8 C_1}\int\left(\frac{R_{SET}}{R_4}V_{IN}\right)dt \qquad (21)$$

$$Z(s) = \frac{R_{SET}}{R_7 R_8 C_1 s} \qquad (22)$$

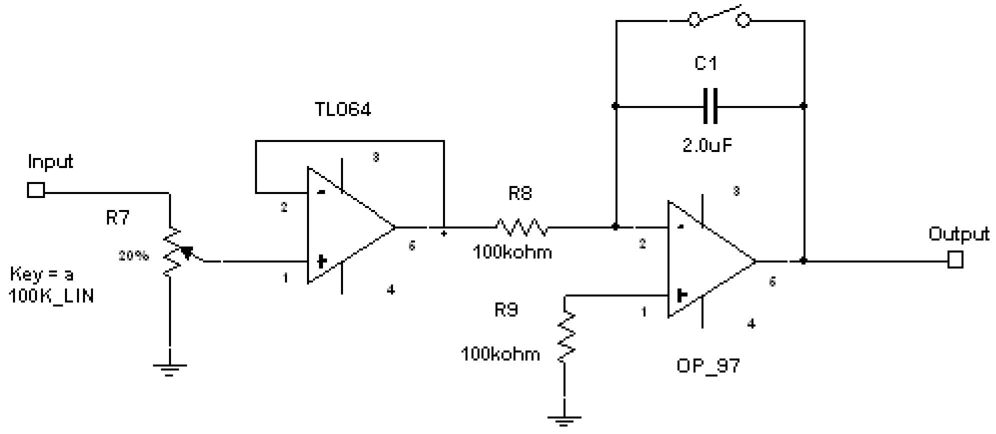


Figure 15: Integrator

10.5 Differentiator

After further research into the circuits it was discovered that the current differentiating amplifier could incur some problems in its practical application. They have problems with noise and instabilities at high frequencies because of the op-amps high gain and internal phase shifts. For this reason it would be necessary to roll off the differentiator action at some high frequency [49]. To prevent this, an extra resistor was required to be placed in series with the capacitor and an extra capacitor in parallel with the feedback resistor. For this, the components were chosen to be small as this would give the high frequency required and could be assumed negligible when calculating the voltage and impedance of the system. This improved system is shown in *Figure 16*, it was suggested that the actual values of R_{11} and C_3 should be set so as the multiple of them would be less that the multiple of R_{12} and C_2 divided by 100. The values that were decide upon were 1kΩ for the resistor and 1nF for the capacitor. This enabled a frequency limit of approximately 160 kHz. The calculation of the frequency was done using *Equation 23*.

$$f_H = \frac{1}{2\pi RC} = \frac{1}{2\pi(1nF)(1K\Omega)} = 160kHz \qquad (23)$$

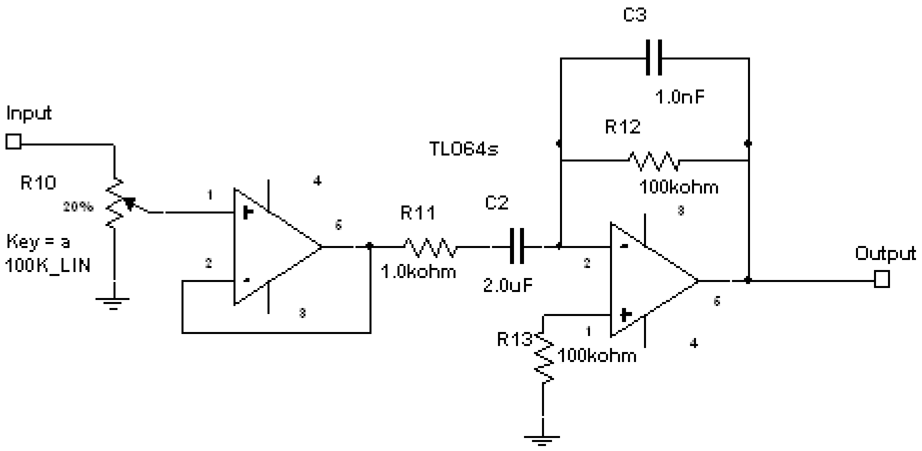


Figure 16: Differentiator

The Equations for this circuit are *Equations 24* and *25*.

$$V_{OUT} - R_{12}C_2 \frac{d\left(\frac{R_{SET}}{R_{10}}V_{IN}\right)}{dt} \qquad (24)$$

$$Z(s) = \frac{R_{SET}R_{12}C_2 s}{R_{10}} \qquad (25)$$

10.6 Operating Range

The input to the PI-D controller is to be a ± 2.5 volts signal which would have a frequency corresponding to the natural frequency at which the platform is oscillating in either the pitch or roll axis. As it was suggested, each of the individual control systems would need to be able to handle a control value of 0-10. The actual PI-D controller would need to be able to process the signal between these ranges.

As the saturation of the op-amps are set to ± 15 volts (due to the power supply rails), it was clear that when looking at the maximum range of the IMU, parts of the control system would saturate. When the IMU performed a maximum tilt, which if it happened would mean the platform would be completely unstable, the proportional mode alone would cause the op-amp to try and drive the output to ± 25 volts. As the proportional mode of the operation would supply the highest gain of the system the input to the controller would need to be scaled so as to allow a useful operating range. The gains on the integral and the derivative mode are susceptible to the frequency of the oscillation of the platform and thus the controlling factor would be said frequency. This was expected to be in the region of 5 HZ due to the natural frequency of the flying platform [50]. When analysed it was seen that the integrator would only go into saturation at low frequencies (below 1 Hz) and after that would start to become quite small. The differentiator was found to steadily increase as the frequency became greater but wouldn't cause it to saturate until it went above 15 Hz. It was decided that it would need to be scaled down so as only ± 1 volt would go into the actual control systems. The circuit is shown in *Figure 17*.

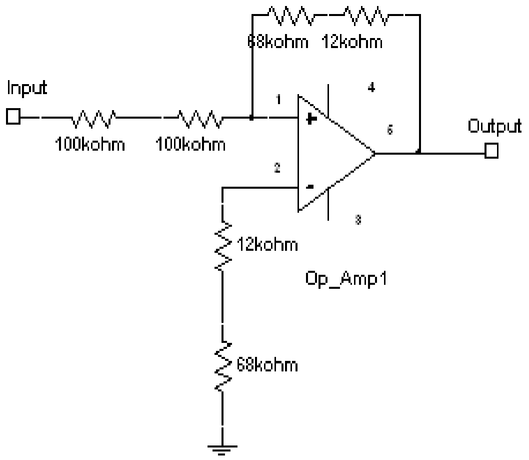


Figure 17: Input Scalar

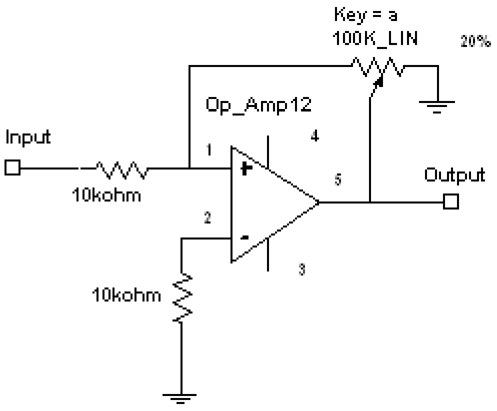


Figure 18: Output Scalar

The output voltage, then, needs to be scaled so as to give out an output between ± 2.5 volts. A potentiometer can be placed over the feedback of the op-amp so as to enable the output to be adjusted as required, this is shown in *Figure 18*. This circuit will allow a gain range of 0.1 -10. The complete electrical interface is discussed in *Section 13.1*.

10.7 Parallel PI-D Layout

Using the circuits developed between *Sections 10.2* and *10.6* a complete PI-D controller was designed, as is shown in *Figure 19*. A detailed version of this circuit with all the relevant resistor and capacitor values is in *Appendix 8*.1.

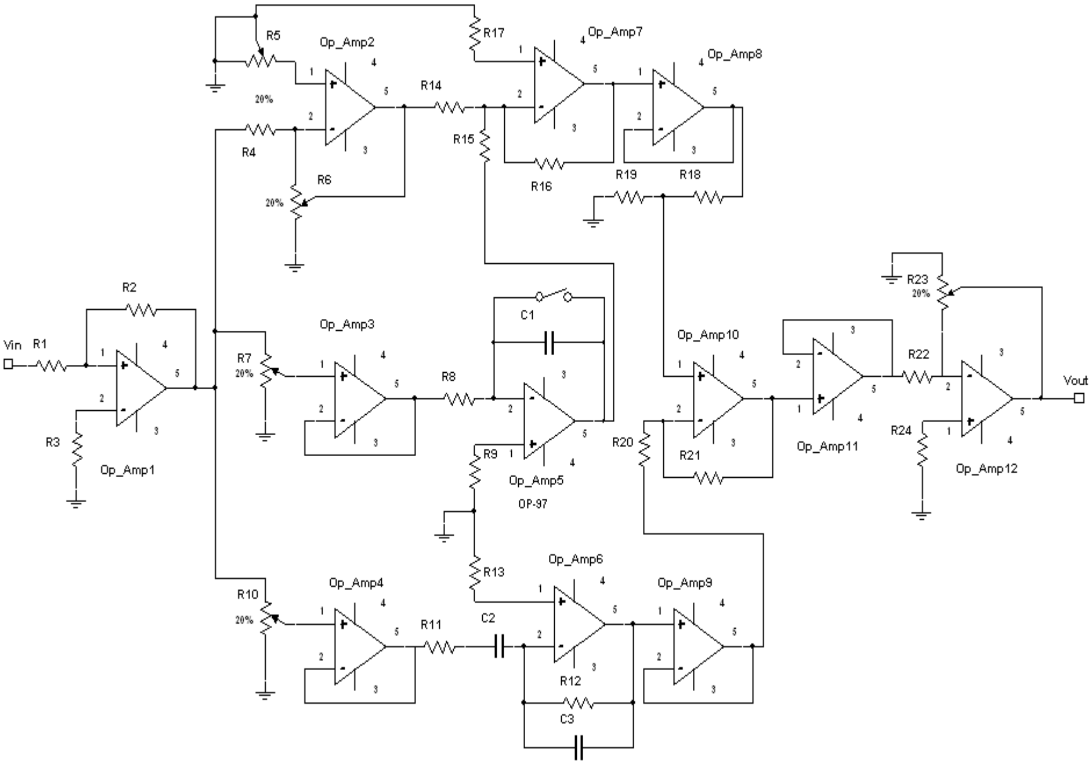


Figure 19: PI-D Controller Circuit

Along with the scalars, proportional mode, integral mode and the derivative mode, the two other main parts are op-amp 7, which is a summing amplifier and op-amp 10 which is a subtracting amplifier. In addition to the subtracting amplifier three others are also required. These are to act as a buffer to the differential circuit. The importance of a buffer is that it has a very high input resistance and a very low output resistance which in this case enables the differential amplifier to work more efficiently [51].

The transfer function the parallel PI-D circuit, as calculated in the LaPlace domain (*Equation 26*):

$$G_{PI-D} = \frac{R_2 R_{23}}{R_1 R_{22}} \left(\frac{R_{K_P}}{R_4} + \frac{R_{K_I}}{R_7 R_8 C_1} - \frac{R_{K_D} C_2 R_{12}}{R_{10}} \right) \tag{26}$$

This transfer function fulfils all the criteria for this system that was stated in equation 16. It has also been designed as required, with variable resistors so as the control values can be changed and set when needed. The final output voltage of this system is dependent on the frequency of the platform and can be calculated using *Equation 27*.

$$V_{OUT} = \frac{R_2 R_{23} V_{IN}}{R_1 R_{22}} \left(\frac{K_P}{R_4} + \frac{K_I \Delta t}{R_7 R_8 C_1} - \frac{K_D R_{12} C_2}{R_{10} \Delta t} \right) \tag{27}$$

11.0 Height Control

As discussed in previous sections the four external fans will be used to control the main movement of the platform, this also includes the height control of the system. As the central fan will be run off of an IC engine it has been decided that it will not be used for this element of control as it has been discovered, through research and testing that their difficult to control [52] and generally have quite a slow reaction time which could prove to be a problem in flight. Therefore, it was decided that the central fan would be set at a constant speed (thrust) so as to enable a steady amount of lift to the system so as the external fans could work at there optimal levels, thus making them more efficient. The height control will need to follow a similar system to the stability in that it will also be part of a feedback system.

11.1 PD Controller

It was decided that a PD controller would be used as it was shown to be a success in previous years and it allows a simplistic but accurate analysis of the system. This type of system is largely proportional control but with the addition of the derivative mode the stability will be increased and the overshoot value will be reduced [53]. The transfer function for the height control system is shown in *Equation 28*.

$$G_c(s) = \frac{U(s)}{E(s)} = K_P + K_D s \tag{28}$$

As with the stability control the circuit design needs to incorporate the ability to change the control values, the range of 0-10 should still be applicable to this system. This will also use the parallel system so as to allow ease when changing the control values.

11.3 PD Controller Layout

The PD layout uses similar sections to that of the stability control this is mainly due to the fact that the time constant is the same for both systems [54]. Using the circuits developed between *Sections 10.2* and *10.6* a complete PD controller was designed, (as is shown in *Figure 20*). A detailed version of this circuit, with all the relevant resistor and capacitor values, is in *Appendix 8.2*.

In addition to the PD circuit, two extra op-amps were required so as to allow the system to work as the platform requires. Op_Amp1 needs to be in place so as the height can be set relative to the input signal from the IMU. This is just basically a differential amplifier which will give an output depending on whether the system needs to be moved up or down. It was set that the input from the IMU would be ± 2.5 volts, but it was unclear due to problems during testing, how to calculate what the ratio for voltage to height would be from the sensors [55]. Op_Amp8 was required due to the requirements from the Control/PWM interface which meant an idle voltage of 2.5 volts was added to the signal this will be discussed in *Section 12*.

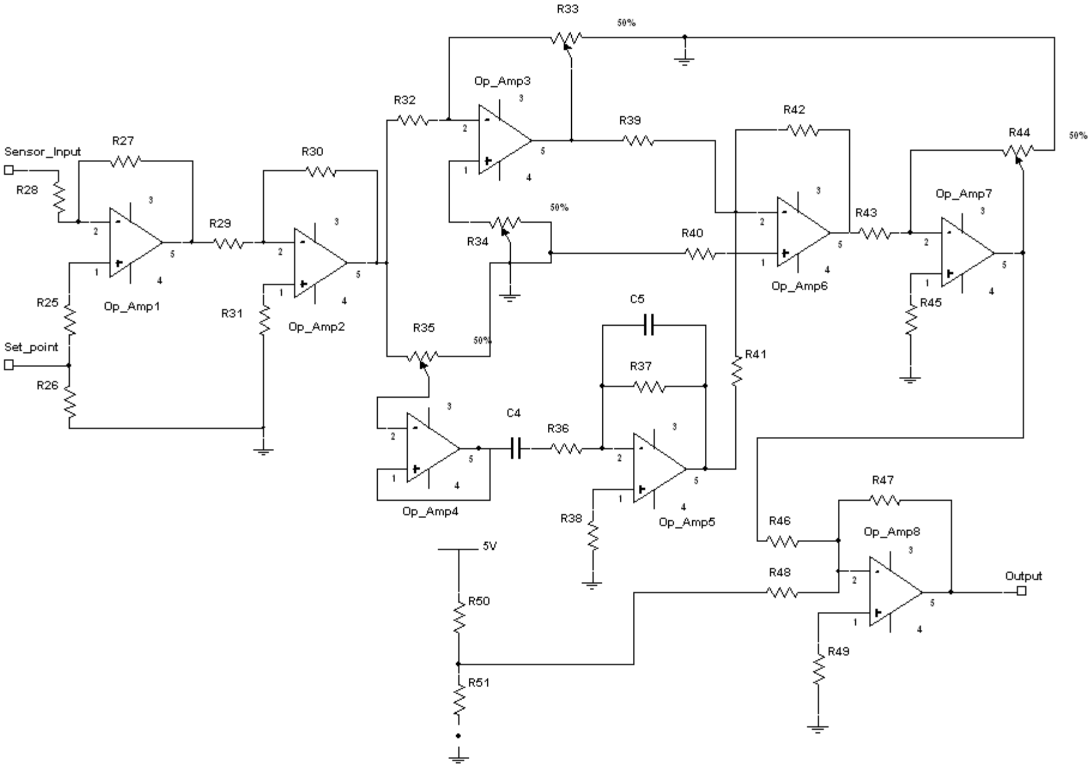


Figure 20: PD controller Circuit

The transfer function the parallel PI-D circuit, as calculated in the LaPlace domain (*Equation 29*):

$$G_{PI-D} = \frac{R_{30}R_{44}}{R_{29}R_{43}}\left(\frac{R_{K_P}}{R_{32}} + \frac{R_{K_D}C_4R_{37}}{R_{35}}\right) \tag{29}$$

The final output voltage of this system is dependent on the frequency of the platform and can be calculated using *Equation 30*.

$$V_{OUT} = \frac{R_{30}R_{44}V_{IN}}{R_{29}R_{43}}\left(\frac{K_P}{R_{32}} + \frac{K_D R_{37} C_4}{R_{35}\Delta t}\right) \tag{30}$$

12.0 Control / PWM Interface

As both the height control and the stability control are using the four external fans an interface was required so as to link them up to the speed controller at each fan. The input to this system from the stability control is ± 2.5 volts and the input from the height control is 0 - 5 volts. The reason why the two inputs are different is because the output from this system needs to be in the range of 0-5 volts. The addition of the idle voltage in the PD circuit allows the minimum output from the interface to be 0v, and to enable the maximum is met, the final op-amps in the circuit, (shown in *Appendix 8.3*), were set to have a single power rail (0-5V) which would make sure that no signal outside this range could be produced.

The initial part of the interface needed to split the output signal from the stability controls and inverse it so as there was a control wave for both of the fans in pitch and in role. Along with this the height control had to be added to each signal so as this would also be taken into account. After this section four signals are produced, each with a DC output of 0 volts to +5 volts. From this the signal would be sent into the pulse wave modulator [56] where it would be adapted so as to work within the required ranges of the external fans optimum range.

13.0 Circuit Construction and Mounting

Four circuits were required in order to have a complete control system. Two identical PI-D circuits so as to control the Pitch and the roll axes, one for the PD control and another for the interface to link the other three together. It was decided that two separate circuits should be built as it would then allow a greater amount of option when it came to attaching them to the platform. It would also enable easier reference when it came to setting up the pitch or the control systems.

Prior to the building of the final circuits, several test circuits were made so as to test the different effects of various capacitor and resistor values. This also gave the chance to discover and calculate the type of outputs that should be expected from the system.

It was decided for ease of building that the actual circuit should try and mimic the circuit diagram as this would allow the ease of not only construction but the testing of the final circuit. To allow the circuit to be as light as possible it was decided that quad op-amps should be used. This also enabled the circuits to be more compact whilst still enabling the operator to distinguish the separate parts and follow the circuit through.

As the circuits required the potentiometers to be set to the required control setting, it was decided that these parts should be easily accessible and removable. It was necessary to remove these devices so as to get an accurate setting without any other resistive values affecting the outcome. Each of the circuits was constructed on to separate boards and was linked together via twisted connection wires. The complete system is shown in *Figure 21*. Additional circuit photos are present in *Appendix 9*.

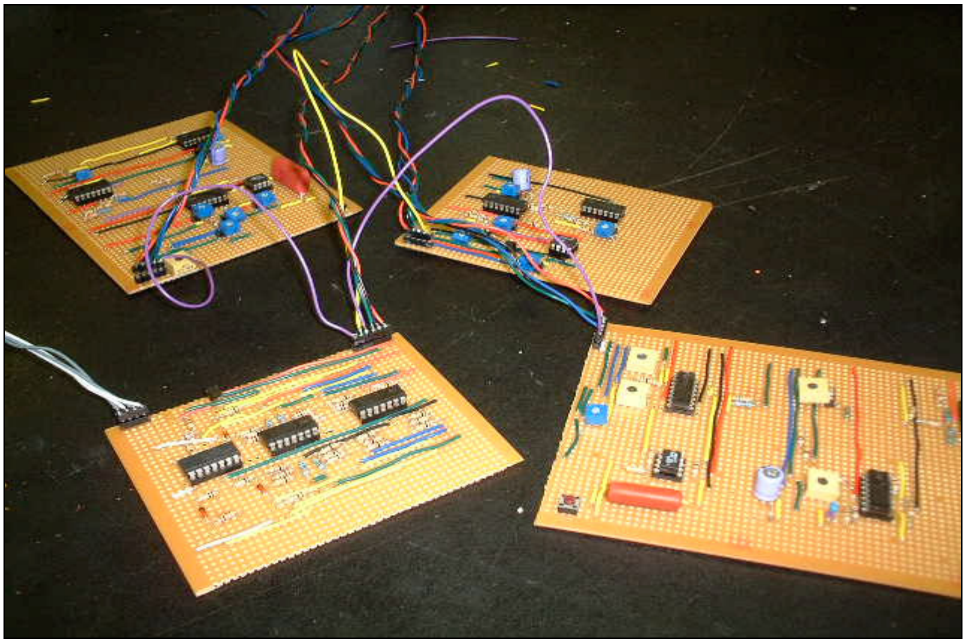


Figure 21: Complete Control Circuitry

13.1 Power Requirements and Connections

The power requirement for this system was ± 15 volts and Ground. At certain points in the system, 5 volts were required. At these points a voltage regulator was used as this would save any additional wires being attached to the circuitry. The power rails to this system did not require any additional coupling as they had already been set to the exact voltage by the power supply [57].

Before all the circuits were completely developed it was decided that a set interface would be needed so as to be able to correctly connect all the different components of the platform. If this had not been carried out then when each member connected up there part of the circuit it could cause problems due to poor compatibility. (The complete electronic interface is in *Appendix 10*). In the majority of the system it was decided that the standard interfaces would be 0-5 volts. It was left open, however, for individuals to discuss and amend these interfaces if required.

13.2 Costing

The costing for this section of the project is split into four sections as shown in *Table 4*. The cost of the PI-D, the PD, the Interface and the testing prior to the construction. The complete breakdown of the control systems parts are shown in *Appendix 2*. This costing however does not include the cost of Vero board, wire and solder as this has been collectively put together for the entire project and is present in the miscellaneous section of the accounts.

Section	**Cost**
Stability Control	£42.92
Height Control	£5.95
Control/PWM Interface	£5.19
Testing	£12.80
Total Cost	£66.86

Table 4: Control Costing

If the circuit was to be produced as part of an actual product then the cost should be lower due to the fact that there would not need to be any further development tests. Also, the circuitry would be constructed using PCB technology which will not only lower the costs in the long run but will enable the system to be smaller lighter and more efficient. Costing would also be lowered due to economies of scale and the more components required, the less expensive they will be.

13.3 Mounting

There are many different types of noise sources through out an electrical system but some of them are negligible such as thermal noise and flickler noise. There are however, other sources of noise that could cause a lot more of an affect within the system [60]. As the platform will be using IC engines and electric motors there will be

a large amount of vibration and electromagnetic interference which could provide a great deal of noise throughout the control system.
To limit the amount of vibration produced by the IC engines rubber mounts will be used to enable the vibration to be damped thus lowering the vibration noise [61, 62]. The mounting of the actual circuitry has also been considered and the best way of mounting this is to either have foam padding or additional rubber feet on the connection points of the circuitry. There should be no problem with noise from the power supply to the system as this will have been looked at in the power interface.

14.0 Circuit Testing

14.1 Initial Testing

Before an input signal was put through the system the circuit was checked so as to make sure that all the supply rails were providing the correct voltage and the op-amps were behaving as required. There were many basic faults that occurred at this point showing that some of the tracks had been crossed or a track had not been broken properly so was not going to perform the required operation.

The op-amps also needed to be checked so as to make sure they had the required supply rails attached. Along with this, the voltage at the two inputs of the op-amps required checking as if it was connected correctly then the voltage between these two points would be within millivolts of zero. Once this had been checked it would be easier to test the actions of the circuit.

14.2 Bench Testing PI-D Circuit

Once the PI-D circuit had been completed and was initially tested, it was then bench tested so as to enable a check to make sure all the control signals were being dealt with and controlled in the correct manner. As the PI-D circuitry, when mounted on the flying platform, would be operating under an irregular DC voltage sine wave that would be oscillating at a low frequency, it would be necessary for more reliable testing to mimic this during bench testing. Therefore it was decided that a signal of ± 2.5 volts at a frequency of 5 Hz should be used as this would correspond to the time constants setup for the integral and derivative modes. This would also allow easier analysis of the control waves and the controllers affects.

The test signal, from a signal generator, was connected to the input of the PI-D controller and at the required stages was measured so as to analyse the wave signals produced. The complete results from this test are present in *Appendix 11*. It was found during testing that the waveform effects occurring in the integral and derivative sections were more difficult to determine using a sine wave. It was therefore decided that a 5 Hz square wave would be more appropriate. The final output from the system when this signal is passed through it, is demonstrated in *Figure 22*.

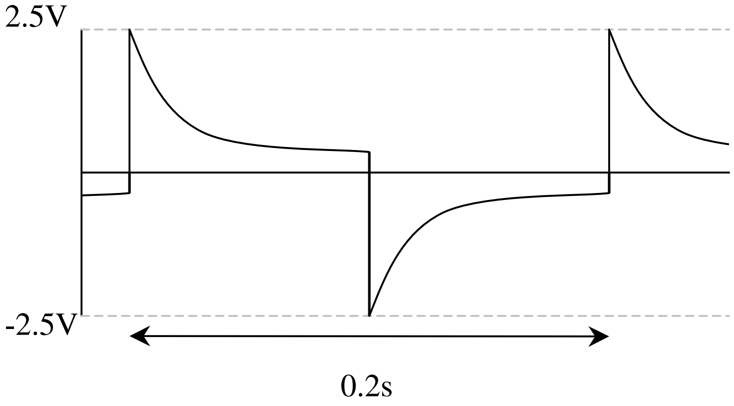


Figure 22: PI-D Controller Output Signal

It found that all the components exhibited the expected operation for this control system. It also made clearer that the frequency of the platform would have a large impact on the output from the control signals as both the integral section and the derivative section changed when the frequency was altered. This type of change was expected as discussed in *Section 10.6*.

14.3 Bench Testing PD Circuit

The testing of this circuit was also done with an input from a signal generator of ± 2.5 volts using a 5 Hz square wave. The final output from this system was similar to that of the PI-D wave this is because in that circuit the integral portion has very little effect on the output of the system. However the main difference was that this output was required to be between 0-5V. This circuit also demonstrated the required wave signals at each section of the testing.

14.4 Bench Testing Control / PWM Interface

This circuit was tested slightly differently to the previous two. A signal generator was used to simulate the input from the stability control system and a power supply was used to input a voltage from the height control. This was used as it could be increased and decreased making it easier to check that the circuit was producing the correct wave movements. This circuit also demonstrated the required wave signals and gave a voltage output between 0-5 V which could be transmitted as required to the pulse wave modulator.

14.5 Testing of Combined Systems

Once the system had been bench tested the input to the stability control was attached to the output of the inclinometer from the IMU. The control values were set at some arbitrary values and the output scalar was set so a final output of ± 2.5 volts was produced.

The IMU was rotated about the required axis and a corresponding signal was produced from the output of the PI-D circuit. It would be difficult to check whether the signal that was output was of the correct magnitude as it just resembled a linear DC voltage which, when the angle was tilted one way, the voltage increased and vice versa. It was discovered when performing these tests that the signal started to drift away for the central point depending on the movement of the IMU. It was decided that a circuit would need to be designed so as to reset the control system every time the IMU crossed the 0 degrees line [58].

15.0 Discussion and Recommendations

Unfortunately, due to time constraints and various breakages within the system it could not be determined weather the complete system would function as a whole. Further tests are required so as to ascertain whether the complete system will collectively work on the final flying platform but at this stage it was impossible to determine the complete effectiveness of the system. This is due to a variety of problems in each of the project areas, it is hoped that these problems can be overcome after the hand in of this report and further progress will be made. This will need to include complete fan testing and power supply using the generator [59], single axis testing on the platform and then a complete dual axis testing and tethered flight.

15.1 Management

Working as a group, a large amount was achieved in a short period of time and the project was pushed a lot closer to fulfilling the goal of making an autonomous flying platform. This was achieved due to the hard working nature of the majority of the group members, although unfortunately there were some problems and, it was found, that in some instances other members of the group had to take on additional tasks so as to allow the continual movement of the project. It has been found that a strong leader is needed within the group so as to enable deadlines to be set and completed and to carry on the momentum through out the project. It is recommended that future years try to follow a professional approach to their management and set clearly defined objectives early on. It is also suggested that along with a treasurer, a secretary and a chairperson, an official manger for the project should be appointed as this would leave the running of the meetings to the chairperson and would allow the manger to observe the running of the group. It is also advisable to set up an area of web space where all documentation can be saved and accessed by the group members as it was found to reduce the amount of time in finding the relevant information.

15.2 Control

The task of designing and developing a control system to be placed on to the flying platform has been completed and can effectively alter the input signals to the required output. Unfortunately, as mentioned in testing, due to operational problems within the project the control values could not be tested so as to evaluate their effectiveness at controlling the stability or the height of the flying platform.

The drifting of the actual control system was able to be reduced by using a high precision amplifier and by following the recommended alterations to reduce the effects of drift on the circuit. Another problem with the circuits is the integral and derivative modes as these are very frequency dependant and when the platform moves away from the pre-set frequency due to unexpected disturbances this could cause problems with the reliability of the control system.

It is recommended that to have a completely competent control system across the entire range of operation, digital control should be considered. The analysis of other systems has shown that most UAV's use digital control as it does not work directly on real time and it can be programmed to use predictive control, making the problem of time delays solved. After completion of the design and development for the control system it is clear that the digital controller could improve the overall system, as although the analogue system proved effective, it only allowed the system to work over a small range of values, and as the structure will be dynamic it will cause the platform to stray away form the intended linear regions where the set values would be effective. Digital control could allow the system to compute accurately over a range of different variables. Time constants and control values could be varied so as the system would use the required values depending on the situation of the platform.

The use of a digital control system would also allow the decrease of electronic components making the circuitry ultimately lighter, this would also simplify the actual circuit. The main hurdle with the use of digital control will be that it needs a very advanced control system which may require specialist knowledge or increased learning, but once this has been devised the control software can be placed on to a microprocessor and should allow a more reliable and adaptable piece of control for both the stability and the height.

Unfortunately, the final values of the control system could not be produced as there were still too many unknowns to enable an accurate calculation for the system. This is generally down to unknown quantities such as mass and the placement of that mass on the platform. It was discovered at the end of the analysis of the height control that it would be extremely difficult to produce a completely stable system it was therefore found that the best way to solve this would be to use a P-D control system. Due to time constraints this system was unable to be constructed.

This year's project did not take into account the yaw of the platform but it was felt that this section was not critical to the initial aim of enabling a platform to hover autonomously. It was considered however that the counter rotation of the fans would enable the platform to have less movement in this axis. It was discovered at the end of the analysis of the height control, that it would be extremely difficult to produce a completely stable system it was therefore found that the best way to solve this would be to use a P-D control system.

15.3 Sensors

The development of the sensors was vastly improved during this project. A clear signal was produced that allowed the testing of the control section. There is still development required in the processing of these signals, as algorithms are required so as to allow the signals which will be output to be compensated with the effects of other axes. Also additional development needs to be considered into the calculation of the actual position of the flying platform, compared to its initial starting point. As the IMU outputs a digital data stream it may be easier and more beneficial if the algorithms for the compensation of the system were developed in a digital circuit.

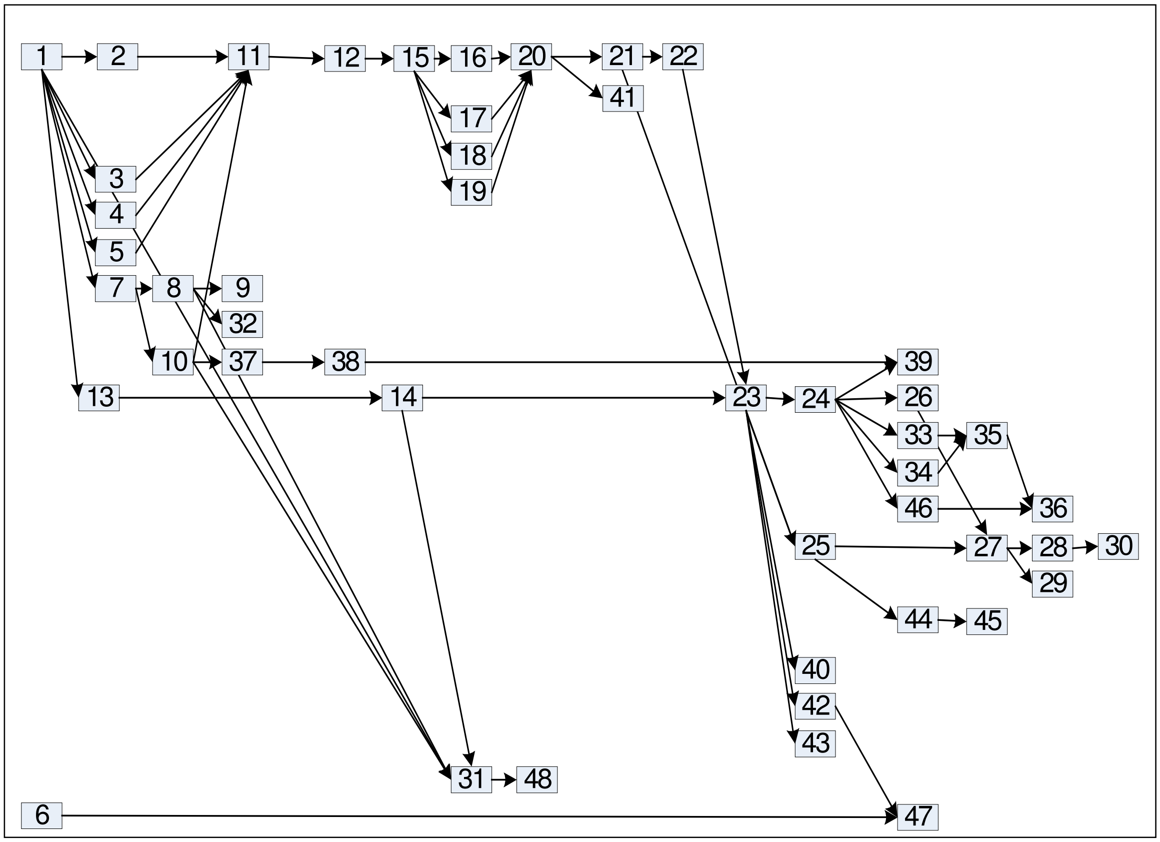
16.0 Conclusion

The flying platform project 2004 has been able to improve on the previous years attempts and has been able to reach a point where the development of an onboard power supply is near accomplishment and the control system has been developed with the improvement of an IMU sensor system. Unfortunately problems occurred in every aspect of the project from time delays to a range of operational breakages. There are still areas that need to be complete but hope to solve on the completion of the report.

To bring this project together a wide range of disciplines had to be put into action, this meant that all the members in the group had to improve there understanding of the system and apply it in areas to which they had only a basic knowledge of, if any at all. Due to time constraints the final accomplishment to fly an autonomous platform has not been completed but vast improvements have been made to allow further development in the hope that this aim will ultimately be achieved.

Appendix 1: PERT Chart

Appendix 1: PERT Chart



1, Read Previous Years Reports
2, Research IC Engines
3, Research Batteries
4, Research Dynamos
5, Research Central Fan
6, Research Fuzzy Logic
7, Make Fans Safe
8, Test Electric Fans
9, Determine Time Response Of Fan
10, Determine Average / Peak Power In Controllable Thrust Range
11, Determine System
12, Come Up With Table Of Systems
13, Determine PDS
14, Determine Time Of Flight / Payload Trade off
15, Refine Mathematical Model
16, Determine Moment Of Inertia
17, Determine Gyroscopic Forces
18, Determine Max. Differential Thrust
19, Determine Response Time Of Control Fans
20, Determine Control Mathematical Model Parameters
21, Determine Control Process / Loop By Mat lab Or Spreadsheets
22, Determine Control Response Time Of Platform
23, Select Optimum System
24, Buy Propulsion System Components
25, Determine Control Theory Parameters
26, Test Propulsion System Parts And Compare with Data sheets
27, Electronic Design Of Control System
28, Bench Testing
29, Modify Structure
30, Fly Platform
31, Research Generators
32, Construction Of Voltage to PWM Converter
33, Research Radio Control Mechanisms
34, Investigate Start up Engine Procedure
35, Radio Control Circuitry Construction
36, Construct Start up Engine Procedure
37, Determine Motor and Dynamo Spec
38, Determine Motor Testing Procedure
39, Test Motors
40, Research Load Levelling
41, Check Mathematical Model
42, Research Engine Control Systems
43, Examine Pendulum Effect On Control System
44, Research into Control Theory Stability
45, Design a spread sheet to link all data
46, Research IC Engine Running Operations
47, Research into IC Engine Control with Fuzzy Logic
48, Chose A Second Engine / Generator

Appendix 2: Financial Accounts

This includes:

2.1 Treasurers Report
2.2 Platform Accounts
2.3 Section Breakdown
2.4 Balance Sheets
2.5 Proposed Expenditure
2.6 General Expenditure Form
2.7 Proposal Form

Appendix 2: Financial Accounts

2.1 Treasurers Report

There was an initial budget given to the group of £500 which was open for change dependent on the progress of the project. This was needed to be added to due to the cost of some of the larger items that were required; the final budget negotiated was £1,550. A set of balance sheets were drawn up a preset dates through out the project so as to allow the group to have knowledge to the projects finances.

A system was devised to allow the purchase of products to be properly put forward to the treasurer and the group along with proposal forms for more expensive items. The proposal for purchase of more expensive items was put forward at meetings for the approval of the group. The majority of the purchases were made through the Engineering Department accounts; the project was also given a separate account with the Exeter University Engineering Stores which was settled on completion of the project.

Table 1 below shows an outline of costs for each section of the project. The miscellaneous section includes components and rigs that were used in various parts of the project along with more general construction components.

Section	**Cost**
Control	£186.23
Propulsion	£526.68
Power Generation	£901.63
Structure	£88.40
Miscellaneous	£334.89
Total Cost	£2,143.71

Table 1: Section Cost and Total Cost

Unfortunately due to extra purchases of unforeseen item such as a new engine for the generator the project went above the allocated budget by £593.71. This was however approved for purchase by the project supervisors before the transition was made. The balance sheets show the current financial situation at that moment in time. The product expenditure shows the amount of money which was spent throughout the project in 2003/04 it has taken into account the depreciation of the components which was estimated to be approximately 15%.

2.2 Platform Accounts

2.2 Platform Accounts

2.3 Section Breakdown

2.3 Section Breakdown

2.3 Section Breakdown

2.3 Section Breakdown

2.3 Section Breakdown

2.4 Balance Sheets

2.4 Balance Sheets

2.5 Proposed Expenditure

2.6 General Expenditure Form

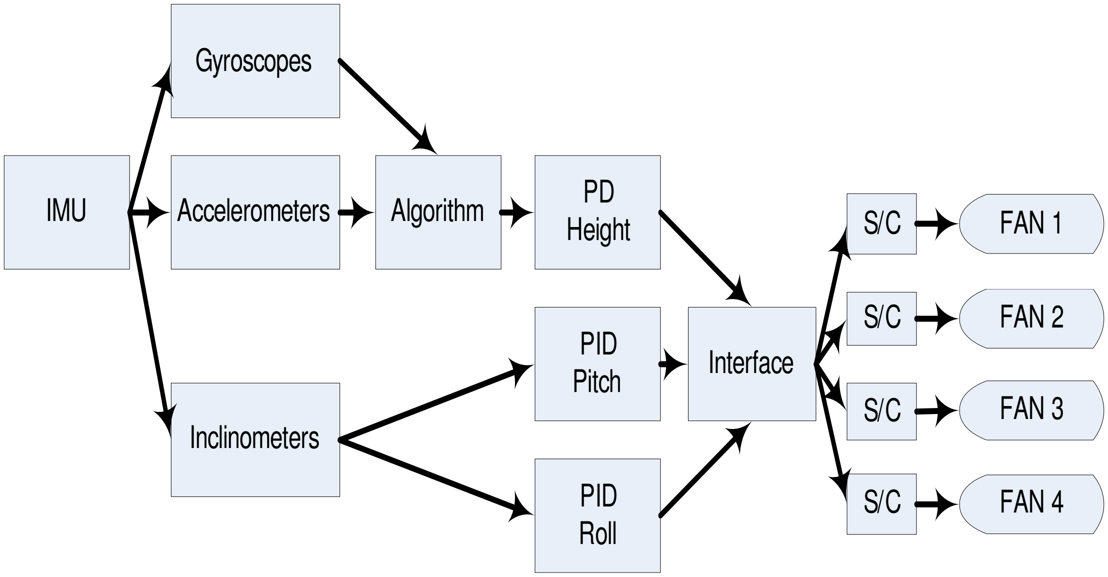
2.7 Proposal Form

Appendix 3: System Analysis

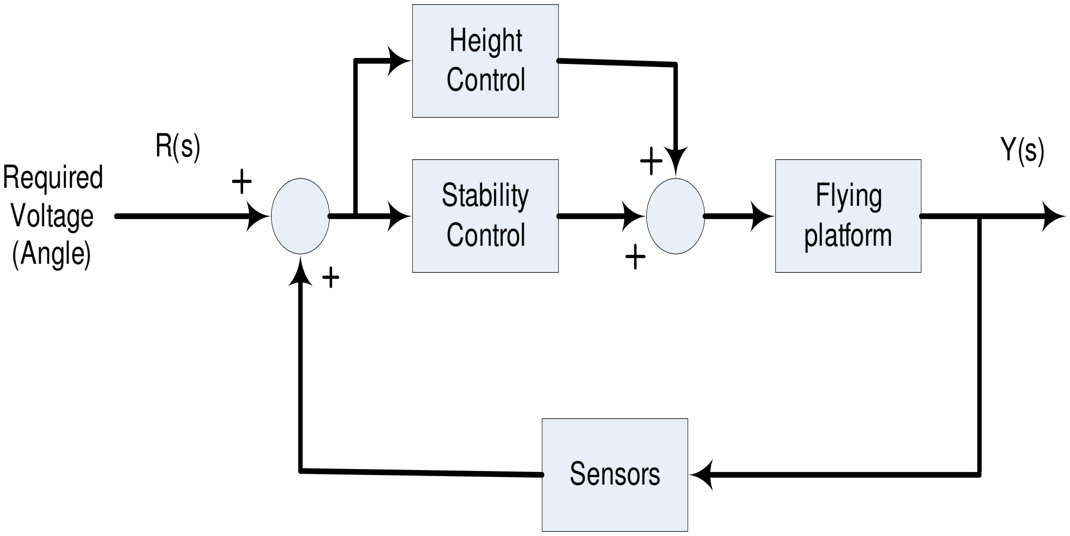
This includes:

Appendix 3: System Analysis

3.1 Control System Approach



3.2 Control Flow Diagram



Appendix 4: Digital Control Techniques

This includes:

4.1 Predictive Control
4.2 Fuzzy Logic

Appendix 4: Digital Control Techniques

4.1 Predictive PID Controllers

Abstract: The design of the predictive PID controllers with similar features to a model-based predictive controller (MPC). Simulation studies for a number of different systems show that the controller performance is close to an MPC type control algorithm.

PID tuning can be done using a variety of algorithms such as the Ziegler and Nichols methods, and the coon method. These algorithms are based either on time domain or frequency response characteristics of the system [1, 2].

This paper presents a predictive PID controller, which has important characteristics of MPC. A PID controller is defined by using a bank of M parallel conventional PID controllers, where M is the prediction horizon as shown in **Fig. 1.** All the controllers have the same three terms, proportional, integral and derivative gains.

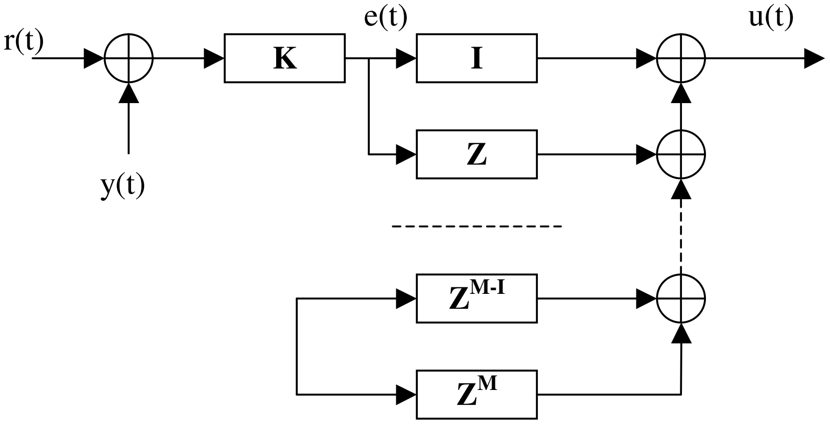


Fig. 1.

The *i*th PID controller operates on the predicted error at time (t + i). The controller can easily incorporate the future set point and dead time of the process for a general system with no restriction on the system order or any need for approximating the process time-delay.

Conventional PID controller configuration is as follows:

$$u(t)=\left[k_p e(t)+k_i\sum_{i=1}^{t} e(t)+k_d\left[e(t)-e(t-1)\right]\right]$$

For a predictive controller a control signal needs to be considered, which is calculated by adding the output of M PID controllers, where *i*th PID operates an the error at future time (t + i). M can be considered as the prediction horizon of the controller. Such a control signal is defined by:

$$\Delta u(t) = K\sum_{i=0}^{M} e(t+i) = K\sum_{i=0}^{M}\left[r(t+i) - y(t+i)\right]$$

To implement the proposed controller the values of the error over the horizon are required.

Stability Issues:

The stability region is defined as the space over the parameters k_p, k_i and k_d where the closed loop system is stable and this needs to be generated for different values of M.

It is important to analyse the factors which limit the stability and performance of the control systems. A more detailed stability analysis and performance limitation can be pursued (Astrom [3]).

Constraint handling:

The constraints acting on a process can originate from amplitude limits in the control signal, slew rate limits of the actuator and limits on the output signals. This can cause the output of the controller to be different to the input to the system. When this takes place the controller output does not drive the system as expected and so the states of the controller are wrongly updated.

Conclusion:

The proposed controller can deal with future set points. The controller reduces to the same structure as a PI or PID controller for both first and second order systems, respectively. One of the main advantages of the proposed controller is that it can be used with systems of any order. It has also been shown that input constraints could be handled by making the PID gains adaptive according to the solution of a QP problem [4].

References:

1, Astrom, K.J and Hagglund, T.A.: “PID controllers: theory, design and tuning”
2, Gorez, R and Calcev, G “A survey of PID auto tuning methods”
3, Astrom, K.J.: “limitation on control system performance”
4, Katebi, M.R., and Johnson, M.A.: “Predictive control designs for large scale systems” pp.421-426

4.2 Fuzzy Logic

What is Fuzzy logic?

In this context, fuzzy logic is a problem-solving control system methodology that lends itself to implementation in systems ranging from simple, small, embedded micro-controllers to large, networked, multi-channel PC or workstation-based data acquisition and control systems. It can be implemented in hardware, software, or a combination of both. Fuzzy logic provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing input information. Fuzzy logic's approach to control problems mimics how a person would make decisions, only much faster.

How it works

Fuzzy logic requires some numerical parameters in order to operate such as what is considered significant error and significant rate-of-change-of-error, but exact values of these numbers are usually not critical unless very responsive performance is required in which case empirical tuning would determine them. For example, a simple temperature control system could use a single temperature feedback sensor whose data is subtracted from the command signal to compute "error" and then time-differentiated to yield the error slope or rate-of-change-of-error, hereafter called "error-dot". Error might have units of degs F and a small error considered to be 2F while a large error is 5F. The "error-dot" might then have units of degs/min with a small error-dot being 5F/min and a large one being 15F/min. These values don't have to be symmetrical and can be "tweaked" once the system is operating in order to optimise performance. Generally, fuzzy logic is so forgiving that the system will probably work the first time without any tweaking.

Reasons for fuzzy logic

Fuzzy logic offers several unique features that make it a particularly good choice for many control problems.

1) It is inherently robust since it does not require precise, noise-free inputs and can be programmed to fail safely if a feedback sensor quits or is destroyed. The output control is a smooth control function despite a wide range of input variations.

2) Since the fuzzy logic controller processes user-defined rules governing the target control system, it can be modified and tweaked easily to improve or drastically alter system performance. New sensors can easily be incorporated into the system simply by generating appropriate governing rules.

3) Fuzzy logic is not limited to a few feedback inputs and one or two control outputs, nor is it necessary to measure or compute rate-of-change parameters in order for it to be implemented. Any sensor data that provides some indication of a system's actions and reactions is sufficient. This allows the sensors to be inexpensive and imprecise thus keeping the overall system cost and complexity low.

4) Because of the rule-based operation, any reasonable number of inputs can be processed (1-8 or more) and numerous outputs (1-4 or more) generated, although defining the rule base quickly becomes complex if too many inputs and outputs are chosen for a single implementation since rules defining their interrelations must also be defined. It would be better to break the control system into smaller chunks and use several smaller fuzzy logic controllers distributed on the system, each with more limited responsibilities.

5) Fuzzy logic can control non-linear systems that would be difficult or impossible to model mathematically. This opens doors for control systems that would normally be deemed unfeasible for automation.

Steps to implementing fuzzy logic

1) Define the control objectives and criteria: What am I trying to control? What do I have to do to control the system? What kind of response do I need? What are the possible (probable) system failure modes?

2) Determine the input and output relationships and choose a minimum number of variables for input to the fuzzy logic engine (typically error and rate-of-change-of-error).

3) Using the rule-based structure of fuzzy logic, break the control problem down into a series of IF X AND Y THEN Z rules that define the desired system output response for given system input conditions. The number and complexity of rules depends on the number of input parameters that are to be processed and the number fuzzy variables associated with each parameter. If possible, use at least one variable and its time derivative. Although it is possible to use a single, instantaneous error parameter without knowing its rate of change, this cripples the system's ability to minimize overshoot for a step inputs.

4) Create fuzzy logic membership functions that define the meaning (values) of Input/Output terms used in the rules.

5) Create the necessary pre- and post-processing fuzzy logic routines if implementing in software, otherwise program the rules into the fuzzy logic hardware engine.

6) Test the system, evaluate the results, tune the rules and membership functions, and retest until satisfactory results are obtained.

References

Neural Network and Fuzzy logic applications in C/C++, Stephen T.Welstead, 1994, USA

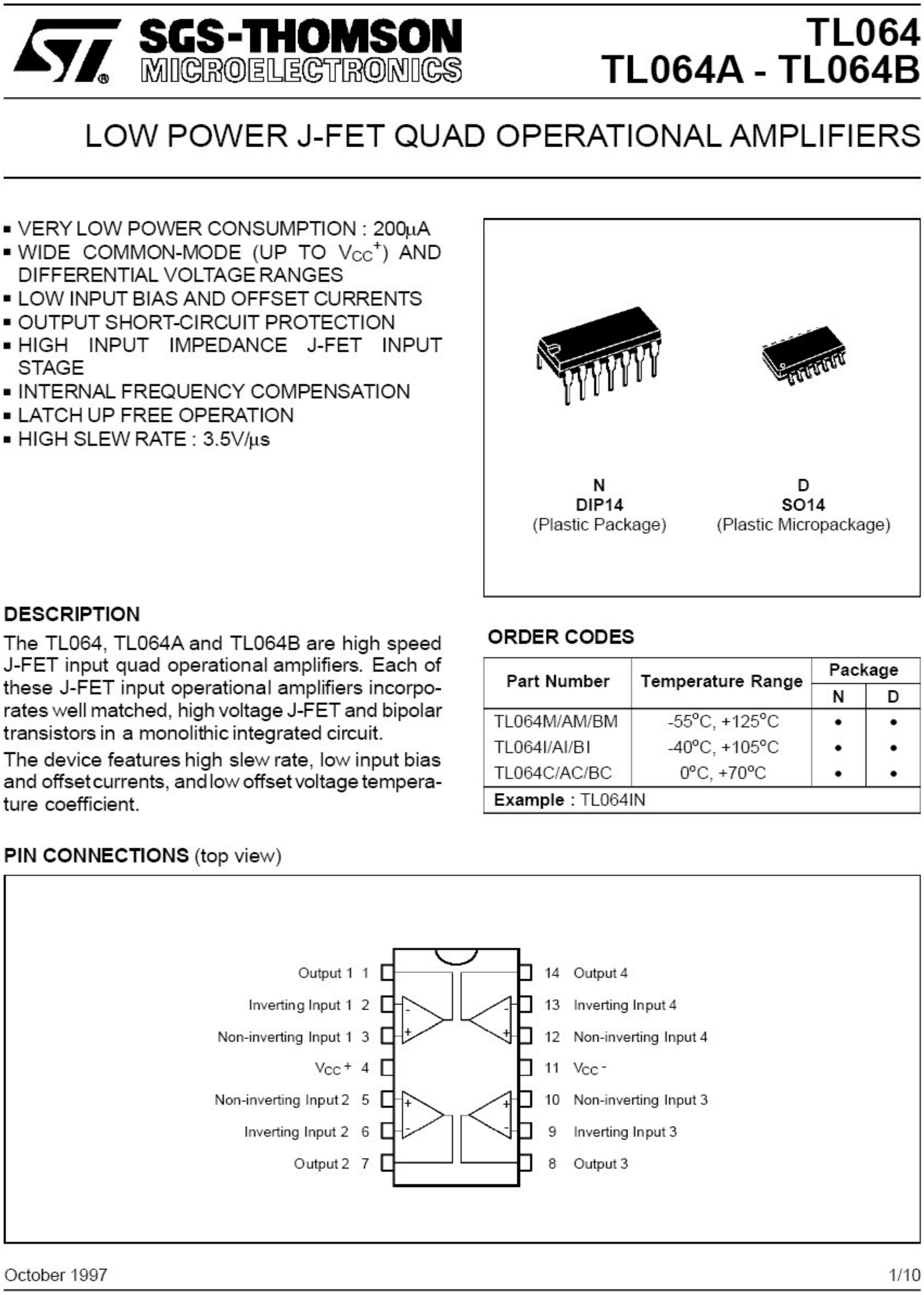
Modern Control Technology, Christopher T.Kilian, 1996, USA, pg 397-406

Appendix 5: Data Sheets

This Includes:

5.1 TL064 Operational Amplifier
5.2 OP-97 High Precision Operational Amplifier

5.1 TL064 Operational Amplifier



SGS-THOMSON
MICROELECTRONICS

TL064
TL064A - TL064B

LOW POWER J-FET QUAD OPERATIONAL AMPLIFIERS

- VERY LOW POWER CONSUMPTION : 200µA
- WIDE COMMON-MODE (UP TO V_{CC}^{+}) AND DIFFERENTIAL VOLTAGE RANGES
- LOW INPUT BIAS AND OFFSET CURRENTS
- OUTPUT SHORT-CIRCUIT PROTECTION
- HIGH INPUT IMPEDANCE J-FET INPUT STAGE
- INTERNAL FREQUENCY COMPENSATION
- LATCH UP FREE OPERATION
- HIGH SLEW RATE : 3.5V/µs

N
DIP14
(Plastic Package)

D
SO14
(Plastic Micropackage)

DESCRIPTION

The TL064, TL064A and TL064B are high speed J-FET input quad operational amplifiers. Each of these J-FET input operational amplifiers incorporates well matched, high voltage J-FET and bipolar transistors in a monolithic integrated circuit.

The device features high slew rate, low input bias and offset currents, and low offset voltage temperature coefficient.

ORDER CODES

Part Number	Temperature Range	Package	
		N	D
TL064M/AM/BM	-55°C, +125°C	•	•
TL064I/AI/BI	-40°C, +105°C	•	•
TL064C/AC/BC	0°C, +70°C	•	•

Example : TL064IN

PIN CONNECTIONS (top view)

Output 1 1
Inverting Input 1 2
Non-inverting Input 1 3
V_{CC} + 4
Non-inverting Input 2 5
Inverting Input 2 6
Output 2 7
14 Output 4
13 Inverting Input 4
12 Non-inverting Input 4
11 V_{CC} -
10 Non-inverting Input 3
9 Inverting Input 3
8 Output 3

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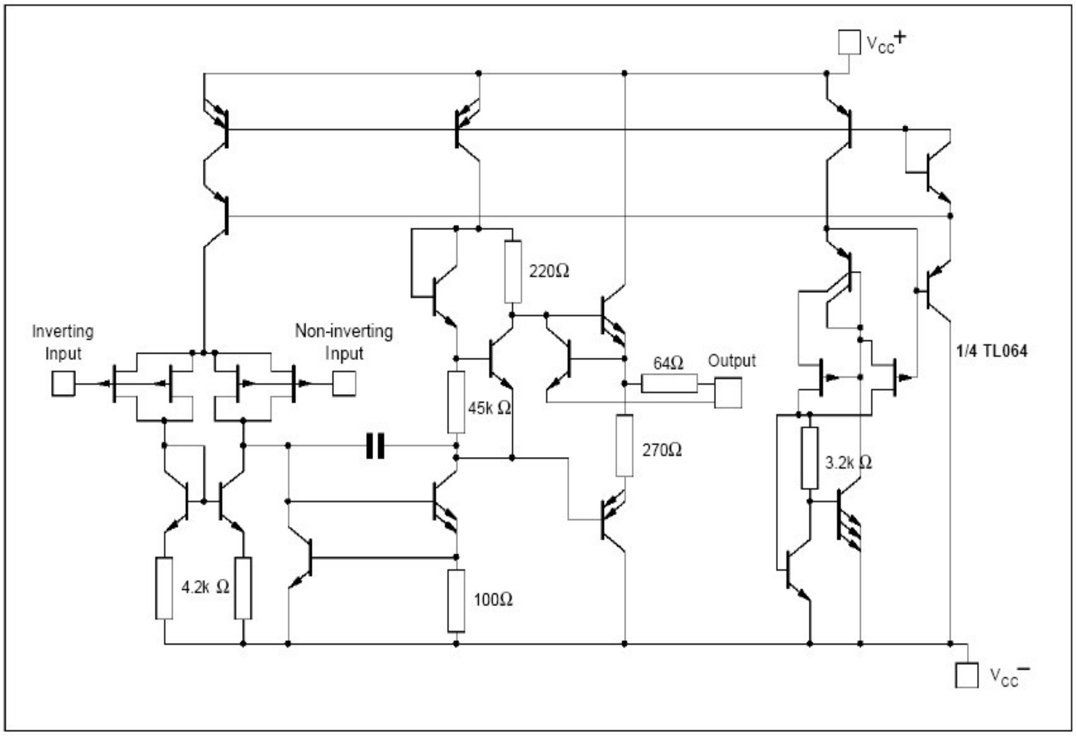
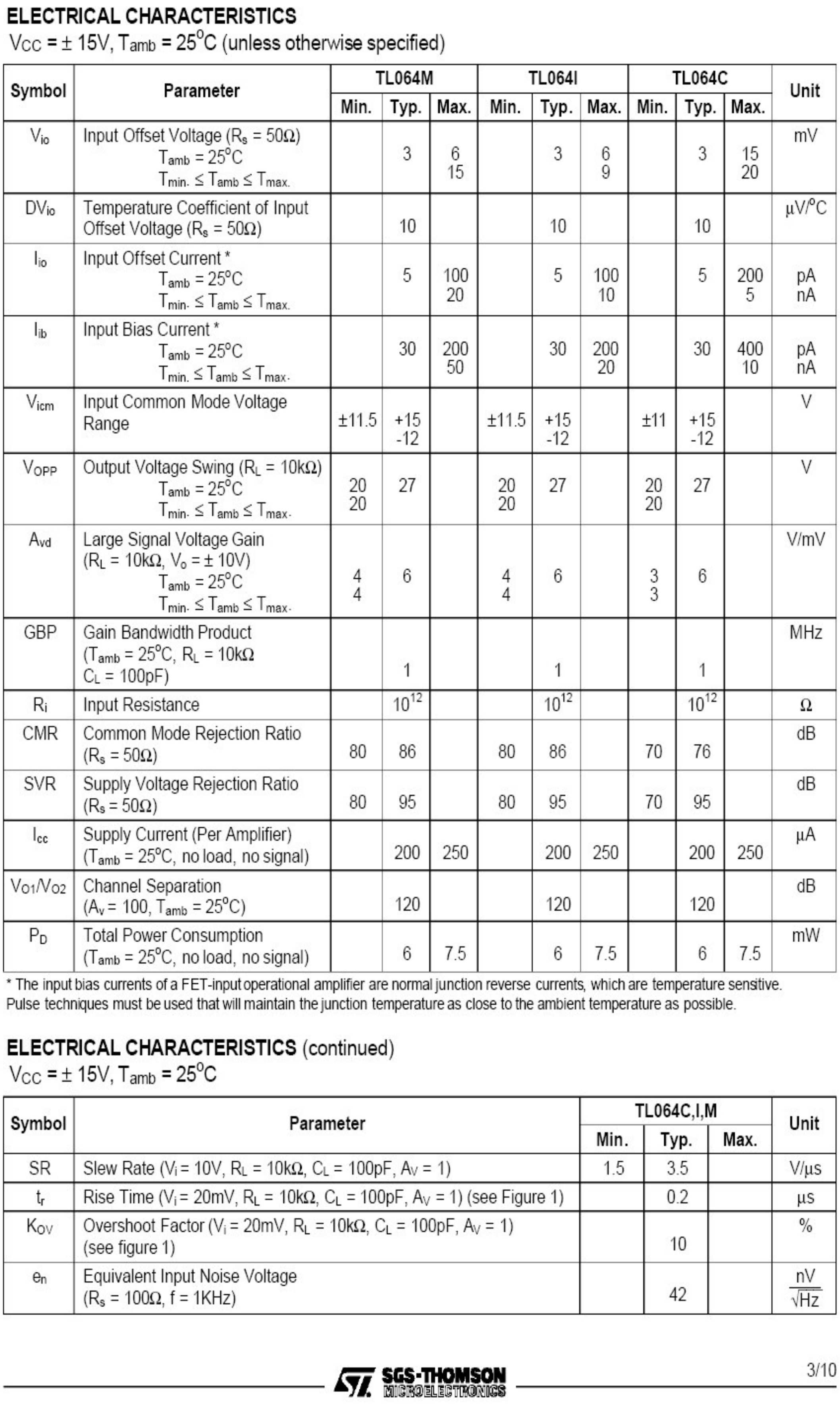
SCHEMATIC DIAGRAM



MAXIMUM RATINGS

Symbol	Parameter	TL064M,AM,BM	TL064I,AI,BI	TL064C,AC,BC	Unit
V_{CC}	Supply Voltage - (note 1)	±18	±18	±18	V
V_i	Input Voltage - (note 3)	±15	±15	±15	V
V_{id}	Differential Input Voltage - (note 2)	±30	±30	±30	V
P_{tot}	Power Dissipation	680	680	680	mW
	Output Short-Circuit Duration (Note 4)	Infinite	Infinite	Infinite	
T_{oper}	Operating Free-Air Temperature Range	-55 to +125	-40 to +105	0 to +70	°C
T_{stg}	Storage Temperature Range	-65 to +150	-65 to +150	-65 to +150	°C

Notes :
1. All voltage values, except differential voltage, are with respect to the zero reference level (ground) of the supply voltages where the zero reference level is the midpoint between V_{CC}^+ and V_{CC}^-.
2. Differential voltages are the non-inverting input terminal with respect to the inverting input terminal.
3. The magnitude of the input voltage must never exceed the magnitude of the supply voltage or 15 volts, whichever is less.
4. The output may be shorted to ground or to either supply. Temperature and/or supply voltages must be limited to ensure that the dissipation rating is not exceeded.



ELECTRICAL CHARACTERISTICS

V_{CC} = ± 15V, T_{amb} = 25°C (unless otherwise specified)

Symbol	Parameter	TL064M			TL064I			TL064C			Unit
		Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.	
V_{io}	Input Offset Voltage (R_s = 50Ω) T_{amb} = 25°C $T_{min.} \leq T_{amb} \leq T_{max.}$		3	6 15		3	6 9		3	15 20	mV
DV_{io}	Temperature Coefficient of Input Offset Voltage (R_s = 50Ω)		10			10			10		μV/°C
I_{io}	Input Offset Current * T_{amb} = 25°C $T_{min.} \leq T_{amb} \leq T_{max.}$		5	100 20		5	100 10		5	200 5	pA nA
I_{ib}	Input Bias Current * T_{amb} = 25°C $T_{min.} \leq T_{amb} \leq T_{max.}$		30	200 50		30	200 20		30	400 10	pA nA
V_{icm}	Input Common Mode Voltage Range	±11.5	+15 -12		±11.5	+15 -12		±11	+15 -12		V
V_{OPP}	Output Voltage Swing (R_L = 10kΩ) T_{amb} = 25°C $T_{min.} \leq T_{amb} \leq T_{max.}$	20 20	27		20 20	27		20 20	27		V
A_{vd}	Large Signal Voltage Gain (R_L = 10kΩ, V_o = ± 10V) T_{amb} = 25°C $T_{min.} \leq T_{amb} \leq T_{max.}$	4 4	6		4 4	6		3 3	6		V/mV
GBP	Gain Bandwidth Product (T_{amb} = 25°C, R_L = 10kΩ C_L = 100pF)		1			1			1		MHz
R_i	Input Resistance		10^{12}			10^{12}			10^{12}		Ω
CMR	Common Mode Rejection Ratio (R_s = 50Ω)	80	86		80	86		70	76		dB
SVR	Supply Voltage Rejection Ratio (R_s = 50Ω)	80	95		80	95		70	95		dB
I_{cc}	Supply Current (Per Amplifier) (T_{amb} = 25°C, no load, no signal)		200	250		200	250		200	250	μA
V_{O1}/V_{O2}	Channel Separation (A_v = 100, T_{amb} = 25°C)		120			120			120		dB
P_D	Total Power Consumption (T_{amb} = 25°C, no load, no signal)		6	7.5		6	7.5		6	7.5	mW

* The input bias currents of a FET-input operational amplifier are normal junction reverse currents, which are temperature sensitive. Pulse techniques must be used that will maintain the junction temperature as close to the ambient temperature as possible.

ELECTRICAL CHARACTERISTICS (continued)

V_{CC} = ± 15V, T_{amb} = 25°C

Symbol	Parameter	TL064C,I,M			Unit
		Min.	Typ.	Max.	
SR	Slew Rate (V_i = 10V, R_L = 10kΩ, C_L = 100pF, A_V = 1)	1.5	3.5		V/μs
t_r	Rise Time (V_i = 20mV, R_L = 10kΩ, C_L = 100pF, A_V = 1) (see Figure 1)		0.2		μs
K_{OV}	Overshoot Factor (V_i = 20mV, R_L = 10kΩ, C_L = 100pF, A_V = 1) (see figure 1)		10		%
e_n	Equivalent Input Noise Voltage (R_s = 100Ω, f = 1KHz)		42		$\frac{nV}{\sqrt{Hz}}$

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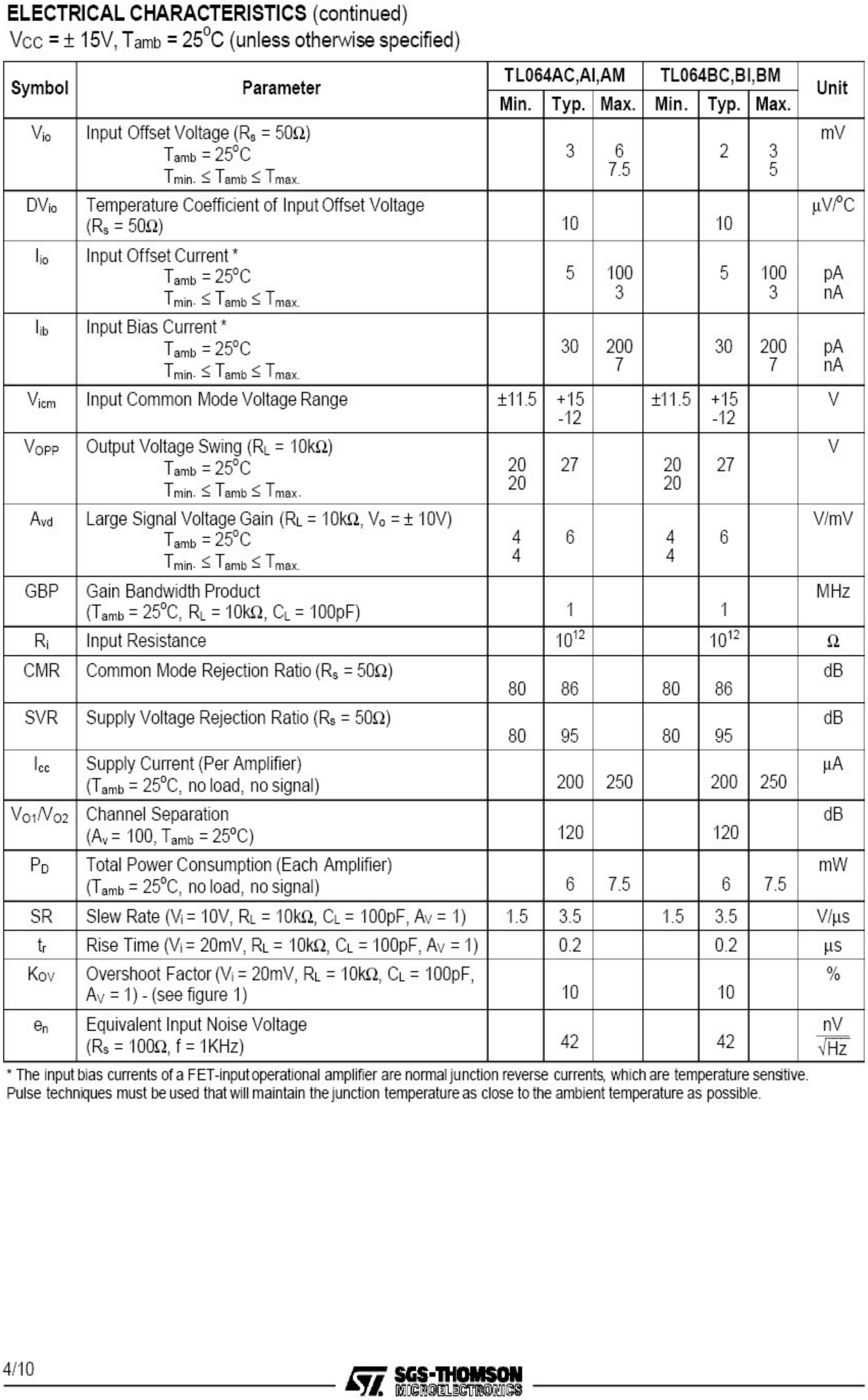


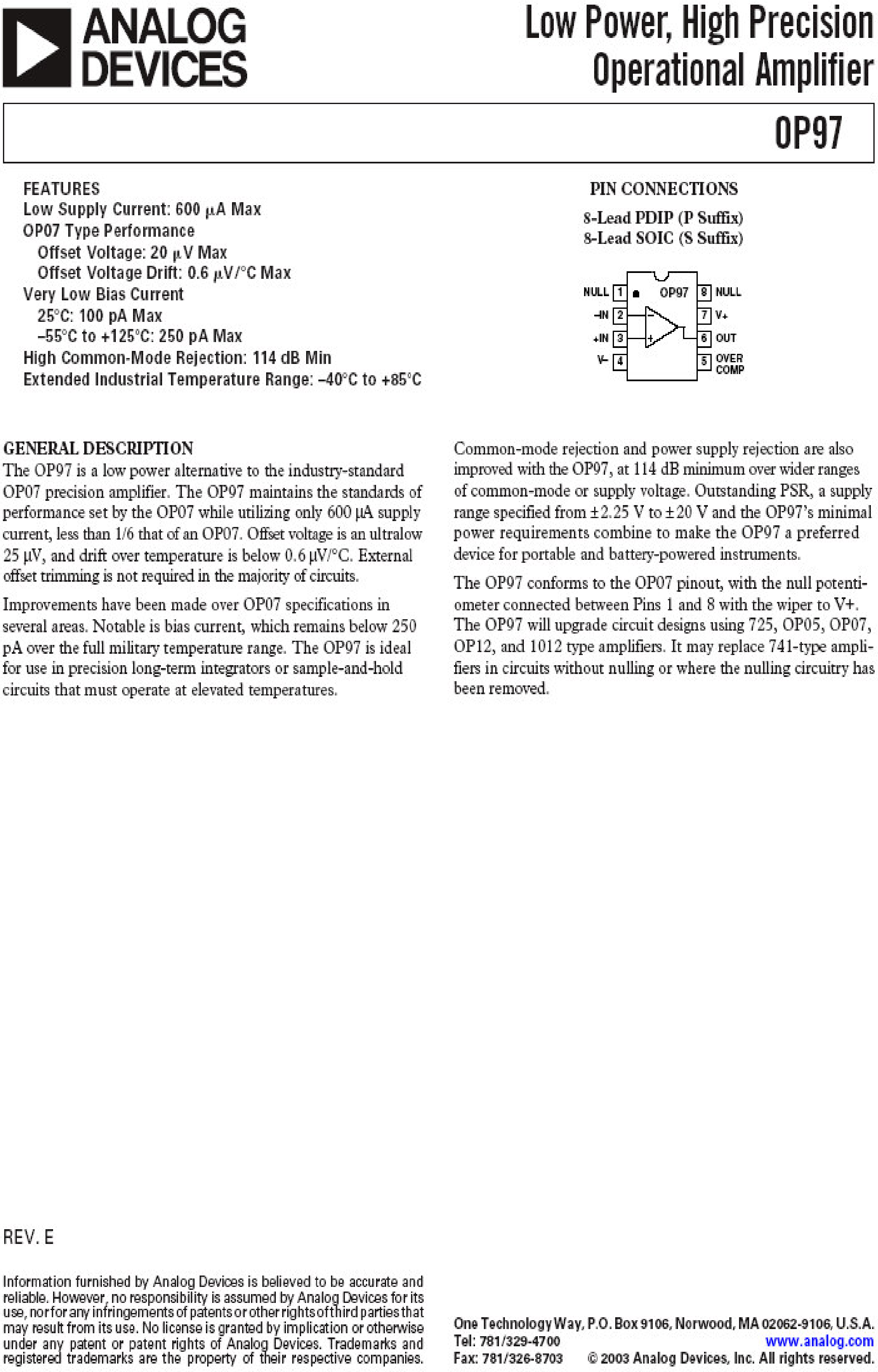
ELECTRICAL CHARACTERISTICS (continued)

V_{CC} = ± 15V, T_{amb} = 25°C (unless otherwise specified)

Symbol	Parameter	TL064AC,AI,AM			TL064BC,BI,BM			Unit
		Min.	Typ.	Max.	Min.	Typ.	Max.	
V_{io}	Input Offset Voltage (R_s = 50Ω) T_{amb} = 25°C $T_{min.} \le T_{amb} \le T_{max.}$		3	6 7.5		2	3 5	mV
DV_{io}	Temperature Coefficient of Input Offset Voltage (R_s = 50Ω)		10			10		µV/°C
I_{io}	Input Offset Current * T_{amb} = 25°C $T_{min.} \le T_{amb} \le T_{max.}$		5	100 3		5	100 3	pA nA
I_{ib}	Input Bias Current * T_{amb} = 25°C $T_{min.} \le T_{amb} \le T_{max.}$		30	200 7		30	200 7	pA nA
V_{icm}	Input Common Mode Voltage Range	±11.5	+15 -12		±11.5	+15 -12		V
V_{OPP}	Output Voltage Swing (R_L = 10kΩ) T_{amb} = 25°C $T_{min.} \le T_{amb} \le T_{max.}$	20 20	27		20 20	27		V
A_{vd}	Large Signal Voltage Gain (R_L = 10kΩ, V_o = ± 10V) T_{amb} = 25°C $T_{min.} \le T_{amb} \le T_{max.}$	4 4	6		4 4	6		V/mV
GBP	Gain Bandwidth Product (T_{amb} = 25°C, R_L = 10kΩ, C_L = 100pF)		1			1		MHz
R_i	Input Resistance		10^{12}			10^{12}		Ω
CMR	Common Mode Rejection Ratio (R_s = 50Ω)	80	86		80	86		dB
SVR	Supply Voltage Rejection Ratio (R_s = 50Ω)	80	95		80	95		dB
I_{cc}	Supply Current (Per Amplifier) (T_{amb} = 25°C, no load, no signal)		200	250		200	250	µA
V_{O1}/V_{O2}	Channel Separation (A_v = 100, T_{amb} = 25°C)		120			120		dB
P_D	Total Power Consumption (Each Amplifier) (T_{amb} = 25°C, no load, no signal)		6	7.5		6	7.5	mW
SR	Slew Rate (V_i = 10V, R_L = 10kΩ, C_L = 100pF, A_V = 1)	1.5	3.5		1.5	3.5		V/µs
t_r	Rise Time (V_i = 20mV, R_L = 10kΩ, C_L = 100pF, A_V = 1)		0.2			0.2		µs
K_{OV}	Overshoot Factor (V_i = 20mV, R_L = 10kΩ, C_L = 100pF, A_V = 1) - (see figure 1)		10			10		%
e_n	Equivalent Input Noise Voltage (R_s = 100Ω, f = 1KHz)		42			42		$\frac{nV}{\sqrt{Hz}}$

* The input bias currents of a FET-input operational amplifier are normal junction reverse currents, which are temperature sensitive. Pulse techniques must be used that will maintain the junction temperature as close to the ambient temperature as possible.

5.2 OP-97 High Precision Operational Amplifier



ANALOG DEVICES

Low Power, High Precision Operational Amplifier

OP97

FEATURES
- Low Supply Current: 600 µA Max
- OP07 Type Performance
  - Offset Voltage: 20 µV Max
  - Offset Voltage Drift: 0.6 µV/°C Max
- Very Low Bias Current
  - 25°C: 100 pA Max
  - –55°C to +125°C: 250 pA Max
- High Common-Mode Rejection: 114 dB Min
- Extended Industrial Temperature Range: –40°C to +85°C

PIN CONNECTIONS

8-Lead PDIP (P Suffix)
8-Lead SOIC (S Suffix)

GENERAL DESCRIPTION

The OP97 is a low power alternative to the industry-standard OP07 precision amplifier. The OP97 maintains the standards of performance set by the OP07 while utilizing only 600 µA supply current, less than 1/6 that of an OP07. Offset voltage is an ultralow 25 µV, and drift over temperature is below 0.6 µV/°C. External offset trimming is not required in the majority of circuits.

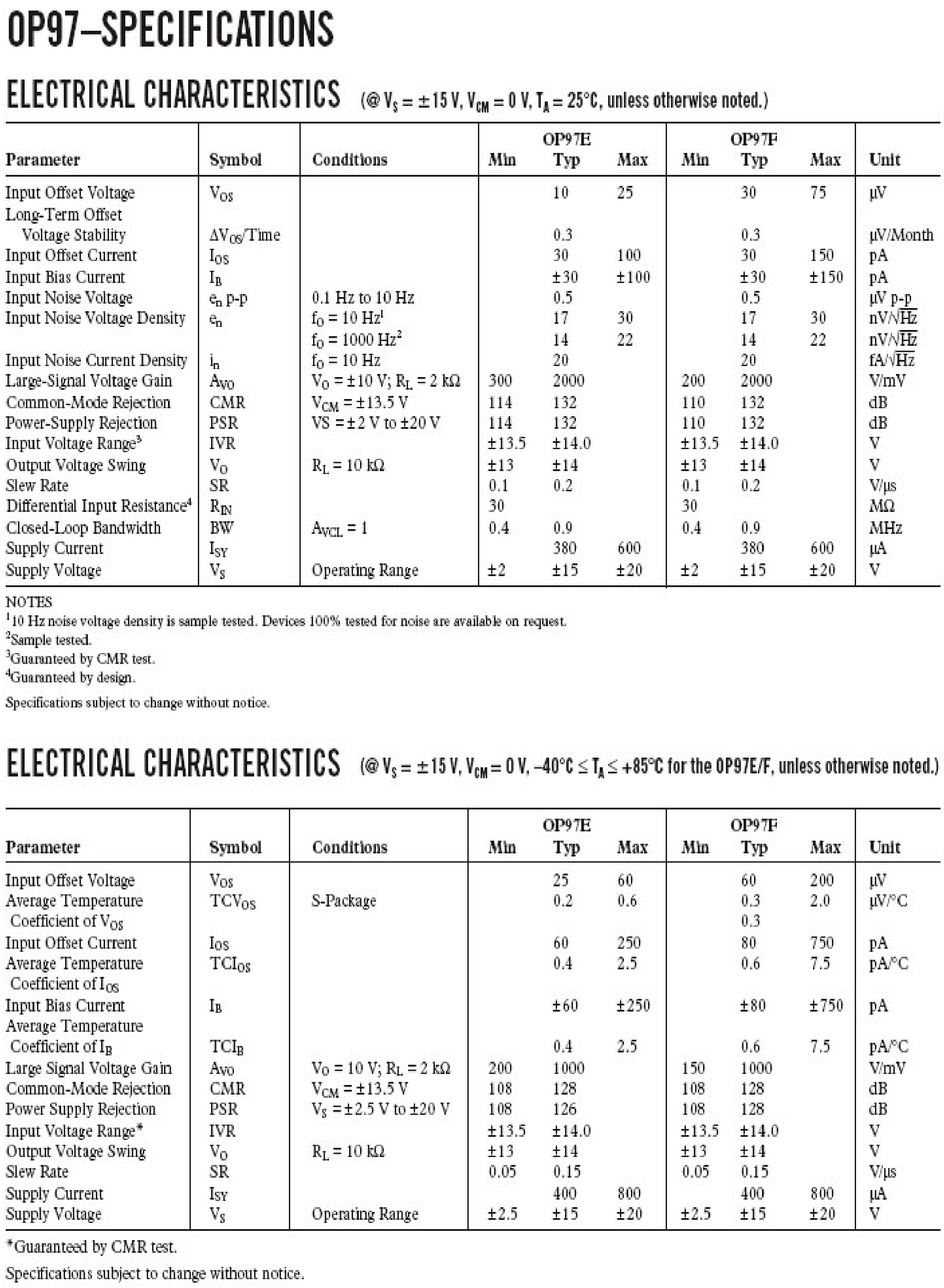
Improvements have been made over OP07 specifications in several areas. Notable is bias current, which remains below 250 pA over the full military temperature range. The OP97 is ideal for use in precision long-term integrators or sample-and-hold circuits that must operate at elevated temperatures.

Common-mode rejection and power supply rejection are also improved with the OP97, at 114 dB minimum over wider ranges of common-mode or supply voltage. Outstanding PSR, a supply range specified from ±2.25 V to ±20 V and the OP97's minimal power requirements combine to make the OP97 a preferred device for portable and battery-powered instruments.

The OP97 conforms to the OP07 pinout, with the null potentiometer connected between Pins 1 and 8 with the wiper to V+. The OP97 will upgrade circuit designs using 725, OP05, OP07, OP12, and 1012 type amplifiers. It may replace 741-type amplifiers in circuits without nulling or where the nulling circuitry has been removed.

REV. E

One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
Tel: 781/329-4700 www.analog.com
Fax: 781/326-8703



OP97–SPECIFICATIONS

ELECTRICAL CHARACTERISTICS (@ $V_S = \pm 15$ V, $V_{CM} = 0$ V, $T_A = 25°C$, unless otherwise noted.)

Parameter	Symbol	Conditions	OP97E			OP97F			Unit
			Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	V_{OS}			10	25		30	75	µV
Long-Term Offset Voltage Stability	ΔV_{OS}/Time			0.3			0.3		µV/Month
Input Offset Current	I_{OS}			30	100		30	150	pA
Input Bias Current	I_B			±30	±100		±30	±150	pA
Input Noise Voltage	e_n p-p	0.1 Hz to 10 Hz		0.5			0.5		µV p-p
Input Noise Voltage Density	e_n	$f_O = 10$ Hz[1]		17	30		17	30	nV/√Hz
		$f_O = 1000$ Hz[2]		14	22		14	22	nV/√Hz
Input Noise Current Density	i_n	$f_O = 10$ Hz		20			20		fA/√Hz
Large-Signal Voltage Gain	A_{VO}	$V_O = \pm 10$ V; $R_L = 2$ kΩ	300	2000		200	2000		V/mV
Common-Mode Rejection	CMR	$V_{CM} = \pm 13.5$ V	114	132		110	132		dB
Power-Supply Rejection	PSR	VS = ±2 V to ±20 V	114	132		110	132		dB
Input Voltage Range[3]	IVR		±13.5	±14.0		±13.5	±14.0		V
Output Voltage Swing	V_O	$R_L = 10$ kΩ	±13	±14		±13	±14		V
Slew Rate	SR		0.1	0.2		0.1	0.2		V/µs
Differential Input Resistance[4]	R_{IN}		30			30			MΩ
Closed-Loop Bandwidth	BW	$A_{VCL} = 1$	0.4	0.9		0.4	0.9		MHz
Supply Current	I_{SY}			380	600		380	600	µA
Supply Voltage	V_S	Operating Range	±2	±15	±20	±2	±15	±20	V

NOTES

[1] 10 Hz noise voltage density is sample tested. Devices 100% tested for noise are available on request.

[2] Sample tested.

[3] Guaranteed by CMR test.

[4] Guaranteed by design.

Specifications subject to change without notice.

ELECTRICAL CHARACTERISTICS (@ $V_S = \pm 15$ V, $V_{CM} = 0$ V, $-40°C \le T_A \le +85°C$ for the OP97E/F, unless otherwise noted.)

Parameter	Symbol	Conditions	OP97E			OP97F			Unit
			Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	V_{OS}			25	60		60	200	µV
Average Temperature Coefficient of V_{OS}	TCV_{OS}	S-Package		0.2	0.6		0.3 0.3	2.0	µV/°C
Input Offset Current	I_{OS}			60	250		80	750	pA
Average Temperature Coefficient of I_{OS}	TCI_{OS}			0.4	2.5		0.6	7.5	pA/°C
Input Bias Current	I_B			±60	±250		±80	±750	pA
Average Temperature Coefficient of I_B	TCI_B			0.4	2.5		0.6	7.5	pA/°C
Large Signal Voltage Gain	A_{VO}	$V_O = 10$ V; $R_L = 2$ kΩ	200	1000		150	1000		V/mV
Common-Mode Rejection	CMR	$V_{CM} = \pm 13.5$ V	108	128		108	128		dB
Power Supply Rejection	PSR	$V_S = \pm 2.5$ V to ±20 V	108	126		108	128		dB
Input Voltage Range*	IVR		±13.5	±14.0		±13.5	±14.0		V
Output Voltage Swing	V_O	$R_L = 10$ kΩ	±13	±14		±13	±14		V
Slew Rate	SR		0.05	0.15		0.05	0.15		V/µs
Supply Current	I_{SY}			400	800		400	800	µA
Supply Voltage	V_S	Operating Range	±2.5	±15	±20	±2.5	±15	±20	V

*Guaranteed by CMR test.

Specifications subject to change without notice.

ABSOLUTE MAXIMUM RATINGS[1]

Supply Voltage	±20 V
Input Voltage[2]	±20 V
Differential Input Voltage[3]	±1 V
Differential Input Current[3]	±10 mA
Output Short-Circuit Duration	Indefinite
Operating Temperature Range	
OP97E, OP97F (P, S)	–40°C to +85°C
Storage Temperature Range	–65°C to +150°C
Junction Temperature Range	–65°C to +150°C
Lead Temperature (Soldering, 60 sec)	300°C

Package Type	θ_{JA}[4]	θ_{JC}	Unit
8-Lead PDIP (P)	103	43	°C/W
8-Lead SOIC (S)	158	43	°C/W

NOTES

[1] Absolute maximum ratings apply to both DICE and packaged parts, unless otherwise noted.

[2] For supply voltages less than ±20 V, the absolute maximum input voltage is equal to the supply voltage.

[3] The OP97's inputs are protected by back-to-back diodes. Current-limiting resistors are not used in order to achieve low noise. Differential input voltages greater than 1 V will cause excessive current to flow through the input protection diodes unless limiting resistance is used.

[4] θ_{JA} is specified for worst-case mounting conditions, i.e., θ_{JA} is specified for device in socket for PDIP package; θ_{JA} is specified for device soldered to printed circuit board for SOIC package.

ORDERING GUIDE

Model	Temperature Range	Package Description	Package Option*
OP97EP	–40°C to +85°C	8-Lead PDIP	N-8
OP97FP	–40°C to +85°C	8-Lead PDIP	N-8
OP97FS	–40°C to +85°C	8-Lead SOIC	R-8
OP97FS-REEL	–40°C to +85°C	8-Lead SOIC	R-8
OP97FS-REEL7	–40°C to +85°C	8-Lead SOIC	R-8

*For outline information, see Package Information section.

CAUTION

ESD (electrostatic discharge) sensitive device. Electrostatic charges as high as 4000 V readily accumulate on the human body and test equipment and can discharge without detection. Although the OP97 features proprietary ESD protection circuitry, permanent damage may occur on devices subjected to high energy electrostatic discharges. Therefore, proper ESD precautions are recommended to avoid performance degradation or loss of functionality.

WARNING!

ESD SENSITIVE DEVICE

APPLICATION INFORMATION

The OP97 is a low power alternative to the industry-standard precision op amp, the OP07. The OP97 may be substituted directly into OP07, OP77, 725, 112/312, and 1012 sockets with improved performance and/or less power dissipation and may be inserted into sockets conforming to the 741 pinout if nulling circuitry is not used. Generally, nulling circuitry used with earlier generation amplifiers is rendered superfluous by the OP97's extremely low offset voltage and may be removed without compromising circuit performance.

Extremely low bias current over the full military temperature range makes the OP97 attractive for use in sample-and-hold amplifiers, peak detectors, and log amplifiers that must operate over a wide temperature range. Balancing input resistances is not necessary with the OP97. Offset voltage and TCV_{OS} are degraded only minimally by high source resistance, even when unbalanced.

The input pins of the OP97 are protected against large differential voltage by back-to-back diodes. Current-limiting resistors are not used so that low noise performance is maintained. If differential voltages above ± 1 V are expected at the inputs, series resistors must be used to limit the current flow to a maximum of 10 mA. Common-mode voltages at the inputs are not restricted and may vary over the full range of the supply voltages used.

The OP97 requires very little operating headroom about the supply rails and is specified for operation with supplies as low as ±2 V. Typically, the common-mode range extends to within 1 V of either rail. The output typically swings to within 1 V of the rails when using a 10 kΩ load.

Offset nulling is achieved utilizing the same circuitry as an OP07. A potentiometer between 5 kΩ and 100 kΩ is connected between Pins 1 and 8 with the wiper connected to the positive supply. The trim range is between 300 μV and 850 μV, depending upon the internal trimming of the device.

AC PERFORMANCE

The OP97's ac characteristics are highly stable over its full operating temperature range. Unity-gain small-signal response is shown in Figure 2. Extremely tolerant of capacitive loading on the output, the OP97 displays excellent response even with 1000 pF loads (Figure 3). In large-signal applications, the input protection diodes effectively short the input to the output during the transients if the amplifier is connected in the usual unity-gain configuration. The output enters short-circuit current limit, with the flow going through the protection diodes. Improved large-signal transient response is obtained by using a feedback resistor between the output and the inverting input. Figure 4 shows the large-signal response of the OP97 in unity gain with a 10 kΩ feedback resistor. The unity-gain follower circuit is shown in Figure 5.

The overcompensation pin may be used to increase the phase margin of the OP97 or to decrease gain-bandwidth product at gains greater than 10.

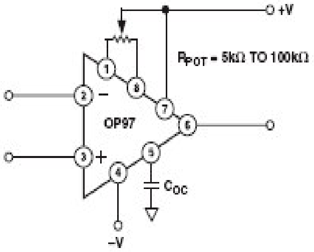


Figure 1. Optional Input Offset Voltage Nulling and Overcompensation Circuits

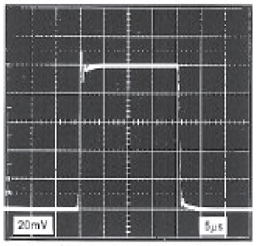


Figure 2. Small-Signal Transient Response (C_{LOAD} = 100 pF, A_{VCL} = 1)

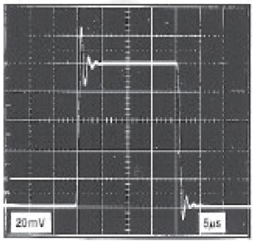


Figure 3. Small-Signal Transient Response (C_{LOAD} = 1000 pF, A_{VCL} = 1)

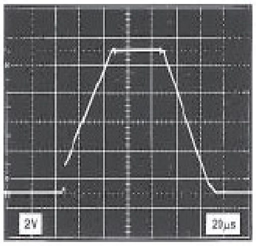


Figure 4. Large-Signal Transient Response (A_{VCL} = 1)

OP97

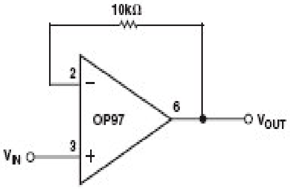


Figure 5. Unity-Gain Follower

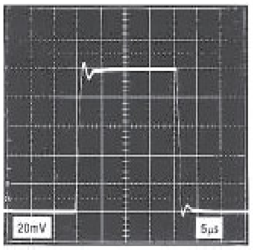


Figure 6. Small-Signal Transient Response with Over-compensation (C_{LOAD} = 1000 pF, A_{VCL} = 1, C_{OC} = 220 pF)

GUARDING AND SHIELDING

To maintain the extremely high input impedances of the OP97, care must be taken in circuit board layout and manufacturing. Board surfaces must be kept scrupulously clean and free of moisture. Conformal coating is recommended to provide a humidity barrier. Even a clean PC board can have 100 pA of leakage currents between adjacent traces, so that guard rings should be used around the inputs. Guard traces are operated at a voltage close to that on the inputs, so that leakage currents become minimal. In noninverting applications, the guard ring should be connected to the common-mode voltage at the inverting input (Pin 2). In inverting applications, both inputs remain at ground, so that the guard trace should be grounded. Guard traces should be made on both sides of the circuit board.

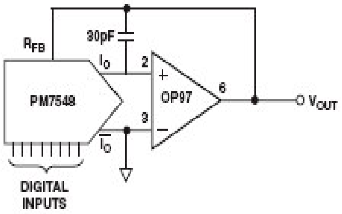


Figure 7. DAC Output Amplifier

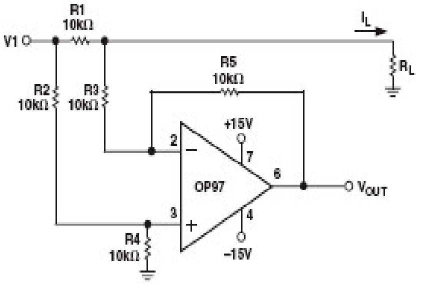


Figure 8. Current Monitor

High impedance circuitry is extremely susceptible to RF pickup, line frequency hum, and radiated noise from switching power supplies. Enclosing sensitive analog sections within grounded shields is generally necessary to prevent excessive noise pickup. Twisted-pair cable will aid in rejection of line frequency hum.

The OP97 is an excellent choice as an output amplifier for higher resolution CMOS DACs. Its tightly trimmed offset voltage and minimal bias current result in virtually no degradation of linearity, even over wide temperature ranges.

Figure 8 shows a versatile monitor circuit that can typically sense current at any point between the ±15 V supplies. This makes it ideal for sensing current in applications such as full bridge drivers where bidirectional current is associated with large common-mode voltage changes. The 114 dB CMRR of the OP97 makes the amplifier's contribution to common-mode error negligible, leaving only the error due to the resistor ratio inequality. Ideally, $R2/R4 = R3/R5$.

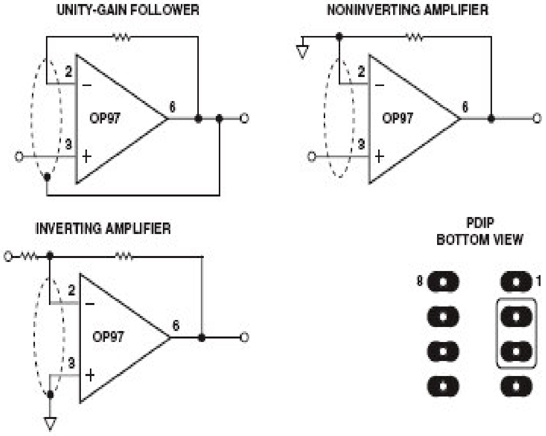


Figure 9. Guard Ring Layout and Connections

The digitally programmable gain amplifier shown in Figure 10 has 12-bit gain resolution with 10-bit gain linearity over the range of −1 to −1024. The low bias current of the OP97 maintains this linearity, while C1 limits the noise voltage bandwidth allowing accurate measurement down to microvolt levels.

DIGITAL IN	GAIN (Av)
4095	−1.00024
2048	−2
1024	−4
512	−8
256	−16
128	−32
64	−64
32	−128
16	−256
8	−512
4	−1024
2	−2048
1	−4096
0	Open Loop

Many high speed amplifiers suffer from less-than-perfect low frequency performance. A combination amplifier consisting of a high precision, slow device like the OP97 and a faster device such as the OP44 results in uniformly accurate performance from dc to the high frequency limit of the OP44, which has a gain-bandwidth product of 23 MHz. The circuit shown in Figure 11 accomplishes this, with the OP44 providing high frequency amplification and the OP97 operating on low frequency signals and providing offset correction. Offset voltage and drift of the circuit are controlled by the OP97.

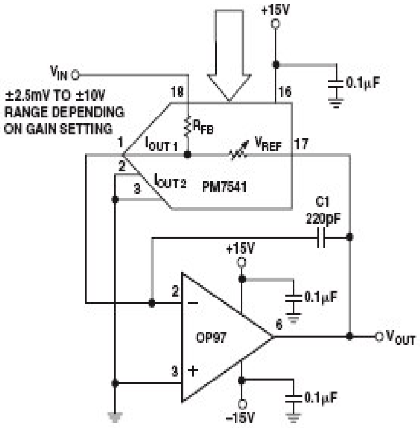


Figure 10. Precision Programmable Gain Amplifier

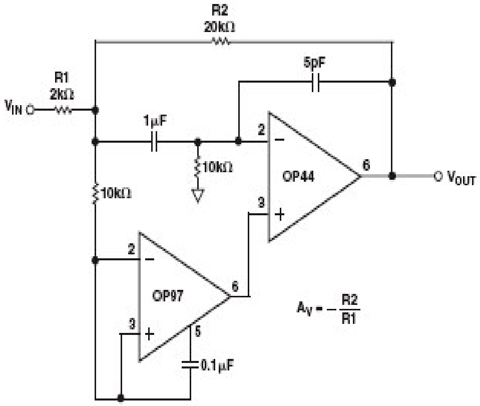


Figure 11. Combination High-Speed, Precision Amplifier

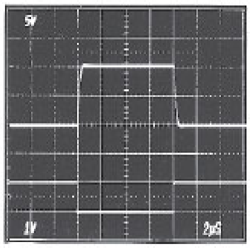


Figure 12. Combination Amplifier Transient Response

Appendix 6: Error Budget

Appendix 6: Error Budget for the Integrator

In error budget construction for the purpose of integrating a gyro the operational amplifiers bias errors are given as equivalent input accelerations. For this system it was found that the input voltage from the inclinometer would be 0.165 V/° with a maximum range of ± 93.87°.

When considering the systems error budget for an integrator the time constant needs to be known as this will set the values of the capacitor and resistor that will be used. The time constant for this system was set at 0.19s, which gave the capacitor value to be 2µF and t resistor value of 100kΩ.

I_{bias} Error:

The input bias error would be

$$\frac{I_{bias} \times R}{V_{Input}} = Error$$

V_{Input} = input voltage from the inclinometer

I_{OS} Error:

The input offset current will be:

$$\frac{I_{OS} \times R}{V_{Input}} = Error$$

V_{OS} Error:

The voltage offset error will be:

$$\frac{V_{OS}}{V_{Input}} = Error$$

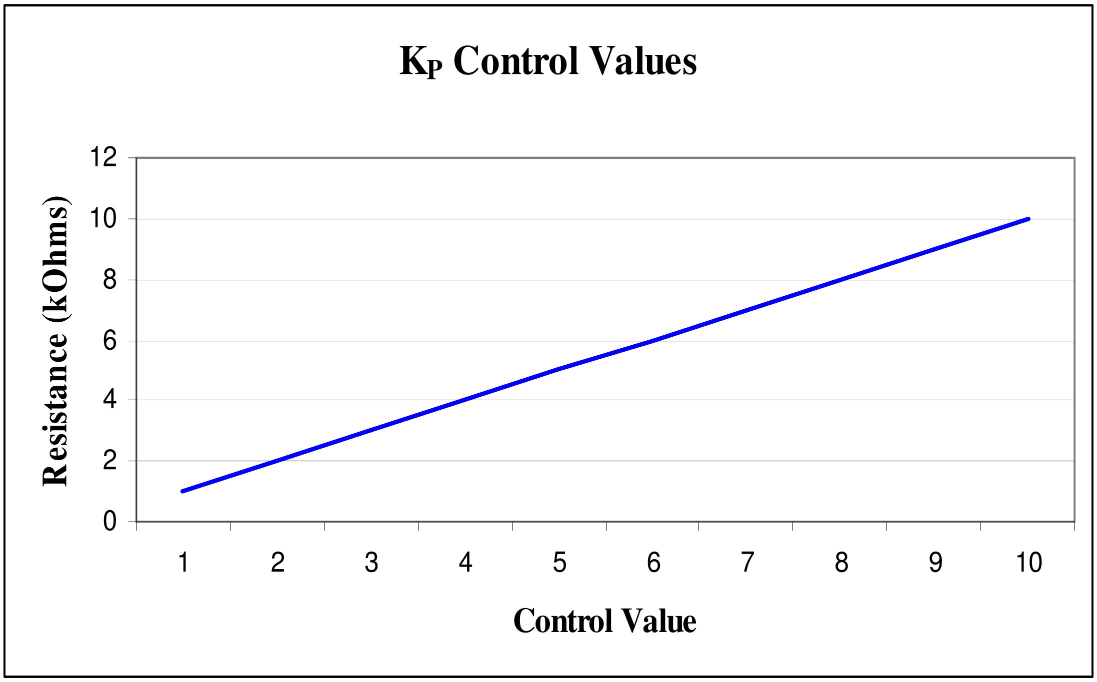
Several op-amps where tested using this error budget method and the results are shown below along with the costs of them, op-amps which have no costs are now out of stock.

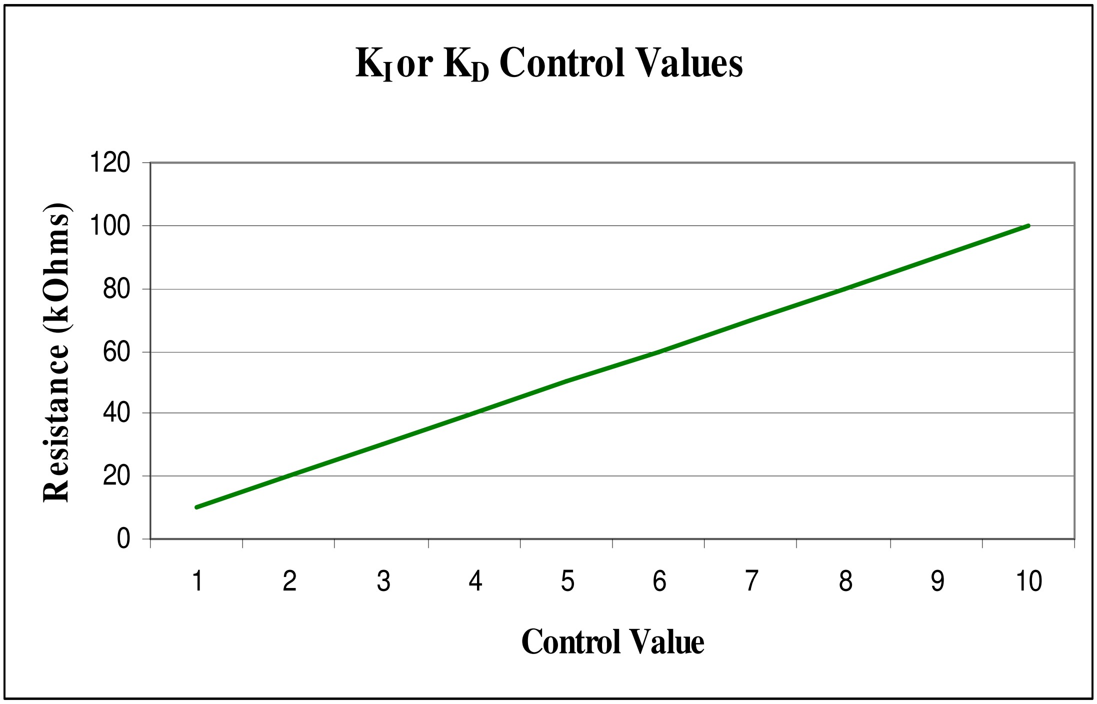
Op-Amp	I_{bias}	Error	I_{os}	Error	V_{os}	Error	Cost (£)
LM741	8E-08	0.075117	2E-08	0.018779	0.001	0.00939	0.33
OPA277	5E-10	0.000469	5E-10	0.000469	0.00001	9.39E-05	1.48
AD705	1E-10	9.39E-05	8E-11	7.51E-05	0.00005	0.000469	3.29
LT1884	1E-10	9.39E-05	1E-10	9.39E-05	0.000025	0.000235	-
LMC6084	1E-14	9.39E-09	5E-15	4.69E-09	0.00015	0.001408	3.01
HA5170	2E-11	1.88E-05	3E-12	2.82E-06	0.0001	0.000939	-
OP97	3E-11	2.82E-05	3E-11	2.82E-05	0.00001	9.39E-05	2.09

Appendix 7: Control Value Settings

Appendix 7: Control Value Settings

These values are based on the reference resistance being set at 10k =1.





Appendix 8: Circuit Diagrams

This Includes:

8.1 PI-D Controller
8.2 PD Controller
8.3 Control Interface

8.4 PI-D Controller

8.5 PD Controller

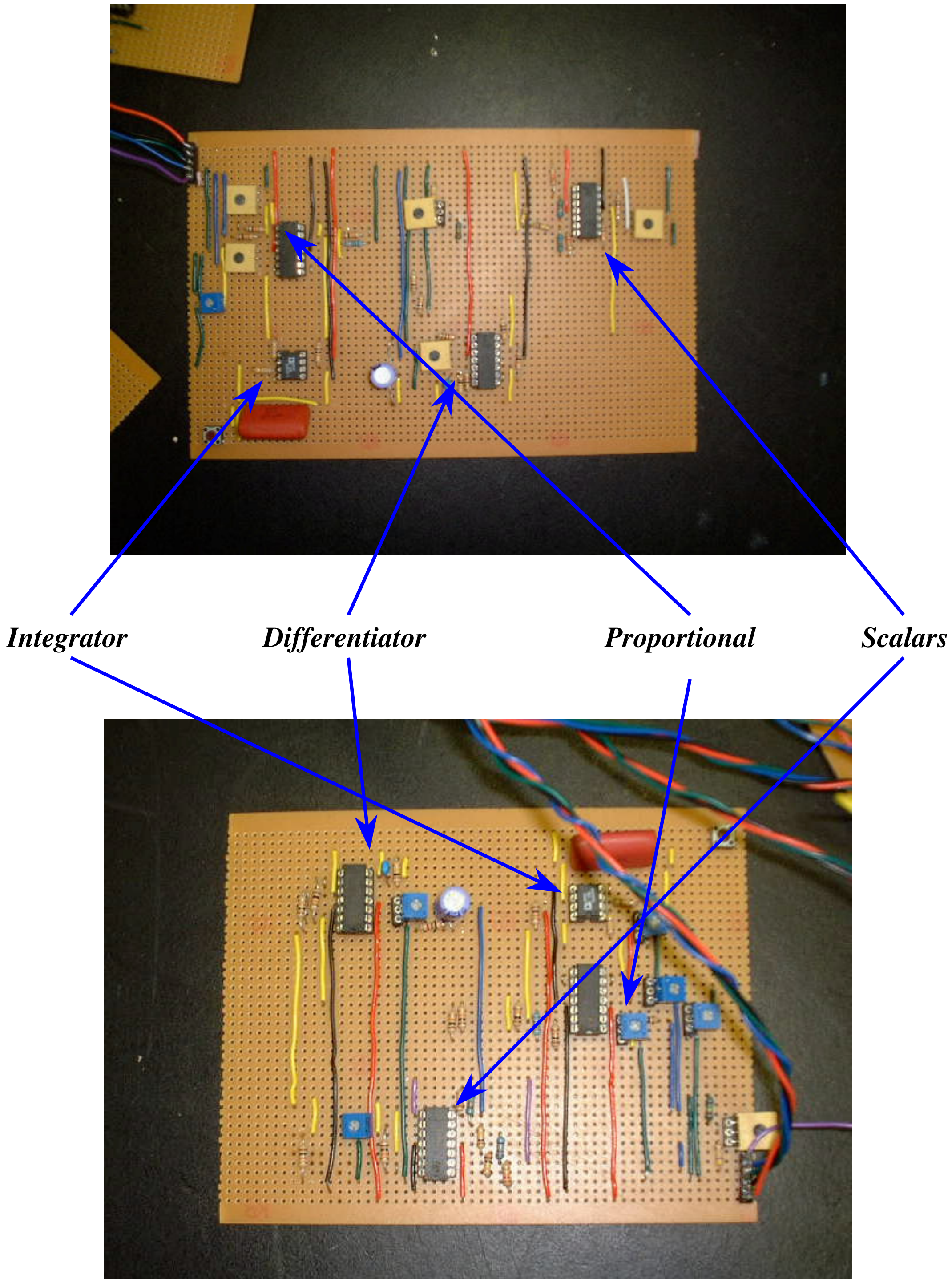
8.6 Control Interface

Appendix 9: Circuit Pictures

Appendix 9: Circuit Pictures

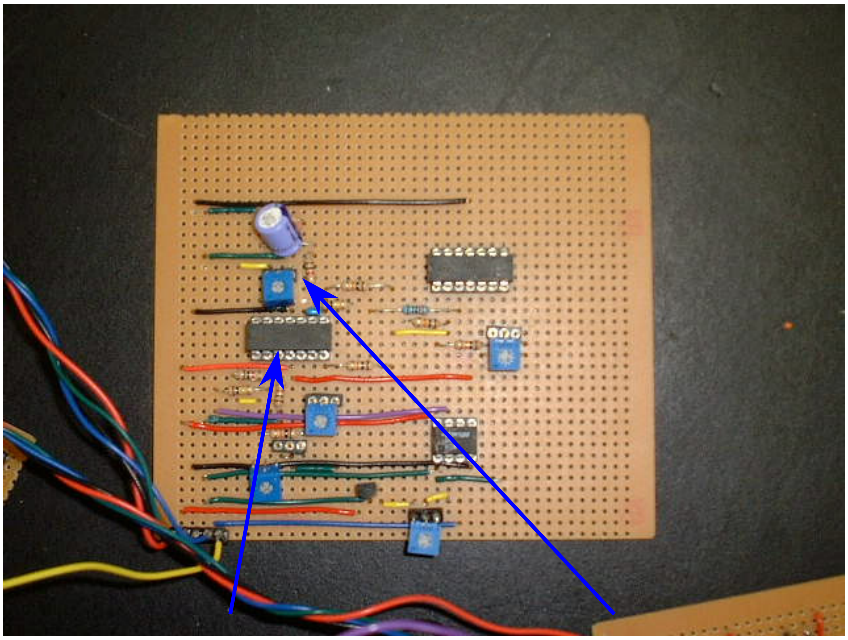
PI-D controller

PI-D Circuit 1



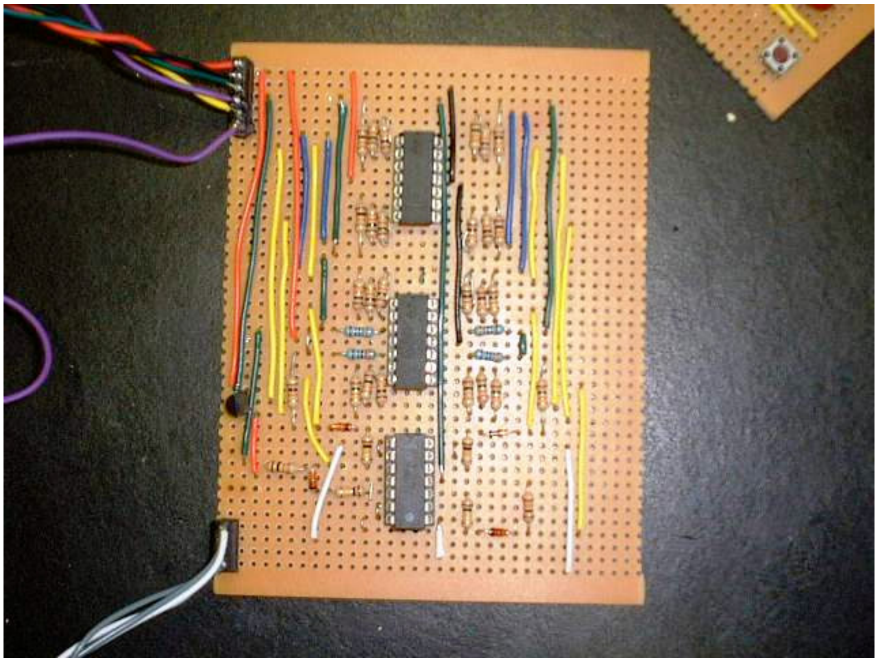
PI-D Circuit 2

PD Controller

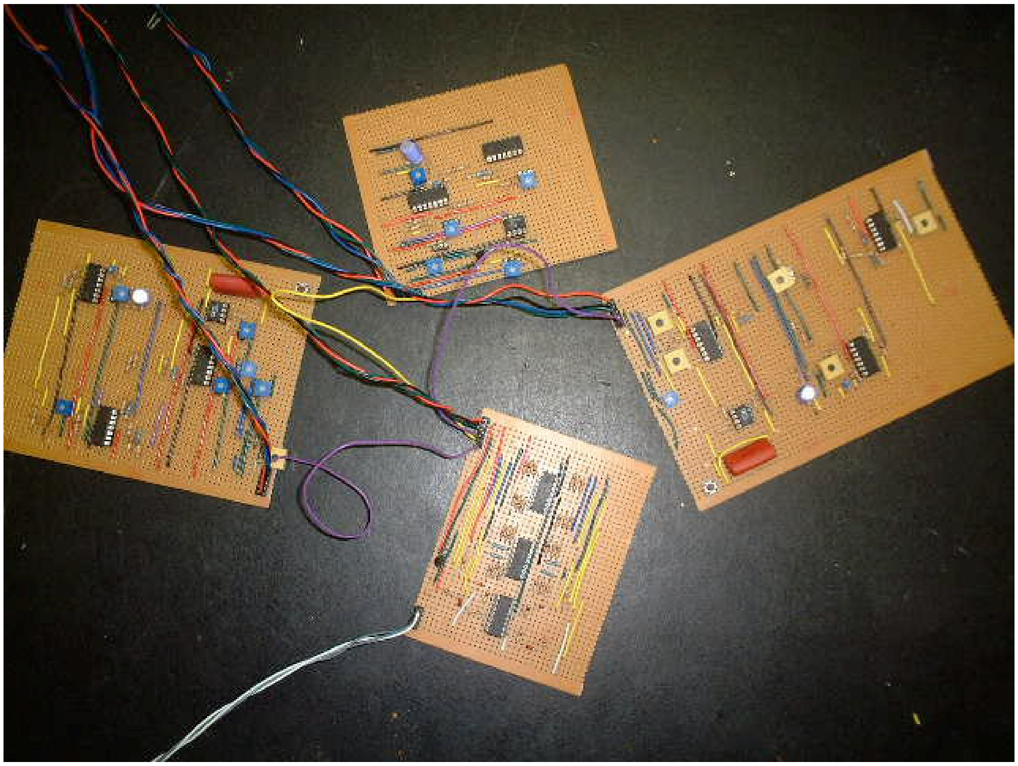


Proportional ***Differentiator***

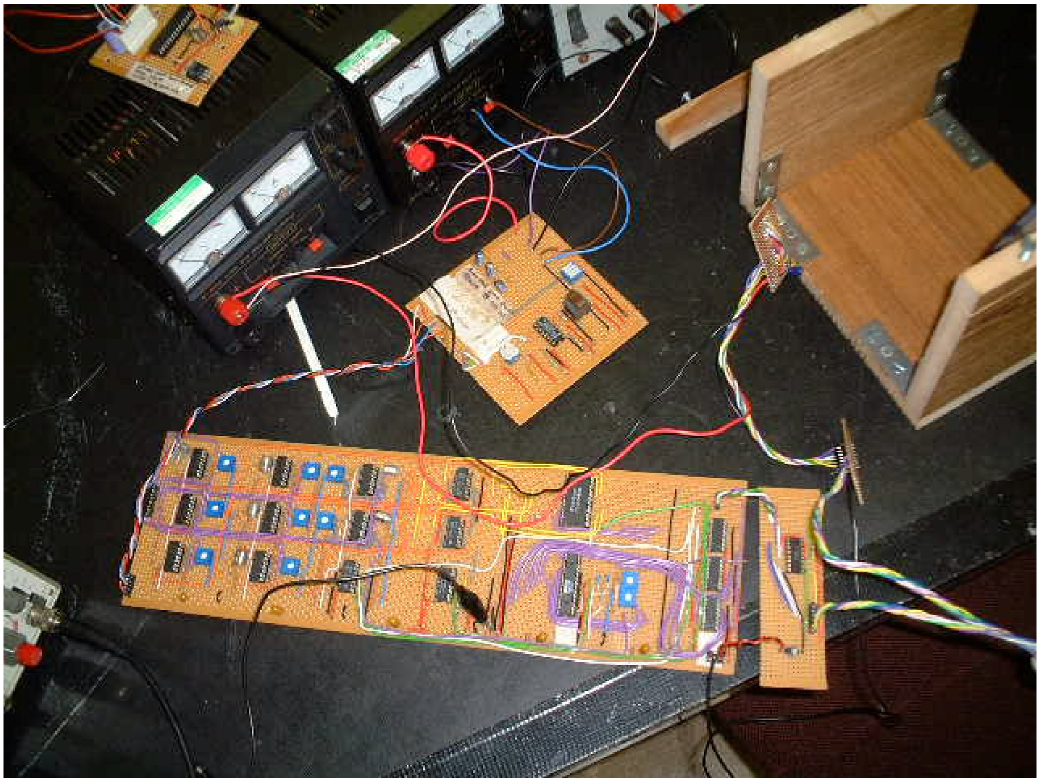
Interface Control/PWM



Complete Control Circuitry



IMU Interface



Appendix 10: Electronic Interface

Electronic Interface

Appendix 11: Circuit Bench Testing

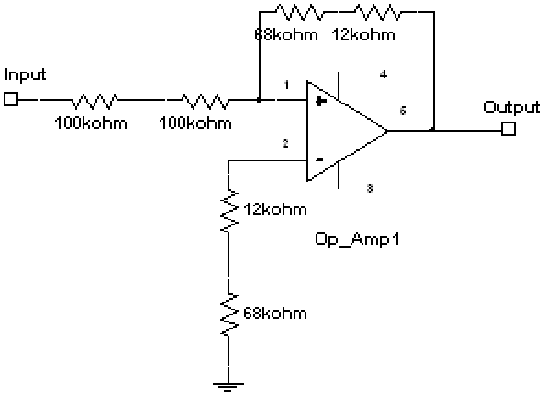
Appendix 11: Circuit Bench Testing

The whole PI-D circuit is tested using an initial input signal of ±2.5 volt square wave at a frequency of 5 Hz. The output of each stage in the circuit has been analysed using an ossioscope to determine the wave shape and magnitude.

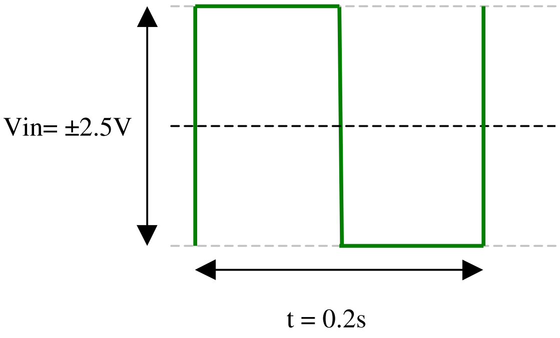
Initial Scalar

Comments:

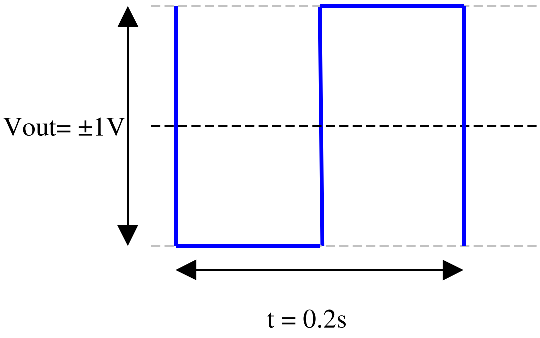
The initial scalar operates as designed it scales the magnitude down by 0.4 and inverses the signal. It does not affect the frequency or general pattern of the wave form. The input and output graphs are shown below.



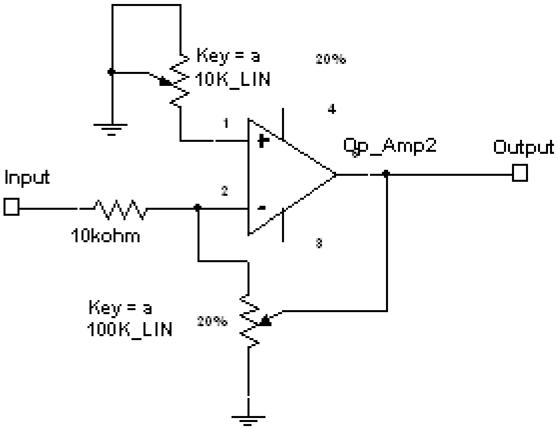
Input signal



Output Signal



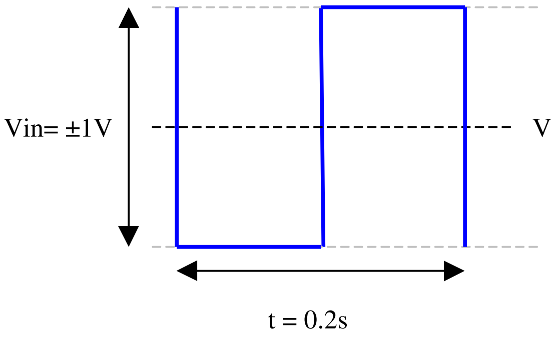
Proportional Mode



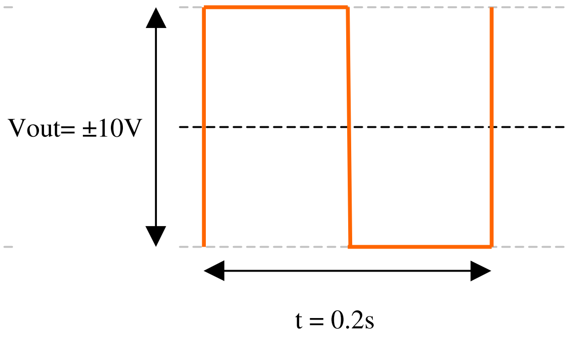
Comments:

This proportional mode circuit at its maximum gain scales the voltage up to ± 10V and at its lowest exhibits 0V. The signal is inverted and continues on the same frequency.

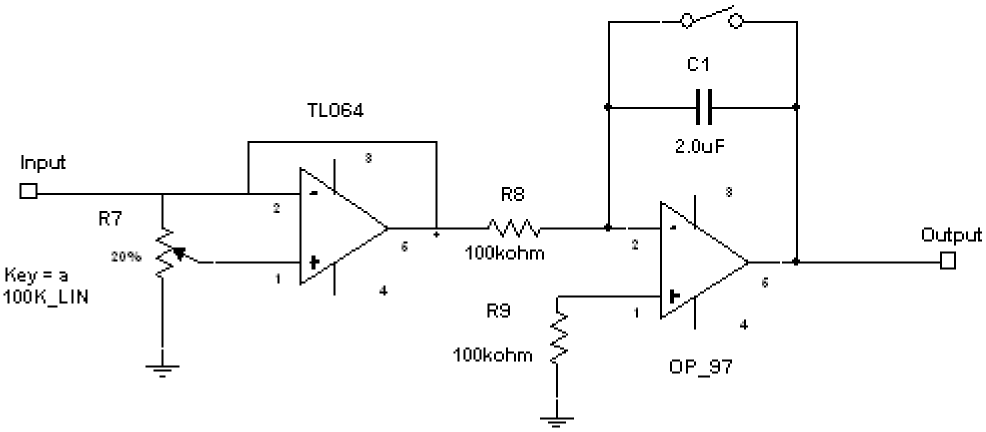
Input Signal



Output Signal



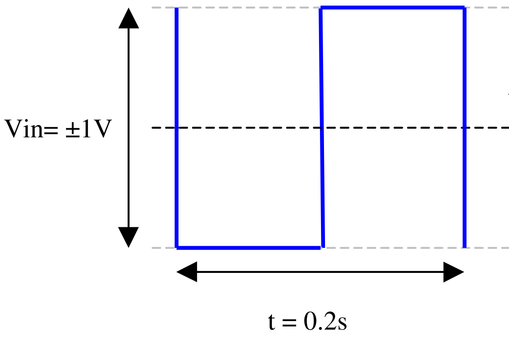
Integral Mode



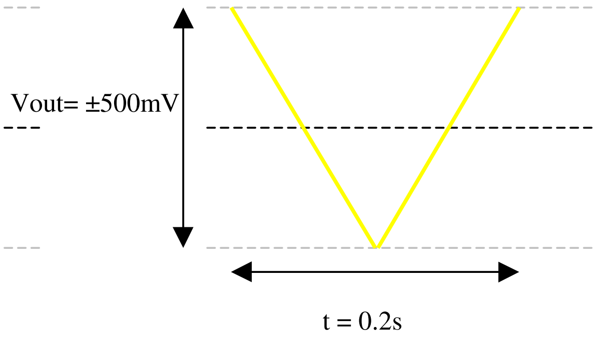
Comments:

The integrator is seen to be quite small in comparison to the input signal but this is to be expected as at this frequency the integrator gain would be smaller when the frequency was lowered so as to analyse the behaviour of the circuit at very low frequencies the integrator was found to saturate. The output also seems to be drifting but not very quickly, the pressing of the switch enables the signals to go back to oscillating about the zero point. The waveform is a triangular wave as expected, when tested with a sine wave it showed there was a minus 90 degree phase shift. The square wave pattern is shown below. At maximum it exhibits a ± 500mV signal and 0V at the minimum.

Input Signal



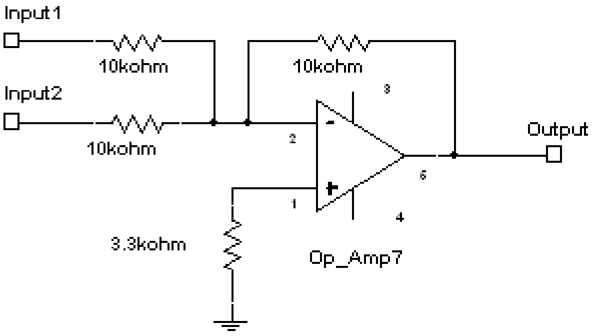
Output Signal



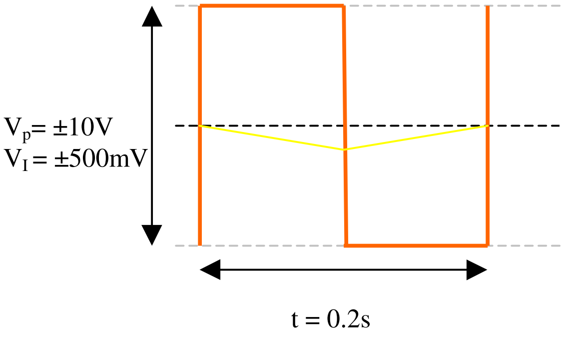
Summing Circuit

Comments:

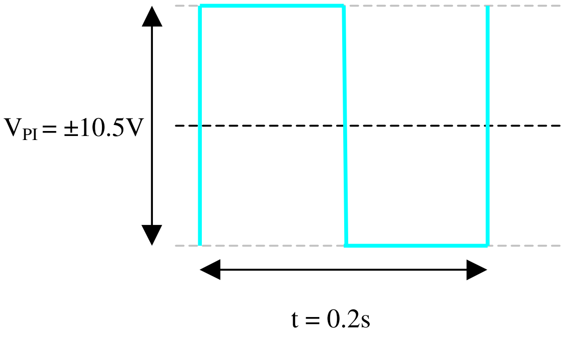
The summing demonstrates how it was designed to, it exhibits a gain 1. It also inverses the waveform therefore it just adds the input circuits together.



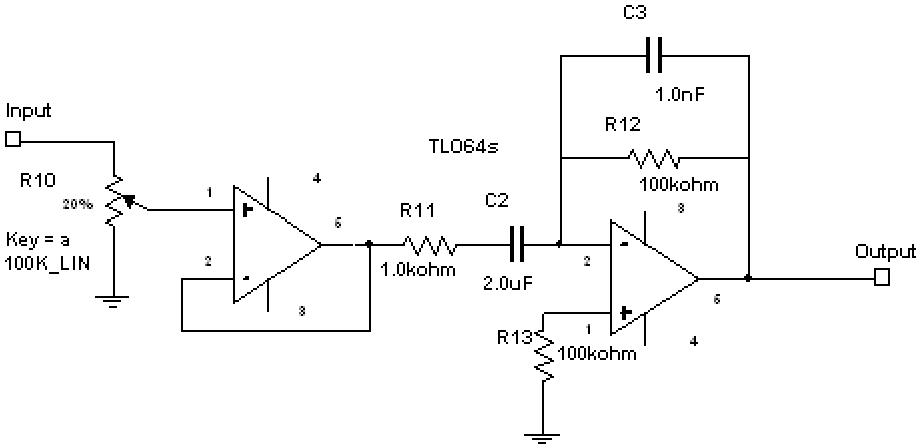
Input Signal



Output Signal



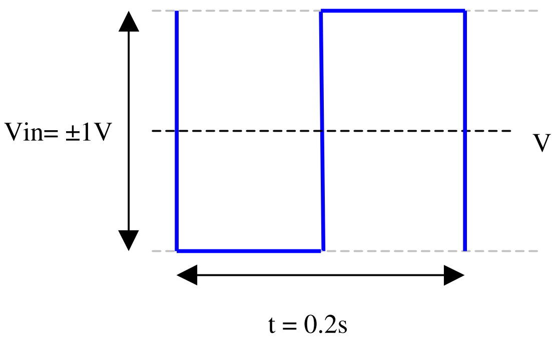
Derivative Mode



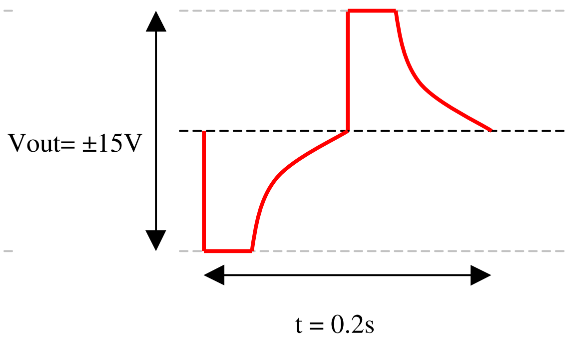
Comments:

The differentiator was seen to go into saturation extremely easily it was found that it went into saturation when R10 was set on anything above 50K, the frequency had a big impact on this saturation point as it was lees likely to hit this point when the frequency was lower. However the tests showed the expected waveform and at maximum it saturated and at the minimum setting on R10 it stayed at 0V. This system was also tested with a sine wave and demonstrated a phase shift of 90 degrees. This signal is shown below.

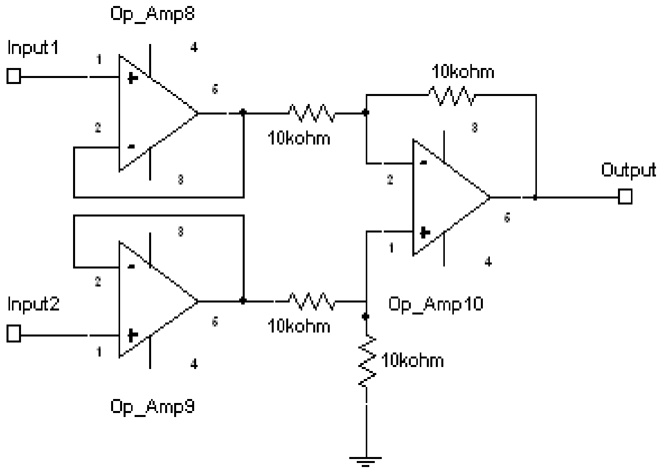
Input Signal



Output Signal



Subtraction Circuit

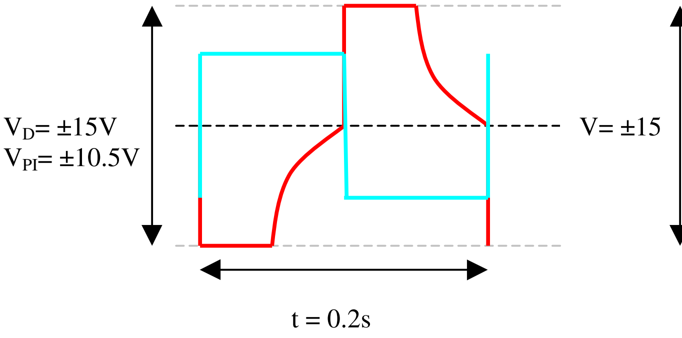


Comments:

The output of this exhibits a subtraction of the two waves. The waveform is not inversed at this stage. The output of this system is highly dependent upon the derivative output.

Input signals

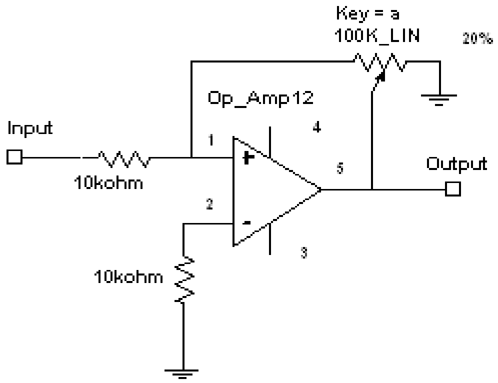
Output Signal



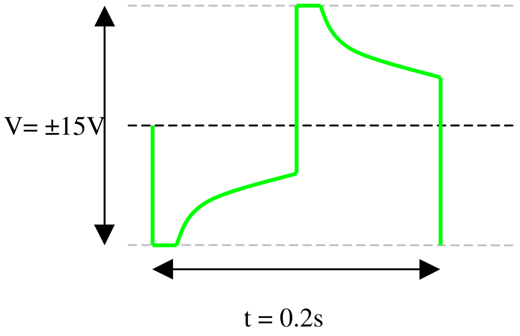
Final Scalar

Comments:

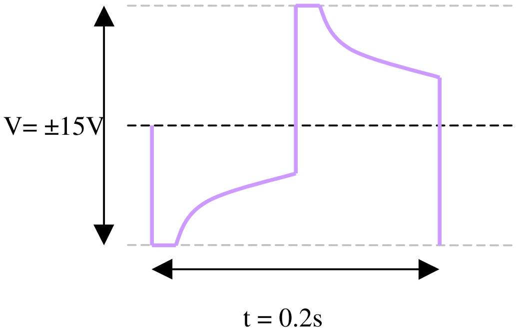
The final scalar operates as designed it scales the magnitude so as it produces an output of ± 2.5V. It does not affect the frequency or general pattern of the wave form. The input and output graphs are shown below.



Input signal



Output signal



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