1 Abstract

This report is 1 of 9 reports that, together, describe the process involved in the design and manufacture of an autonomous flying platform. The report includes information relating to the propulsion and on-board power generation required for the platform. The report starts with a brief analysis of what has been achieved by previous years working towards a similar goal. Different modes of propulsion for the platform are discussed, including ducted fans, propellers, and gas turbines. The process for selecting a suitable propulsion system is outlined including the development of the system to produce the maximum thrust. Conclusions are drawn as to the overall suitability of the selected propulsion system and some potential improvements are listed. The report also discusses a potential system that could be used to provide on-board power for the four control fans required to stabilise the platform, and for all other on-board systems. The power system comprises a high speed two stroke internal combustion engine that is used to drive a three phase electric motor in reverse, thus acting as a dynamo. A test rig is developed that allows the power generation unit (Genset) to be tested to see if it can produce enough power for the platform. Methods for furthering the testing of the Genset are then discussed and conclusions of the systems suitability are made.

2 Acknowledgements

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The author would also like to thank all his fellow group members for the patience and commitment to the project: Liam Dushynsky, Richard Forder, Rebecca Hughes, Kevin Lowis, James-Mackenzie-Burrows, Jody Meulaner, Christopher Poczka and Alex Tombling.

Special thanks should also be given to the rest of The School of Engineering and to The School of Computer Science for being so understanding about the high noise levels during the running of the IC engines.

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3 Introduction[i]

3.1 Background to Autonomous Flying Vehicles

Unmanned Aerial Vehicles (UAV's) were first developed by the military towards the end of the First World War in the form of self guiding bombs[1]. The first UAV capable of making several flights was the British Fairey Queen plane first launched in 1933[1]. They were mainly used for weapons platforms and distraction devices. The original UAV's were not completely autonomous; they required a person to be in control of them from the ground. Truly autonomous vertical takeoff UAV's have only been around for the past 30-40 years. The role they have in modern day society is much larger than it was originally, with uses in civil as well as the original military areas. They can be used for weather forecasting, crop ripeness predictions, road accident advanced alerts, reconnaissance work, weapons platforms, and many other uses. In 1998 the worldwide annual revenue from UAV sales was $2.7 billion, with a forecast for 2004 of $3.98 billion.[2]

3.2 Previous Years Work[3]

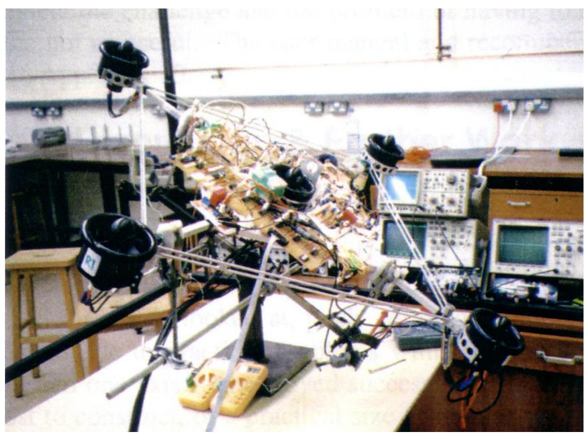

Figure 1 -Last Years flying platform[3]

Last year the main achievement of the project was the development of a 2 Dimensional control system[4] that could control the platform in either pitch or roll, but it was never tested to see if it would also work in 3 dimensions. A lightweight and strong platform was also designed last year that was suitable for mounting all the components on. The main failure of last year was the development of an onboard power supply, as the batteries could not produce the power required for the 4 outside fans.

3.3 This Years Aim

The long term aim of this project is to develop an autonomous flying platform that can hover approximately 1 metre above the ground. The project has been run at the university for several years. Each Year the final year Mechanical Engineering students take the project further towards its overall goal. The two aims for this year were to design and build an on-board power supply

[i] All photos were taken by Liam Dushynsky unless otherwise stated

and a 3-D control system to replace the 2-D system which is currently in use. The power supply will provide power for the location control fans and for a central ducted fan providing lift.

3.4 Group Organisation

This year there were 9 people in the project group. Three administrative positions were identified: Group Chairman, Secretary and Treasurer. It was decided that these positions should be permanent throughout the year to ensure continuity. The group was initially split on an informal basis into two sections: Control and Power Systems. Over time it became apparent that these sections were not satisfactory and that a more rigid structure was needed. It was therefore decided to have four sub-groups, each working on a specific section of the project: Control, Structure, Propulsion and Power System. The members and chairman of each sub group are shown in Table 1.

Subgroup	Members Names
Control	Liam Dushynsky (Chairman), Richard Forder, Rebecca Hughes, Kevin Lowis
Structure	Christopher Poczka (Chairman), Richard Holbrook
Propulsion	Richard Holbrook (Chairman), Alex Tombling, Liam Dushynsky, Jody Meulaner, James Mackenzie-Burrows
Power Systems	Alex Tombling (Chairman), James Mackenzie-Burrows, Richard Holbrook

Table 1 - Group Organisation

4 Propulsion

4.1 Possible systems

One of this year's aims was to design and build a self contained (non-electric) thrust source that would also generate electricity for the 4 outside control fans. The control fans are shown in Figure 1. Before starting detailed plans for the propulsion system, it was necessary to research what was commercially available. It was decided that one promising solution for the main source of thrust would be an engine from a model aircraft. Such engines can be bought as part of a kit that contains a small gas turbine or a small internal combustion (IC) engine used to drive a propeller or ducted fan.

4.1.1 Basic theory for generating lift from a propeller or ducted fan

In order to calculate the size of propeller and motor it was first necessary to calculate the theoretical lift. A propeller can be considered as a collection of airfoils located about a point. The equation for the lift produced by an infinitely long airfoil is shown in equation 1[5].

$$F_L = ½\, C_L * \rho * U\infty^2 * A \qquad \textbf{Equation 1}$$

Where:
F_L = The Lift force
C_L = the coefficient of lift (dependent upon the shape of the airfoil and its angle of attack)
ρ = the density of the medium that the airfoil is flowing through
$U\infty$ = the speed the airfoil is moving at
A = the plan area of the airfoil

This equation is only accurate if the airfoil is assumed to be infinite in length or is in an enclosed space (a duct, for example). If the propeller has a finite length and does not have a duct around it, the tips of the propeller affect the lift and therefore the thrust.

The pressure on the top of the airfoil is less than the pressure on the underneath; hence, lift is generated. The pressure difference between the top and the bottom of the airfoil causes air to flow around the tip of the airfoil from the bottom to the top[6]. This is shown in Figure 2.

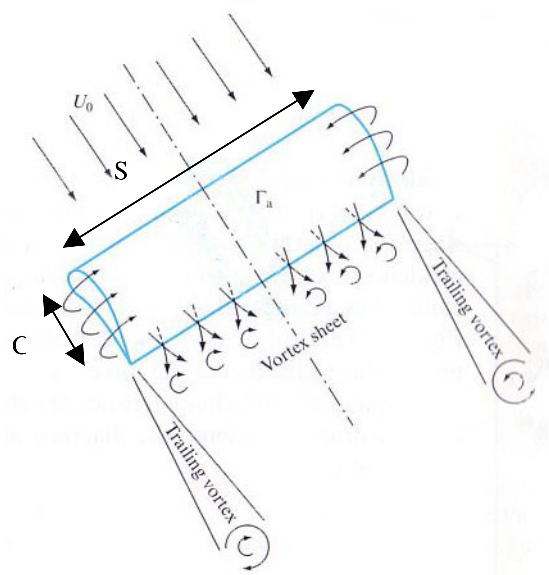

Figure 2 - Diagram show airflow around an airfoil[7]

This leads to the air flow on the top of the airfoil being towards the centre of the airfoil, whereas on the underneath it is towards the edge. This air movement causes vortices to form at the trailing edge. The pressure difference between the top and bottom surfaces is therefore greatest at the centre of the airfoil and is zero at the tips. The circulation is also greatest at the centre and least at the tips. Circulation is proportional to true lift.

This phenomenon leads to the overall lift being decreased. The mathematics involved in calculating the degree of lift reduction is very complex, hence the effect is normally allowed for in the coefficient of lift (C_L). The Equation for this is[8]:-

$$C_L = C_{L0}/(1+(C_{L0}/(AR*\pi)) \qquad \textbf{Equation 2}$$

Where:
C_L = the true lift constant
C_{L0} = the lift constant without tip losses accounted for
AR = the aspect ratio (AR = S/C)

If a propeller with a ten inch (254mm) span, a chord of 20 mm and a coefficient of lift of 1.0, rotates at 5000 rpm it can be shown, using equations 1 and 2, that the difference between a propeller being modelled as an infinite airfoil (no tip losses) and being modelled as a finite airfoil (with tip losses) is a decrease in lift of approximately 2%. This decrease in lift is observed only for a propeller that is finite in length and is not inside a duct.

4.1.2 Duct Design[9]

In order to maximise the theoretical lift, it was decided to investigate the impact of mounting the propeller in a duct. The purpose of a duct is to reduce tip losses and to streamline the flow before and after it passes the propeller or fan. There are two forms of duct that should be investigated; inlet ducts and outlet ducts. Each is important to ensuring that the flow through the ducted fan produces the maximum amount of thrust. The maximum thrust will be achieved when the flow through the duct is most streamlined. The inlet duct should have one of two shapes depending on whether the duct is to be optimised for dynamic or static thrust. As in this case the platform is being designed for vertical take off and not for high speed flying static thrust may be more important than dynamic thrust. The shape of the inlet duct should therefore resemble that shown in Figure 3.

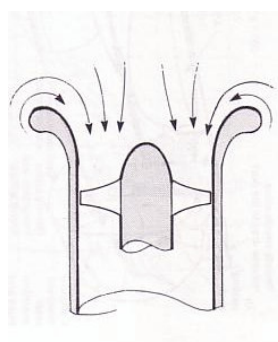

Figure 3 - Bellmouth inlet duct

This design of inlet duct will help to collect air from all around the duct without it separating from the edge of the duct and hence prevent vortices from forming. If the air flow does separate from the edge of the duct then vortices will be formed and these will dramatically decrease the efficiency of the fan.

The outlet duct on the flying platform should be modelled around the constant area rule. That is the area of the duct should be constant from the inlet all the way to the outlet of the platform. The main way that this can be achieved is by channelling the air around the engine and by using "fairings" to fill in the areas where a rapid increase in duct area would occur. The main areas where there are rapid changes in duct area are in front of and behind the engine and around the tuned pipe. Figure 4 shows an example of where fairings have been used to fill in the required areas.

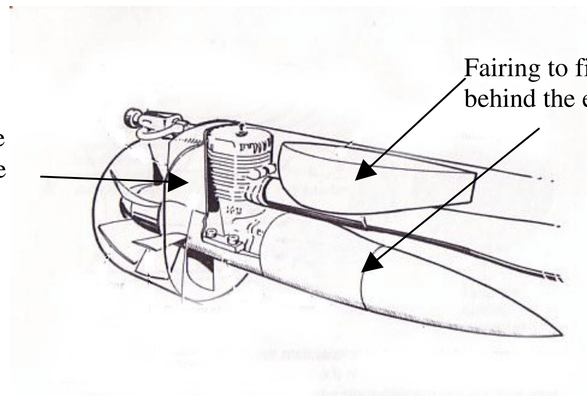

Figure 4 - Constant area rule

4.1.3 Propeller

Model aircraft, generally use propellers (as opposed to fans or turbines) as propellers are cheap to make and easy to use. They can be started easily with a "Starter stick", without the need for an electric starter or the complex start up routine required for a ducted fan or gas turbine. Propellers for model aircraft generally range from 8 to 14 inches in length. They can either be twin or triple bladed, depending on the application. The blades are generally designed to spin at around 10,000 revolutions per minute (rpm), and hence the engines intended for use with them are designed to drive a shaft at this speed. The main drawbacks of using a propeller on the platform are that it would be very large and may not be particularly safe. A propeller and engine could be purchased for as little as £200. A propeller can be made much more efficient by placing it inside a duct.

4.1.4 Ducted Propeller

Propellers in ducts are not used that often in model aircraft. The main advantage of ducted propellers over non-ducted propellers is that they significantly reduce the tip losses. This means that more lift can be produced from a smaller propeller. The duct will also provide protection around the rotating propeller. The advantage of a ducted propeller over a ducted fan is that it is cheaper and easier to manufacture, as there is little work required to design the complex duct shape and the propeller will spin at lower speeds than the fan and therefore will not need to be as strong. This type of propulsion system would cost little more than a system using propeller alone. The additional cost would be the price of the duct material, and any machining time required.

4.1.5 Ducted fan[ii]

This system is used in model airplanes and is very effective. The system produces more thrust than a propeller in a duct and hence more thrust than a non-ducted propeller of the same size. It is for this reason that ducted fan units are generally smaller than propellers. Ducted fan units

[ii] For more information on ducted fans and Gas Turbines[24]

produce more thrust than ducted propellers because they have ducts that are specially designed to maximise air flow. There are also more blades on a ducted fan than a ducted propeller and hence more air can be forced through a smaller area. Ducted fans are generally designed to run at very high rotational speeds, approximately twice those of a ducted propeller. This leads to a faster air flow through the fan and hence more thrust being produced. As ducted fans are designed to run at high speeds they need engines to be specially designed. Normal model aircraft engines are not designed to run at these speeds. The advantage of having a high speed engine is that it has a much higher power to weight ratio. The disadvantage is their potentially short life, caused by their running close to their maximum speed. A suitable ducted fan system can be purchased for around £300-£400.

4.1.6 Gas Turbine[ii]

Gas turbines operate on a different principal from the previous three types of propulsion mentioned; they do not use an IC engine. Although the principle is simple, it is complex to investigate theoretically. The basic concept is shown in Figure 5.

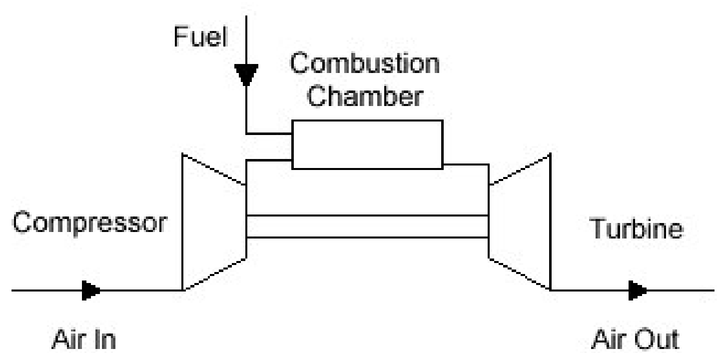

Figure 5 - Gas turbine Basic Principals

A gas turbine works by compressing air, mixing it with a fuel and then igniting it. This leads to very high temperature and pressure exhaust fumes, which are then used to rotate a turbine. Gas turbines can be split into 5 distinct types: turbojet, turbofan, turboprop, after burning turbojet and ramjets. These are illustrated in Figure 6 and Figure 7.

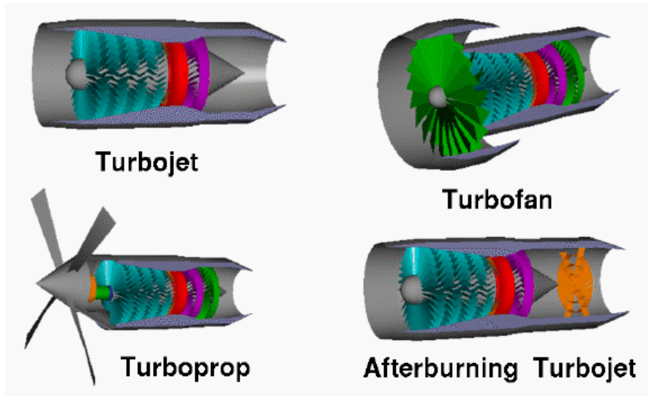

Figure 6 - Main types of Gas Turbine

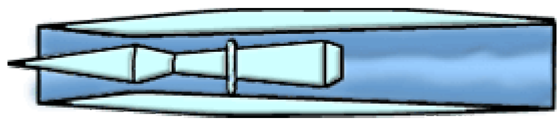

Figure 7 - Ramjet Gas Turbine

Gas turbines can be difficult to control, as they require a precise fuel mixture, which on start-up or shutdown can easily be mixed incorrectly, leading to catastrophic failure. For this reason, most gas turbines are fitted with a control unit that monitors the engine and adjusts the fuel mixture automatically. Gas turbines have a higher power to weight ratio than any of the previously mentioned systems. Thrusts in excess of 13Kg are possible from a turbine that only weighs 1.5 kg. A major drawback of gas turbines is that they produce exhaust gasses that can be in excess of 500°C; this would not be practical for a vehicle that is hovering 1 meter off the ground. There are some gas turbines currently being produced by Wren Turbines, called turbo propeller gas turbines, that only generate exhaust fumes at a temperature around 50°C. These units still have a large power to weight ratio but cost over £3000 to buy, a normal gas turbine costs around £1500.

4.1.7 Propulsion System Choice

The cost of a commercial ducted fan and engine was only a little more than a propeller in a duct, but this extra expense resulted in a system that was significantly more powerful. On this basis it was decided that the most suitable system would be a ducted fan. There was also less machining time necessary as the ducted fan units and engines can be bought off the shelf. Although a turbo propeller driven by a gas turbine would have been more powerful than a ducted fan unit, the initial cost involved was beyond the scope of this project at the current time. It was not cost effective to use a gas turbine if a ducted fan unit could provide the thrust required to lift the platform.

4.1.8 Power characteristics of high speed IC engines and Ducted fans

When selecting the engine, it was important to identify an engine which produced a power output similar to the required power of the ducted fan. If the power required for the fan is greater than the power that the engine can produce, the engine will not be able to rotate the fan at the required speed. Figure 8 and Figure 9 show power outputs for two stroke engines running at high speed.

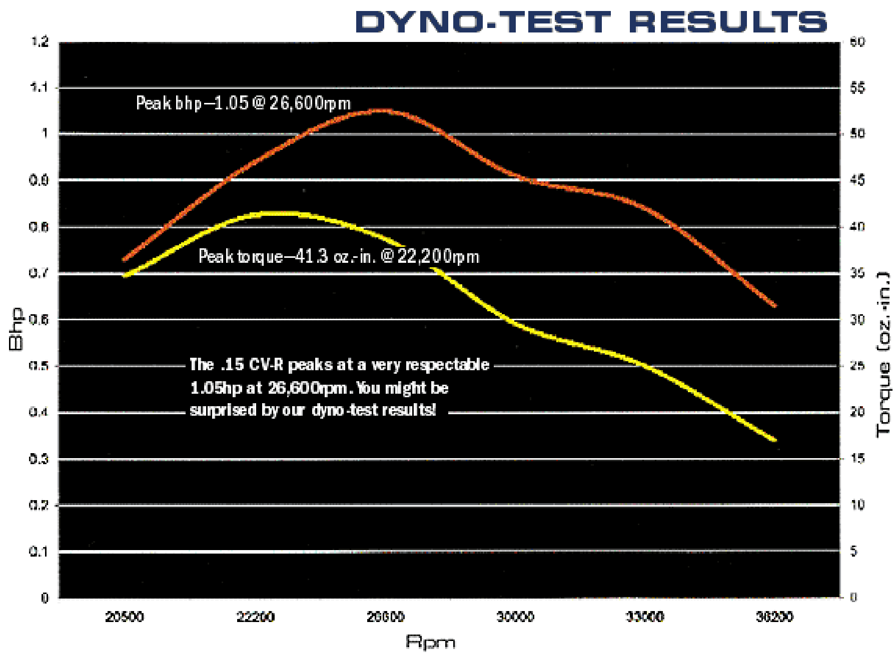

Figure 8 - Example of a high speed two stroke engine power curve[10]

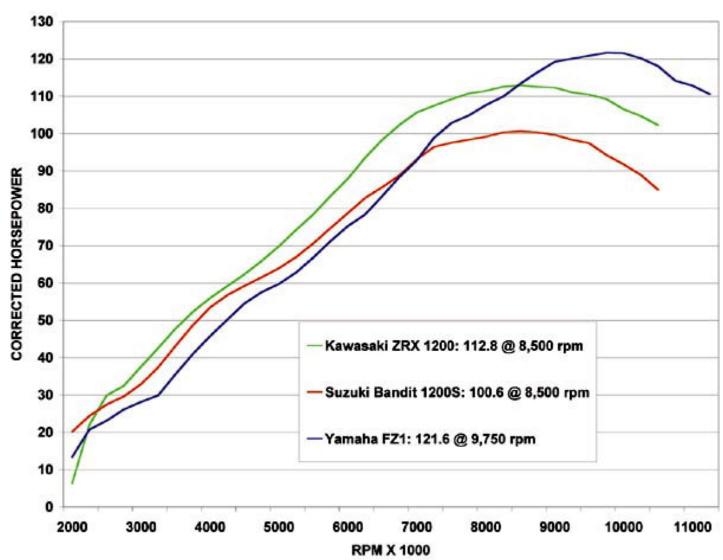

Figure 9 - Example of a high speed two stroke engine power curve[11]

From these graphs it can be seen that the power increases approximately linearly with rpm, but then reaches a peak and begins to decline. This peak is reached when the engines speed is so great that all the exhaust gasses in the cylinder cannot escape though the tuned pipe before the new fuel and air mixture is let into the cylinder. When the engine next reaches compression the combustion process is less powerful as the fuel mixture is not pure. This process can be rectified by designing the tuned pipe such that it sucks the exhaust gasses out of the cylinder when the engine reaches its peak speed. However this will compromise performance at lower speeds.

Figure 10 is a graph showing the power input vs. rotational speed (RPM) of a ducted fan. It can be seen from this curve that the power required to increase the speed of the fan is an exponential curve.

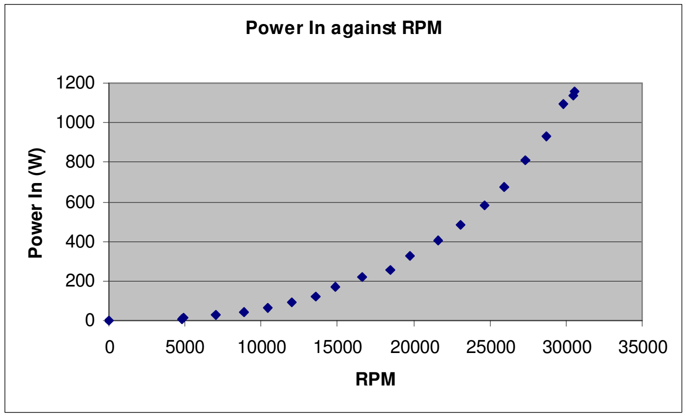

Figure 10 - Power input for a ducted fan[12]

An engine and ducted fan unit should be selected such that the power input exponential curve of the ducted fan crosses the power output curve of the engine at its maximum power output. The relationship between the weight of the engine and the maximum RPM (and hence maximum thrust) should also be considered.

4.1.9 Potential engines[13,14]

It was found that there was a large range of potential engines available. The possibilities ranged from less then 1 bhp at under £50 to in excess of 10bhp at over £500. Some of the more suitable initial findings are shown in Table 2.

Manufacturer	Model Number	Displacement (cc)	RPM (1000's)	Weight (g)	Power		Cost (£)
					BHP	kW	
Saito	FA-120S/FA-120SGK	20	2 to 11	840	2.2	1.6	300
Saito	FA-180/FA-180GK	29	2 to 10.5	900	2.8	2.1	410
Moki		22 - 90	8 to 12	0.8 to 2.9	3.5 - 7.5	2.6 - 5.6	299 - 675
Irvine	120 ring	19.82 (1.2 cubic inches)	1.7 to 12	1020	2.35	1.8	
Irvine	150 ring	1.5 cubic inches			2.55	1.9	
OS	.70 SZ-H Ring 3D heli	11.5 cc	2 to 18	553.5g	2.5	1.9	
OS	BGX-1 3500	35cc	1.5 to 10	1340	4.1	3.1	350
OS	1.4 RX-FI	23	1.8 to 10	807	3.5	2.6	
OS	OS FT-300 (TWIN)	24.38 *2	1.8 to 9	1828	4	3.0	900
OS	OSMAX 91 FX	14.95	2 to 16	550	2.8	2.1	190
OS	OSMax 160FX FI	26.23	1.8 to 9	945	3.7	2.8	700
OS	OS Max 46VX-DF	7.45	2.5-28	462	2.5	1.9	250
OS	OS MAX 91 SX-H C-Spec	14.95	2 to 16	547	3	2.2	270
Super Tigre	G2300	23.21	?	877	3.7	2.8	125
Rossi	Aero 60	10	17	590	2.5	1.9	120-170

Table 2 - Initial IC Engine Research

The two highlighted engines were of particular interest. Both are produced by the same manufacturer, OS Engines. The engine highlighted in red, the OS Max. 1.60FX FI, appears to be very expensive without any special features. On closer inspection it became clear that the reason for this engines' high cost was because the engine came with a separate control unit that provides information on engine speed and engine temperature. The control unit could be used to provide an input for the IC control circuitry in order to dictate power requirements or to shut the engine off if it is overheating. The engine highlighted in yellow, the OS Max. .46VX-DF, is a specially designed ducted fan engine. It was the only engine found during the initial research that could run at over 20,000 rpm. This is the approximate speed required to run a ducted fan.

Ducted fans are generally smaller and hence have a lower moment of inertia than a propeller. As the other engines mentioned in Table 2 are designed to turn propellers that are up to 14 inches (355.6mm) long, it is probable that they will be able to turn a ducted fan at over 20,000 rpm, but this would be running the engine above its maximum specified speed and could lead to engine failure or decreased engine life. None of the engines shown in Table 2 had a secondary power take off that could be used to generate the electricity required for controlling the outside fans. A power take off point could possibly be added, but this would have required a lot of machining, and may not have been feasible in the time available. This machining may also have weakened the engine. A secondary power take off could have been achieved by using an external gear box with two or more output shafts. This would have avoided carrying out any machining on the shaft itself and thus prevented damage to the engine.

After carrying out the initial engine research it became clear that a more detailed specification was required for the engine. The power output, rpm, and maximum cost were required in order for an educated decision to be made.

4.2 Considerations for Engine Choice

4.2.1 Electric Motor and Control Fan Testing

Initial testing was carried out with the control fans in order to determine their performance curve and hence power requirements. From the fans' specification sheet it was understood that the maximum operating speed of the fans was 30000 rpm when used in conjunction with the Plettenberg hp 220/20 A4 S P4. It was therefore necessary to find a safe operating speed for the fans where they could provide the best control, with enough power in reserve to rectify any instability that may occur. Figure 11 shows how the pulse width modulation of the speed controller affects the speed of the fan. From Figure 11 it can be seen that if the fans are operated at 1.60 ms, there is 30% excess potential power that can be used to stabilise the platform should this be necessary.

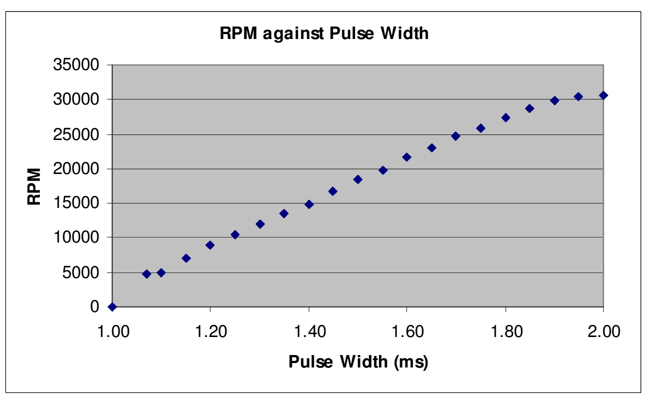

Figure 11 -Pulse width Modulation vs. RPM[12]

Figure 12 shows that with a pulse width modulation of 1.60 ms (60%), the fan motors require approximately 400 Watts per fan. The maximum rotational speed of the fans is 30,000 rpm, which is achieved when the pulse width modulation is set to 2.0 ms. The power input at this operational level is approximately 1100 watts, as shown in Figure 12.

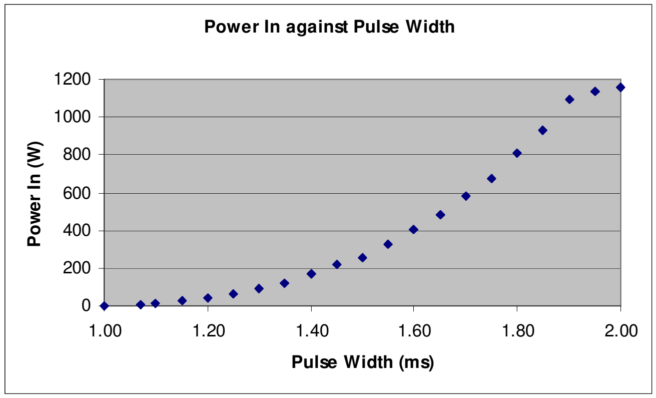

Figure 12 - Pulse Width Modulation vs. Power Input[12]

Figure 13 shows that at a pulse width modulation of 1.60 (60%); the outside control fans produce a thrust of approximately 1Kg per fan. This means that the main propulsion system will need to generate 4 Kg less than the maximum lift required. With a pulse width modulation of 1.90, hence achieving the fans and motors maximum rotational speed, the fans produce a thrust of approximately 2Kg.

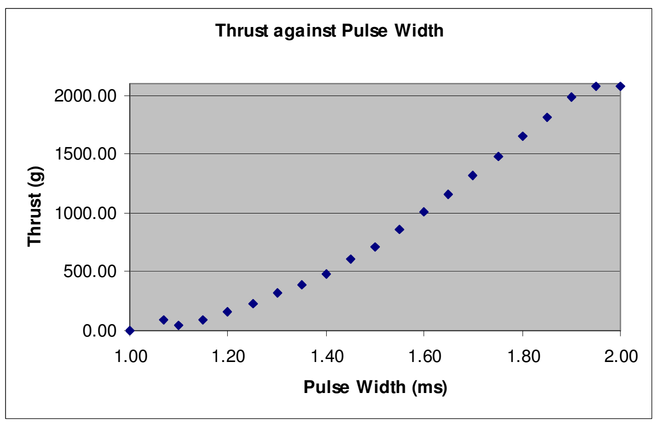

Figure 13 - Pulse Width Modulation vs. Thrust[12]

4.2.2 Weight of Platform

The maximum lift required is dependent on the weight of the platform. From the initial PDS[15] it was made clear that the platform should be able to lift its own weight plus a payload of up to 5 Kg. From last year's work it can be seen that their platform and all of its components weighed less than 4 Kg[16]. The platform this year will probably weigh considerably more than this, as it has to carry an IC engine and fuel. Looking at the engines shown in Table 2 it can be seen that the engine weight varies considerably depending on the power output. It can be assumed that an engine with a power output of greater than 1.6 KW (2.15 hp) is required, based on the required engine to run the control fans. An estimate of 1.5 Kg was allowed for the engine weight based on the data for a medium to large engine (4hp). The weight for fuel was estimated at approximately 500 grams, as this allows for an engine with a fuel consumption of 1oz per minute flying for 20 minutes[17]. If a dynamo weight of 500 grams and an onboard starter motor weight of 500 grams are assumed, then the total platform weight can be estimated at 7 Kg. With a 5 Kg payload this leads to 12 Kg of thrust being required, of which 8 Kg will need to come from the main propulsion unit (ducted fan and IC engine).

4.3 Further Ducted Fan and Engine Research

After carrying out more research into ducted fan units and associated IC engines, it became apparent that what was thought to be an easily available common system was not as readily available as had been initially suspected. Four possible engines were found, two made by OS Engines, and two made by BVM engines. The two BVM engines had customized fans for use with them, and for the OS engines there were two possible fan units, one made by Ramtec and the other by Dynamax. Figure 14 and Figure 15 show photos of the BVM and OS engines[18,19].

Figure 14 - OS .91 ducted fan engine with large cylinder head

Figure 15 - BVM .96 ducted fan engine

None of the units illustrated above produces the thrust required to lift the platform and its 5Kg payload. They would definitely not provide excess power for the four outside control fans. It was therefore decided that it may be more efficient to utilise two engines, one to provide lift and the other to generate electricity for the control fans. Making this decision increased the weight of the platform by approximately 1.5 Kg. The payload capacity was made flexible to enable the project to continue without the need for a large investment of capital. A comparison of all the possible units is shown below, in Table 3.

Engine	Fan unit	Predicted Thrust	Rated RPM	Total Cost (£)
OS .91	Ramtec	13	23000	305
	Dynamax	15	21000-23000	330
BVM .91	Viojet	12	24000	483
BVM .96	Viofan	15	24000	533

Table 3 - Comparison of potential ducted fan systems[20,19]

Power input and output curves were not available for any of the fan units or engines, it was therefore not possible to match the engines to fan units precisely. It was decided to talk to manufacturers and other model enthusiasts to see which engines and fan units worked well together.

4.4 Final engine and fan choice

The engine and fan unit eventually chosen were the OS Max. .91VR-DF large head, and the Ramtec 5 ¼ inch ducted fan unit. These were selected because this engine and fan unit combination gave a similar power output to the BVM unit, but at a significantly lower cost. The Ramtec fan unit was chosen over the Dynamax unit, as it was recommended by the engine manufacturers and said to "load the engine better"[21], i.e. the fan's power input curve is a similar curve to the engine's power output curve and will therefore not cause the engine to stall or its rotational speed to become too high. After selecting this engine, it was soon realised that the suppliers had stopped stocking it. However, they did stock a small headed version which had an equivalent technical specification, but had a smaller cylinder head. It was hoped that as the engine is located directly behind the fan unit, the smaller cylinder head would cause less drag then the larger one and therefore the thrust output would be increased.

4.5 Testing

4.5.1 Test rigs[iii]

Several test rigs were required for the propulsion engine, as it had to be "run in" under certain conditions before any thrust testing could be carried out. The engine had to be run for several short bursts using a 10 inch propeller in the horizontal plane, and then it had to be run for several runs using the ducted fan in the horizontal plane. The engine could then be placed in a test rig to measure the thrust. Figure 16 shows the rig used for running the IC engine in the horizontal plane, using a 10 inch propeller.

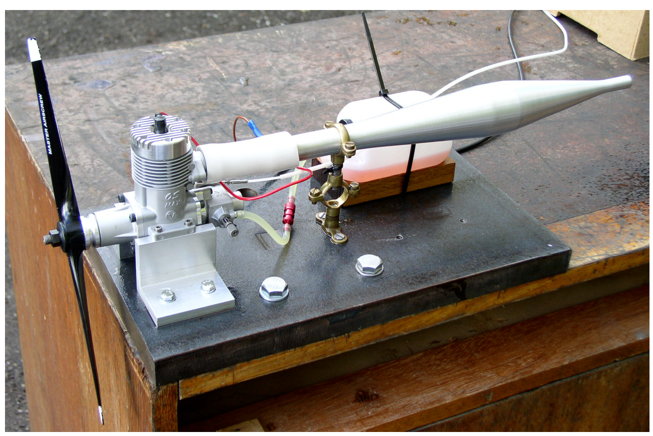

Figure 16 - Horizontal Engine Run in with Propeller Test Rig

The test rig is made from 2 inch aluminium angle, with a width of ¼ inch. The aluminium angle was bolted on to a piece of 20 mm thick steel plate which was then bolted on to a desk, to ensure that the test rig could not move.

The IC engine was fitted on to the Ramtec ducted fan unit and the combined unit fitted to the test rig shown in Figure 17 and Figure 18 for the secondary stage of "running in" the engine.

[iii] Appendix A shows technical drawings for all test rigs required for thrust testing. Appendix F shows a cost breakdown of all components used in the test rigs

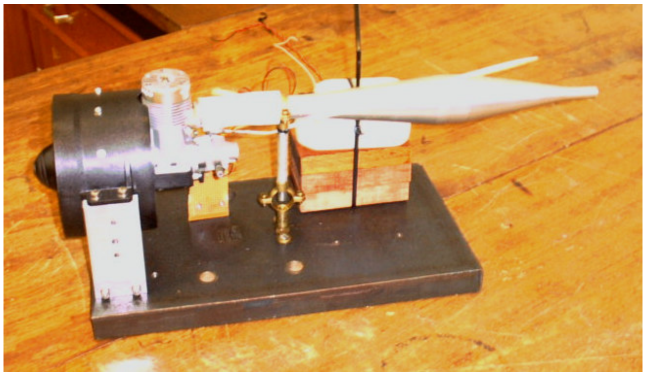

Figure 17 - Horizontal ducted fan test rig (R. Holbrook)

Figure 18 -Horizontal ducted fan test rig (R.Holbrook)

The test rig was made from aluminium flat bar machined on the milling machine to ensure that the rig fitted together properly. When the aluminium cradle was complete it was bolted to the same piece of steel that the horizontal run in rig had been bolted to and this rig then bolted to the table. A small sensing circuit was also attached to the rig so that the speed of fan could be measured, thus ensuring that it did not rotate so fast as to cause engine failure. The circuit was designed to sense a light beam being broken by the fan blades[22].

The third test rig required was a rig that could hold the ducted fan unit in the vertical plane and allow the unit to move, thus allowing thrust to be measured. The rig was modelled on a similar rig that had been designed last year for the electric control fans[16]. The rig is shown in Figure 19.

Figure 19 - Vertical Thrust Test Rig (J. Mackenzie-Burrows)

The rig was made from steel box section, and steel plate. Steel was used as it is it was relatively low cost, readily available, and had the strength required. The components were welded together as there were concerns about the vibrations that the rig would have to endure. The rig was clamped to the table using G-clamps. To reduce the vibrations that may be caused by the fan unit, rubber washers were placed in between the ducted fan unit and the rest of the test rig.

4.5.2 Thrust Testing

4.5.2.1 Various failures

When the ducted fan was first run, a problem occurred with the glow plug unscrewing part way and then blowing out of the top of the engine. This problem was due to the glow plug heater being left attached to the glow plug whilst the engine was running. The problem was rectified in two stages. The first was to "re tap" the damaged threads in the cylinder head, and the second was to use a glow plug heater that could stay attached during operation, as accessing the glow plug heater during operation could be dangerous. The glow plug hole was re-threaded with the cylinder head removed from the rest of the engine; this was done so that no "swarf" from the re-threading process would fall in to the cylinder. Figure 20 shows the glow plug heater which caused the problem.

Figure 20 - Long glow plug heater

After the hole was re-threaded the cylinder head was refitted and the horizontal duct “run in” continued. During this “run in”, problems were experienced with the cylinder head bolts becoming loose when the engine was hot, causing the engine to lose compression. Various remedies to cure this were tried, including using locktite to secure the cylinder bolts and tightening the bolts when hot. Eventually, after discussion with the manufacturer, it was concluded that the engine may be running too hot. This would explain why glow plugs were not lasting as long as they should. It was decided that the recess cut in the top of the duct shroud should be increased. The recess had originally been cut smaller than recommended, to try to maintain thrust. Once this recess had been made larger, the problem of the cylinder losing compression seemed to be resolved, but glow plug life was still shorter than had been initially expected.

4.5.2.2 New cylinder head

After consultation with the manufacturer concerning the engine overheating and losing compression, it was decided to order a new cylinder head for the IC engine. The new cylinder head was a “large cylinder head”, providing more surface area to allow the engine to run cooler. It was decided to incur this extra cost even though the engine could now run for 5 minutes without the glow plug “burning out” or the engine losing compression, since there was a fear that the engine would not last the necessary 20 minutes. The new cylinder heads should prolong the life of the engine by ensuring that the engine does not get too hot. This should save future expense for the project.

There was a concern that as the new cylinder head was larger then the original, drag caused by the engine would increase and the thrust output of the ducted fan unit would decrease. Testing was therefore carried out with the new cylinder head fitted to the engine; it did not affect the performance of the engine, thus alleviating this concern. The thrust from the engine was the same with both new and old cylinder heads. With the new cylinder head, glow plugs lasted longer than they had with the previous cylinder head, even after the recess in the shroud had been increased.

4.5.2.3 Thrust Results[iv]

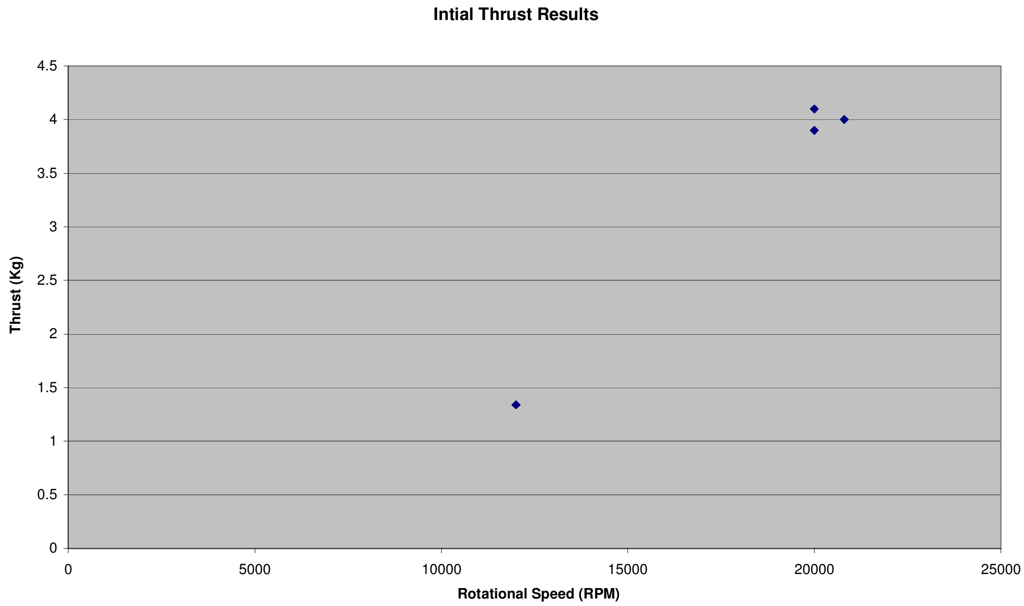

Figure 21 - Initial thrust testing results

It can be seen from Figure 21 that as the rotational speed is increased the thrust increases as expected. It can also be seen that no peak in thrust has been reached, so it can be concluded that if the engine could rotate the fan faster, more lift would be obtained. It was therefore decided that different fuels should be tried to see if these affect the thrust output. After the recess in the duct shroud was enlarged, the thrust output of the fan unit decreased by approximately 200 grams. When the new cylinder head was added, the thrust generated by the unit did not appear to be affected in a negative way. After installing the new cylinder head, the engine produced a similar amount of thrust as had been initially seen (4Kg). This was still not enough to lift the platform. Figure 22 shows the thrust vs. rotational speed curve after the new cylinder head was fitted and with the recess in the shroud made larger. The maximum thrust developed on this day of testing was only 3.6 Kg but on other days the thrust developed was as high as 4 Kg[iv].

[iv] Detailed tabled results can be found in appendix B

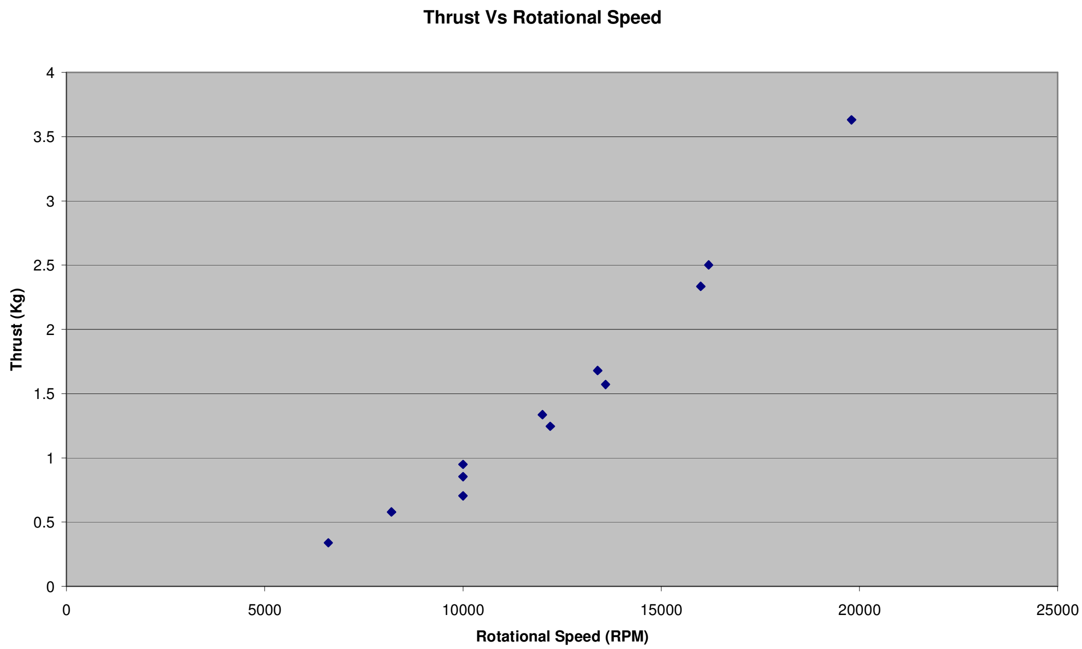

Figure 22 - Graph showing thrust results with new head fitted and recess in shroud made larger

4.5.3 Fuel Mixes[23]

The fuel mix can be adjusted in two ways: firstly, the nitro content of the fuel can be adjusted and secondly the fuel to air mixture can be adjusted. If a fuel with higher nitro content is used, the performance of the engine should increase, but its life expectancy will decrease. The initial fuel used was a 10% nitro fuel. It was exchanged for a fuel with a nitro content of 16%. The maximum thrust output of the system did not change significantly.

When changing the fuel mixture it is important to change it in small increments. As the fuel to air ratio is decreased (less fuel more air), the performance of the engine should increase to a maximum and then decrease. The initial valve setting (by the manufacturer) will decide if the performance of the engine can be increased by this process. The valve should have initially been set so that the mixture was slightly "rich" (more fuel then required) because engines should be "run in" with a rich fuel setting.

After decreasing the fuel to air ratio (leaner) by 1 increment, little effect to the engine performance was seen. It was therefore decided to try adjusting the fuel to air ratio by more significant amounts; both decreasing the ratio and increasing it (richer). The results are shown in Figure 23.

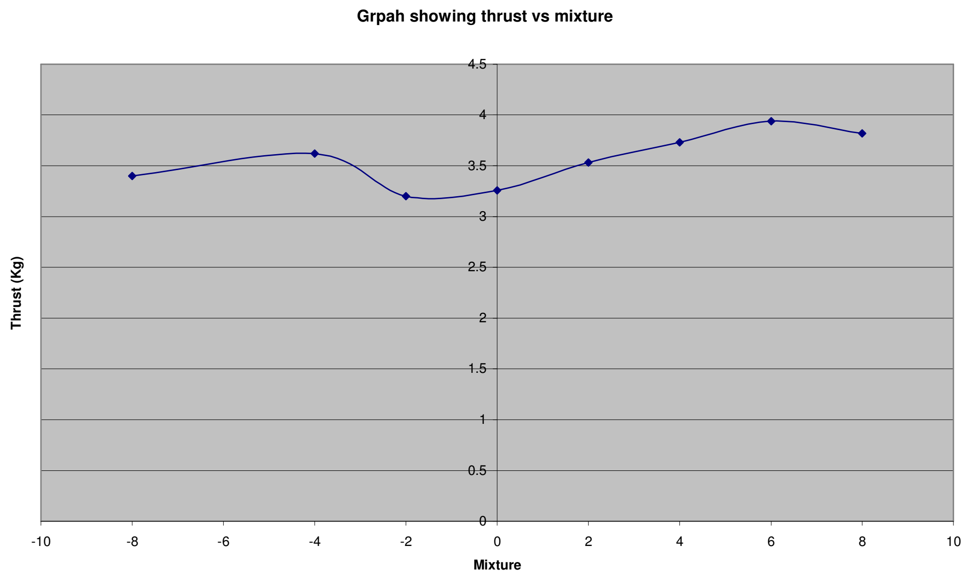

Figure 23 - Graph showing how thrust varies as the fuel mixture is adjusted

It can be seen that as the fuel was made leaner, the thrust output decreased marginally then increased and then began to decrease. This is what might be expected if the mixture had been set slightly rich by the manufacturer to ensure easy starting of the engine. However, when the mixture was made richer, the thrust also increased and achieved an extra 200 grams of lift over the maximum value developed by making the mixture leaner. The thrust then began to decrease when the mixture was made even richer. This implies that the mixture may have in fact been slightly leaner than its optimum setting and this could explain why the engine was hard to start initially[iv].

4.5.4 Additional Top and bottom Ducts

After realising that the thrust being produced by the engine would not be enough to lift the platform's own weight, it was decided to look into the possibility of adding more ducting to the ducted fan unit. It was initially thought that adding a longer duct on the bottom of the fan unit could help to increase the lift, as it would channel the airflow more. After initial testing it was discovered that adding a long duct to the underneath of the ducted fan unit decreased the lift being produced by approximately 400 grams. After more research, it was realised that it may be more effective to channel the inlet of the duct rather than the outlet. An initial duct of approximately 10cm in length was added to the top of the duct, which was tapered slightly so that the top was larger than the bottom. When this duct was tested with the engine it was found that the thrust from the engine increased by approximately 600 grams. After the promising results from this testing, it was decided to carry out more tests using a range of ducts to see if the maximum thrust output could be increased even further. A smaller duct (half the height) and a larger duct (twice the height) were manufactured and tested. The results show that the larger duct increased the thrust so that the total thrust generated was in excess of 5.1 Kg[iv]. The ducts tested were manufactured from cardboard and it is probable that the lift can be increased further by manufacturing these ducts more carefully from sheet aluminium. Figure 24 and Figure 25 show photos of various different combinations of additional ducts that were added to the Ramtec ducted fan in order to try to improve the thrust. For information as to how these ducts were designed see reference 24.

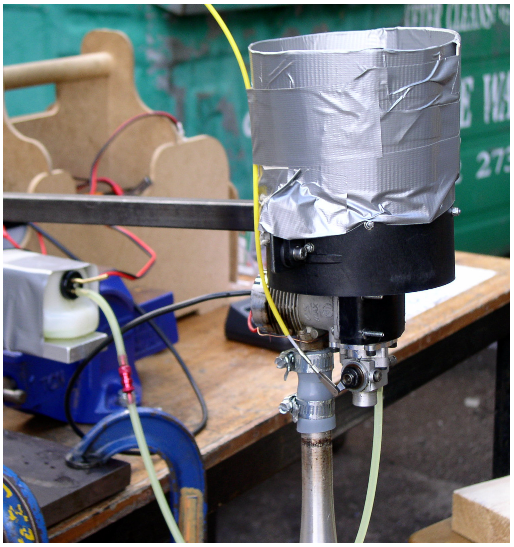

Figure 24 – Ramtec fan plus top duct

Figure 25 – Ramtec fan plus bottom and top ducts

The increase in lift observed when the top ducts were attached to the ducted fan unit is probably because the flow entering the ducted fan has been streamlined. As the rotor is mounted very high inside the duct shroud there is very little inlet duct before the air passes through the rotor and the little inlet duct there is, is not an optimal Bellmouth shape. The air flow entering the duct will therefore not be collected smoothly from all around and vortices will form and pass through the fan unit. Lengthening the inlet duct will move the disrupted area of flow further away from the rotor and give the flow time to stabilise. After ducts of a certain length are reached the thrust begins to fall again because the flow has been stabilised and the drag effects of the edge of the duct are now causing the flow to destabilise.

4.6 Conclusions and Recommendations

The first conclusion that can be drawn from the propulsion section of the project is that the OS Max. .91VR-DF engine is very unreliable. The reliability can be increased by using a large cylinder head on the engine. As well as the cylinder head overheating, thus causing the glow plugs to overheat, there are several other areas where the engine and fan unit will need further work to make it a reliable form of propulsion. The first of these, and possibly the most important, is that the mounting screws that hold the engine onto the ducted fan have sheared off several times. This may be due to the snake arm being attached between these screws and the crankcase mounting holes.

A suitable means for holding the exhaust pipe in place will also need to be designed. The coupling between the engine and the tuned exhaust is made from a rubber-like material that is affected by the heat and the corrosive nature of the exhaust. This causes the coupling to heat up and expand therefore falling off. If the rubber-like coupling is attached to the engine and the tuned pipe by cable ties or any other from of clip to hold it on, then a hole forms in the side of the coupling because it becomes too weak to take the exhaust pressures and temperatures.

The next major problem is the vibration caused by the engine and fan unit. This vibration is so great that it can break the heads off screws; it can cause screws that were held in place using locktite to become loose and most significantly it can cause soldered components to become unsoldered. This was most evident when the two servo motors used to control the throttle on the engine, which were attached to the servo arm, stopped working after a few minutes in contact with the engine. A solution to this may be to completely isolate the ducted fan unit and engine from the structure, using heavily damped anti vibration mounts.

The engine and ducted fan unit at present do not produce enough thrust to lift the platform even with the help of an extra top duct. The sustainable thrust produced by the engine with an extra top duct added is less than 5Kg and the intended mass of the flying platform is 8.3KG. This means that the 4 control fans have to produce at least 1Kg each to lift the platform without a payload. This problem may not be as great a problem as it first appears, as the generator unit may be able to produce the excess power and thus enable the outside control fans to be run at a higher power. The ducts that are currently being used to enhance the lift of the propulsion unit have been quickly designed, so more lift may be possible if more care is taken with duct design and manufacture.

Now that the IC engine is reliable, extensive testing should be carried out, experimenting with several different duct designs. The ducts should be carefully designed and manufactured, paying particular attention to reducing the vortices formed at the entrance to the duct, as this is where most of the thrust is lost. Bottom ducts should also be experimented with to see if one can be designed to channel the flow around the cylinder head. This would stop all the energy from this flow being lost.

The theoretical thrust from the Ramtec fan unit can be calculated using equation 3[25].

$$T = 13(E*P*D)2/3 \qquad \textbf{Equation 3}$$

Where:
T = Thrust (pounds)
E = Fan Efficiency
P = Engine power (bhp)
D = Outlet Diameter of Duct (inches)

Using this equation and assuming a 70% fan efficiency, engine power of 4.5bhp and a duct outlet of 5 ¼ inches the theoretical thrust form this unit is 16.1 pounds, which is equivalent to approximately 7 Kg of thrust. From this calculation it can be seen that the results we are getting are approximately ½ what they should be. This would suggest that either the engine is not producing as high a power as the manufacturers specify or that the fan unit is running less efficiently then it should. The spare Ramtec duct could be built, taking more care to ensure that the rotor is aligned exactly in the centre of the shroud. This would reduce the initial tip wear that was observed and hence reduce tip losses which would in turn increase lift.

More experimentation should be carried out on the impact of adjusting the mixture control to its richer setting on the fuel consumption. Although the richer setting will give up to 300grams more lift, it may use 400gram more fuel over a 20 minute flight, in which case a balance would need to be found between increase in thrust and the increased in fuel weight.

From initial research it was discovered that there were two other possible fan units, which had a lesser pitch then the Ramtec fan unit selected. These two fan units would load the engine less and therefore enable it to reach a higher maximum speed and achieve more thrust. Depending on the financial situation of the project next year, it may be possible to purchase a gas turboprop engine. This would appear to solve all the problems, as it can produce more than enough power for thrust and electrical generation. The major drawback of this would be the cost, £3500. If a gas turbo propeller engine is bought then it should not be used for height control, as gas turbine engines take a long time to respond and this could lead to the platform becoming uncontrollable. If the project cannot afford to invest in a gas turbine, a BVM engine could be considered, as these are considered to be more reliable and produce slightly more thrust then the OS engine; especially if a Viofan unit is used. The Viofan duct is a similar design to the Viojet but has had special attention paid to the drag caused by the engine. The main problem with this is that the Viofan is no longer in production and would have to be obtained second hand.

If the OS Max. .91VR-DF can be developed to achieve the thrust required, discussions with Just Engines should be continued in order to get a silencer manufactured for it. The silencer should be designed to muffle the engine without subtracting from the thrust being produced. If the OS Max. .91VR-DF cannot be made to generate the extra thrust required and a new propulsion unit is bought, a silencer will need to be designed and manufactured for this unit. Without a silencer the platforms eventual applications will be limited.

If the platform is to become completely autonomous an on-board starter motor will need to be found for the propulsion engine. It may be possible to combine this with the 3 phase electric motor currently being used as a dynamo for the Genset.

5 Genset

5.1 The Concept

The “Genset” is a term adopted by the group in order to describe the on-board power generation unit. It is intended to use a small high speed engine in order to rotate a 3 phase motor in reverse. A 3 phase motor was chosen because when tested it had a higher efficiency as a generator then a standard DC motor had. The output from the 3 phase motor will then be passed through rectifying circuitry made up of 6 diodes in order to convert it into a dc signal. This signal will then be used to provide power for the 4 control fans and other units such as the control circuitry that require power.[26]

5.2 Engine choice

The engine chosen for the Genset was the OS Max. .91VR-DF, this was the same engine as used in the propulsion unit. This engine was chosen because its maximum RPM was greater than the maximum specified RPM of the electric motor (although it was later discovered that the electric motor could be run at far higher speeds then initially specified[3]). The engine is capable of developing 4.5 bhp at 23,000 rpm, over double that required by the motor. Even if the motor is only 50% efficient when used as a dynamo the engine will still be able to drive it to produce the power required. It was not possible to match the power output curve if the IC engine to the power input curve of the motor because neither of these graphs were available.

5.3 Test rigs[v]

The first test rig required for the “Genset” (IC engine and Motor) was a rig that could enable the efficiency of an electric motor being used as a generator to be tested. It was initially specified that the test rig should be versatile, so that it could take several different motors. The initial test rig design is shown in Figure 24.

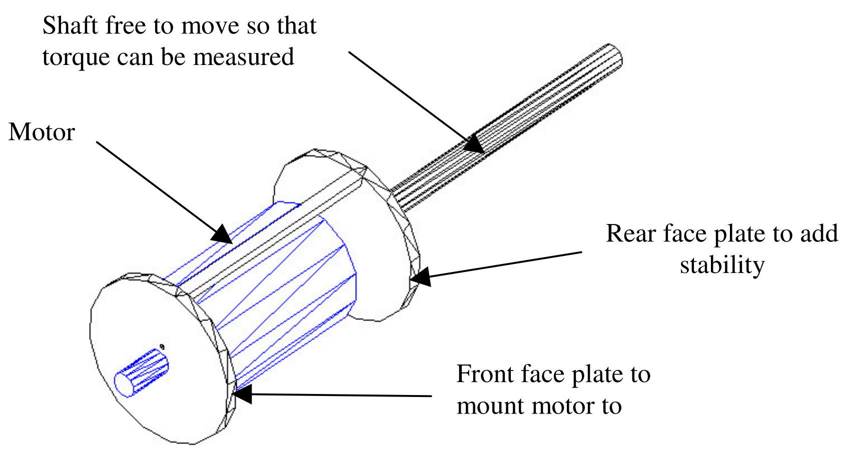

Figure 24 - Concept initial Genset test rig design allowing rotation

After considering the machining time required to make the initial test rig and the time available, a second rig was designed that was not versatile, but the design could be copied to enable different sized motors to be tested. This design was constructed out of two pieces of steel angle bar; this was used because it was readily available, easy to machine, and low cost. The steel angle had holes drilled in it using a pillar drill, the holes allowed the motors to be front mounted into the steel angle using the mounting holes on the front of them. Figure 25 shows a Photograph of the Genset efficiency test rig. For information and results on the efficiency tests see 27.

[v] Technical drawings for all the Genset test rigs including flywheel and coupling designs are shown in appendix C. A cost breakdown of all the test rigs is shown in appendix F.

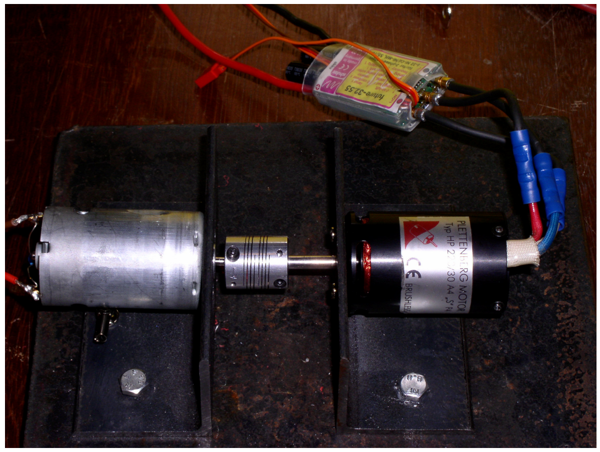

Figure 25 - Initial Motor Test Rig

The second test rig required by the Genset sub group was the same rig that had been used by the propulsion sub-group in order to run in the IC engine with a propeller, Figure 16. This engine was not to be used with a ducted fan and therefore it did not need to be run in using a ducted fan. Instead, this engine had to be run in whilst attached to the motor. This meant that for the first few runs with the motor attached the engine should not be allowed to run at maximum power.

The rig required for the secondary stage of run in and for testing the output of the complete Genset was an adaptation of the previous two rigs mentioned. The engine mountings from the propeller run in rig were used to support the IC engine and the steel angle used to support the 3 phase motor in the initial motor efficiency test were used. An aluminium block was required to be placed under the steel angle bar to bring the motor drive shaft up to the same height as the IC engine drive shaft. To complete this rig a fly wheel and coupling had to be made.

A third test rig had to be designed and manufactured as the first rig was irreparable after catastrophic engine failure (see section 5.6.1). It was decided to machine the new test rig with more precision than the old rig so that misalignment between the engine shaft and the motor shaft could be minimised. The new rig was made from aluminium including the base plate. Although this would be lighter than the previous base plate it could still be bolted to the table and should therefore not move. The new IC engine mount was constructed from a solid piece of aluminium bar. The bar had a trough milled in the top of it so that the IC engine could be mounted onto it, Figure 26 shows this.

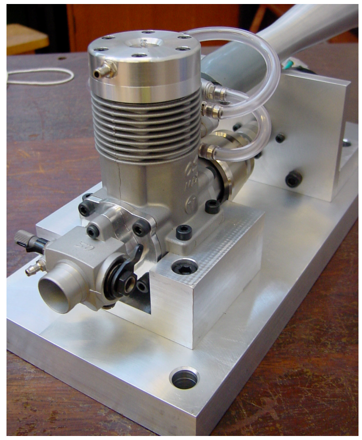

Figure 26 - Aluminium IC engine mount (J. Mackenzie-Burrows)

The reason for the change from the pieces of angle that had previously been used was that the angle (aluminium and steel) will have been drawn and can therefore not be relied upon to be square. The motor support that had previously been made from steel angle was replaced by two pieces of flat aluminium bar for the reason stated above. The aluminium flat bar was machined flat to a tolerance of ±0.05 mm.

The base plate was changed from the non-machined steel plate that had been previously used to a highly machined aluminium plate. The reason for this is that the steel plate was not square or flat and could have been a major contributing factor to the shaft misalignment between the IC engine and the motor. The new fully assembled rig is shown in Figure 27; Figure 28 shows the old fully assembled rig.

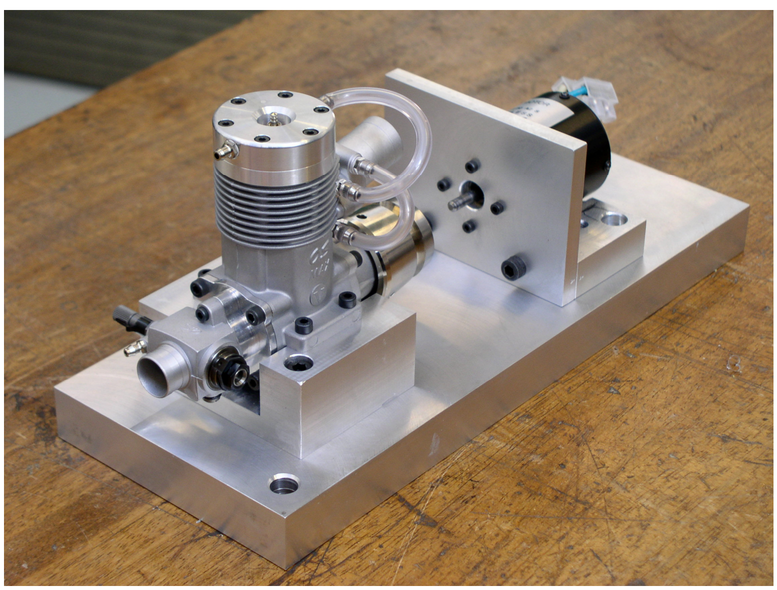

Figure 27 -Fully Assembled New Test Rig (J.Mackenzie-Burrows)

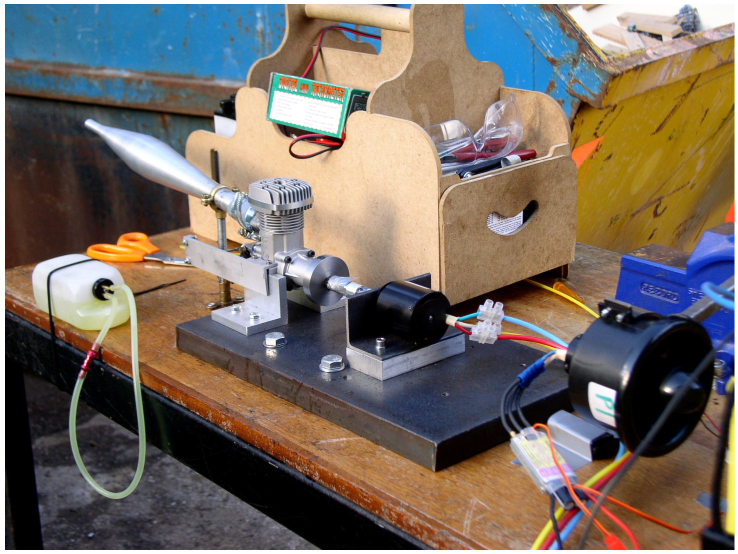

Figure 28 - Fully assembled old Genset test rig

5.4 Fly Wheel Design

The IC engine for the Genset required a flywheel, as it was not going to have a propeller attached. Without the propeller there would be nothing to stop the engines speed escalating to intolerable levels. The fly wheel was made from steel and was designed to replicate the 10 inch propeller. It was suspected that this would be an unnecessarily large fly wheel but it was chosen for the first test to ensure that the engines speed did not become too high.

The equations used to calculate the size of fly wheel are shown in equations 4 and 5[28].

$$Ke = ½*I*\omega^2 \qquad \textbf{Equation 4}$$

Where:
Ke = Kinetic Energy
I = Moment of Inertia
ω = Rotational Velocity (Rpm)

$$I = k*M*R^2 \qquad \textbf{Equation 5}$$

Where:
K = Constant depending on shape
M = Mass
R = Radius

The total Kinetic energy of the propeller rotating at an assumed speed of 1000 rpm is 202 Joules; a value of 0.5 has been assumed for k in this case, as the propeller is being modelled as a straight flat bar. For a flat circular flywheel the value of k can still be assumed to be 0.5. In order to calculate the size and mass of the fly wheel it is necessary to assume one of the variables: mass or radius. In this instance, as size could be a limiting factor on the platform, and was definitely a limiting factor on the test rig already designed and manufactured; a radius of 5cm was assumed, this lead to a theoretical flywheel weight of 0.323Kg. If a flywheel is thinner at the middle than at the edge (edge loaded) then the value of k will tend towards 1. The required mass of the flywheel will therefore tend towards 0.1618 Kg, for a radius of 5cm.

If the flywheel was to be made from aluminium with an assumed density of 2710 Kgm^{-3}, a radius of 5 cm, and not "edge loaded", then the fly wheel would need to be 15mm thick. If the flywheel was "edge loaded", an outer thickness of more than 7.5mm but less than 15.1 mm could be used. If a similar steel fly wheel, with an assumed density of 7850 Kgm^{-3}, was to be made, its thickness would need to be approximately 5.2 mm if it was a flat disc, and between 2.5 mm and 5.2 mm if it was edge loaded[29].

It was decided to make the fly wheel out of steel as this was easily available, low cost and high density. The steel to be used was measured and weighed and its density calculated to be 7820 Kgm^{-3}. This meant that the fly wheel would need to be slightly bigger than initially expected. It was decided that the thickness would need to be increased. After checking the calculations, it worked out that the increase in thickness needed to be by only 0.05mm.

The fly wheel's size may also need to be increased due to it not being a full flat disc. There would be a hole machined in it for the engine shaft to fit in and a second hole to fit a split pin that would lock the flywheel to the shaft. These holes have negligible effect on the flywheel size, as the combined moment of inertia of the materials removed would lead to the flywheels mass needing to be increased by 3 grams.[vi]

When designing the fly wheel it was also necessary to ensure that the high rotational speeds would not cause the flywheel to burst. To calculate whether the flywheel would burst, equation 6 was used.[30]

$$\sigma_a = (\delta*\omega^2*(R^3-R_0^2))/(3*g*(R-R_0)) \quad \textbf{Equation 6}$$

Where:
σ_a = average stress
δ = Weight per unit volume
ω = Rotational speed (radians per second)
R = Outer diameter
R_0 = Diameter of hole in centre
g = Gravity

If the figures shown earlier for the size of the necessary flywheel are used in this equation then it can be seen that a flat steel flywheel will have an average stress of 53.0 MPa , whereas if aluminium is used the average stress is 18.4 MPa . From research carried out it can be seen that for most materials the stress required to burst a flywheel will be approximately 65% of its ultimate tensile strength. The ultimate tensile strengths are 400 MPa for steel and 90 MPa for aluminium. Comparing the σ_a values calculated, with the values for the ultimate tensile strengths,

[vi] For working drawings of the fly wheel see appendix C

it can be seen that the ratio of σ_a to the ultimate tensile strength for a steel flywheel can be expected to be approximately 13% and for an aluminium flywheel it can be expected to be about 20%. Thus both flywheels would be highly unlikely to burst during operation.

5.5 Coupling

5.5.1 Solid couplings[vii]

5.5.1.1 Coupling 1

The coupling is required to connect the threaded shaft of the IC engine to the smooth shaft of the motor. The initial coupling was manufactured from aluminium so that it would be lightweight but still relatively strong. It was important for the coupling to be lightweight so that it would not add too much of a flywheel affect and would reduce weight on the platform. The first coupling is shown in Figure 29.

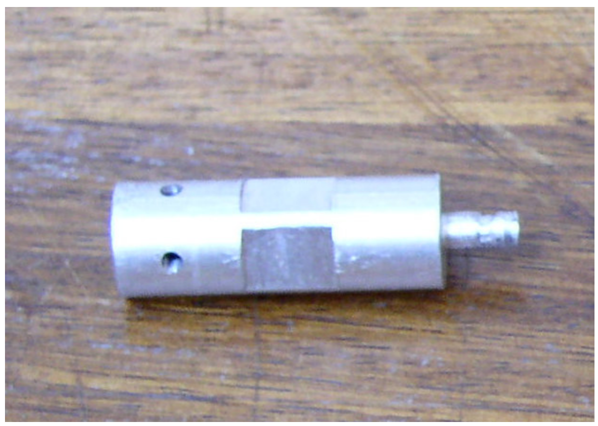

Figure 29 - Coupling 1

The coupling was machined so that it screwed on to the engine shaft and was then locked in place by two grub screws. The grub screws were necessary because on start-up the motor would be trying to undo the coupling. The other end of the coupling was designed to fit into a flexible coupling that would go between the coupling and the motor to absorb any misalignment which there may be between the shafts. The coupling had 4 flats machined onto it using the milling machine so that it could be tightened onto the IC engine shaft before the grub screws were tightened.

5.5.1.2 Coupling 2

Coupling 2 was based on a similar design to the first coupling, the main difference being that coupling 2 was made from steel and had a larger diameter. The material was changed to steel to make it harder and therefore more resistant to the deformation that occurred with the first coupling. The increased diameter was to enable larger grub screws to be used and to enable two of the grub screws to be used in each hole so that the second would lock the first in place thus

[vii] Technical drawings of the solid couplings can be found in appendix C

preventing it from vibrating loose. The coupling had no flats machined on to it, as it was decided that the coupling should be done up finger tight and the grub screws should then locate onto two flats ground on the engine shaft, thus locking the coupling in place. Coupling 2 is shown in Figure 30.

Figure 30 -Coupling 2

5.5.1.3 Coupling 3

This coupling was a compromise between the two previous couplings. It was designed to fit onto the new marine engine rather than the old ducted fan engine (see section 5.6.2). The main difference was that the new engine had only approximately 10mm of threaded shaft and therefore the coupling could be much shorter. The new coupling manufactured was only 25 mm in length as opposed to the 50 mm and 60mm of couplings 1 and 2 respectively. The new coupling had a mass of 40 grams this is 10 grams heavier than coupling 1 but 135 grams lighter than coupling 2. As the new engine was to be started with a pull starter and not by the electric motor, it did not have to have grub screws securing it in place. This meant that the coupling would not be being pulled off centre. The coupling was made from silver steel and had an outside diameter of 15 mm, which is the same as coupling 1's diameter.

5.5.2 Flexible coupling

5.5.3 Torque in shaft

Before a flexible coupling could be ordered the maximum amount of torque it would have to handle needed to be calculated. This was done by using values obtained from the motor efficiency tests using the large Plettenberg motor. The values obtained would not be exactly correct but would be a good guide as to how much torque the coupling would under. Equation 7 shows how the torque can be calculated.

$$T = (P*3918)/N \qquad \textbf{Equation 7}$$

Where:
T = Torque
P = Power (KW)
N = Revolutions per minute (RPM)

Using this calculation and the results obtained from testing the large Plettenberg motor with the small Plettenberg motor driving it, a torque of 0.31Nm resulted, when the Plettenberg had a one ohm load across it[27].

5.5.4 Types of Flexible couplings used

When choosing a coupling it was not possible to select a coupling that would definitely do the job because most manufacturer specifications were vague and did not necessarily quote figures for there couplings but gave wordy non-quantitative descriptions. The couplings selected were ones which appeared from the manufacturers' description to be adequate for the task. Three types of flexible coupling were used in the Genset: the first was an 8 slit Aluminium Panex coupling, this coupling was initially used in the motor efficiency tests and was then used on the IC engine and Motor tests. The coupling failed very quickly when it was used to try to turn the IC engine through compression. The second coupling ordered was a bellows coupling made from stainless steel; it lasted longer then the Panex coupling. Three of these couplings were used and each failed for different reasons. The first failed due to the motor coming loose and applying extra force to the coupling, the second failed during normal engine operation and third failed due to the IC engine shaft breaking. The third coupling to be used was a 4 slit Panex coupling made from Duralium (an aluminium alloy). It had much lower flexibility but was much stronger. The data available for this coupling was quantitative and stated that the coupling could withstand a maximum torque of to 2 Nm, this is over 6 times the calculated torque for the coupling. This flexible coupling is still in use on the Genset.

5.6 Testing and Engine Failure

After applying Locktite to the third bellows coupling and screwing it into place on the shafts, the Genset was tested. Two readings were taken and then the engine failed catastrophically. The two readings taken gave a maximum power output of 225 watts at a speed of just in excess of 12000 rpm. These readings were taken across a 1 ohm load[viii]. The throttle on the engine was below 20% when the engine failed and so it seems likely that the engine accelerated the motor to speeds in excess of 19000 rpm (the motor's maximum quoted speed) and so a larger load would be needed to test the engine's maximum potential power.

A photo of the failed engine is shown in Figure 31. More extensive photos of the damage can be seen in appendix D.

[viii] see appendix E for Genset testing results

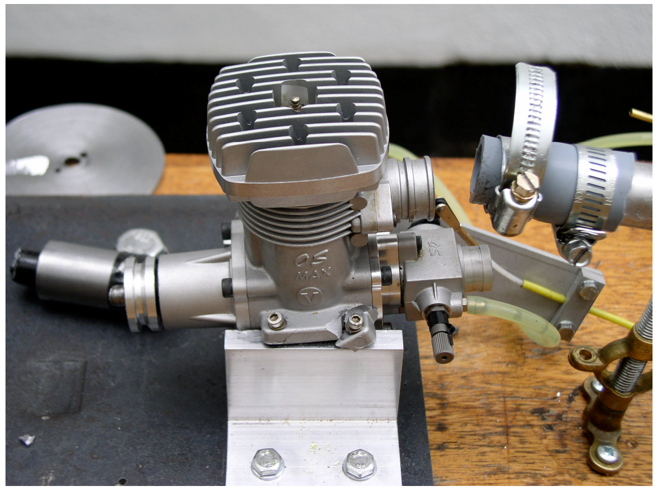

Figure 31 - Catastrophic Genset Failure

When the engine's throttle was opened to increase the rotational speed of the fly wheel up to approximately 16000 RPM, the engine shaft broke, causing the fly wheel to become detached from the engine, the exhaust to come loose and the engine crankcase to break. Control over the throttle was lost due to the servo arm becoming detached from the IC engine and so the speed could not be reduced.

5.6.1 Evaluation of Engine failure

On closer inspection of the IC engine, it became apparent that the engine shaft had broken first and therefore the engine's speed had begun to increase as the moment of inertia of the shaft had suddenly decreased considerably. The increase in speed could not be stopped due to the servo arm no longer being attached to the engine, because the threads in the engine mounting holes had been stripped and the screws pulled out. On inspection inside the IC engine, it was seen that the piston had disintegrated and the connecting rod, piston pin and retainer had all been bent.

After inspection of the shaft, it could be seen that the shaft had not broken at the point where the flats had been ground for the coupling to locate onto, but had broken at the point directly behind the nut and before the engines pulley wheel. Figure 32 shows a photo of the broken shaft, solid coupling (unscathed) and flexible coupling (destroyed).

Figure 32 - Shaft, Solid Coupling and flexible coupling

From this it can be concluded that it was probably not the flats that caused the shaft to break, and may have been the imbalance caused by locating the solid coupling on to the shaft using grub screws. As this coupling was made from steel which is denser and therefore heavier than aluminium and had a larger diameter then coupling 1, the imbalance caused by the grub screws pulling the solid coupling off centre will have been greater than the imbalance had been with the aluminium coupling. Significant cyclic loading when the shaft was rotating at 16000 rpm will have resulted, causing the shaft to break.

The total cost to remake the engine is shown in Table 4. Additional cost will be incurred in the manufacture of a new coupling. This will not completely solve the problem as a design for a new balanced fly wheel and coupling will still be needed. The total cost also does not include postage and packing.

Tower Hobbies ID	OS ID	Part	Price ($)
LXCG90	27501001	O.S. Crankcase .91 VR-DF	77.99
LXCH77	27502000	OS Crankshaft .91 VR-DF	56.99
LXCJ65	27503000	O.S. Cylinder & Piston .91 VR-DF	149.99
LXCF57	27505001	O.S. Connecting Rod New .81-.91 VR	26.99
LXCT02	27506000	O.S. Piston Pin .91 VR-DF	9.49
LXCS43	27517000	O.S. Piston Pin Retainer .91 VR	2.45
		Total	**323.9**

Table 4 - Cost to remake engine

The total cost shown in the table is more than the cost of buying the engine, so it was decided to research other potential engines or to see if a new OS Max. .91 VR-DF could be sourced as the American suppliers no longer stock them.

5.6.2 New engine

After more research it was realised that a marine engine may be suitable, as marine engines come with a flywheel and some also have a universal joint. The potential speeds of marine engines can be similar to that of ducted fan engines: 25,000 rpm, which is faster than the design speed of the electric motor. Two potential engines were selected, the OS Max. .81VR-M and the OS Max. .46VX-M. The OS Max. .81VR-M is capable of producing 4.5 Bhp and the OS Max. .46VX-M is capable of producing 2.5 Bhp. The two engines are shown in Figure 33 and Figure 34.

Figure 33 - OS Max. .81 VR-M

Figure 34 - OS Max. .46 VX-M

Table 5 shows a cost comparison between 4 potential solutions.

Repair old engine and remake flywheel and coupling			
Tower Hobbies ID	**OS ID**	**Part**	**Price ($)**
LXCG90	27501001	O.S. Crankcase .91 VR-DF	77.99
LXCH77	27502000	OS Crankshaft .91 VR-DF	56.99
LXCJ65	27503000	O.S. Cylinder & Piston .91 VR-DF	149.99
LXCF57	27505001	O.S. Connecting Rod New .81-.91 VR	26.99
LXCT02	27506000	O.S. Piston Pin .91 VR-DF	9.49
LXCS43	27517000	O.S. Piston Pin Retainer .91 VR	2.45
		Total	**323.9**
Buy New OS Max. .81 VR-M engine (includes flywheel and coupling)			
LXBY97		OS Max. .81VR-M Marine	299.99
LXZ581		Macs Muffled Tuned Pipe Marine 13cc	72.99
LXZ669		Macs 5/8 Silicone Tuned Pipe Connector	3.39
		Total	**376.37**
Buy new OS Max. .46VX-M engine (flywheel extra, no Coupling)			
LXBY97		OS Max. .46VX-M Marine	239.99
LX0501		Aerotrend ultra blue coupler (3/4*3/6*4)	3.79
LXCB11		OS flywheel #4C .46VX.M	28.99
LXCB47		OS Exhaust header .46VX-M	49.99
LXDR47		Prather 11cc tuned pipe	49.99
		Total	**372.75**
Repair old engine and buy flywheel and coupling to fit			
		repair old engine	323.9
LXCB12		OS Flywheel #7 .61/.65/.81M	32.99
LXCC63	27243109	OS Joint Assembly 5.0 .61-.77 VR	37.99
		Total	**394.88**

Table 5 - Cost analysis

From this cost analysis it can be seen that the cheapest option was still to repair the old engine. However, the imbalance problem would have remained. If the OS Max. .46VX-M was chosen, it could be ordered from suppliers in the United Kingdom (UK)[14] and so delivery costs would be less and delivery time quicker, but the price in the UK is £219.00, (approximately $383), which is more than it would cost to order from America including airmail to the UK. The OS Max. .46VX-M is also less powerful then the OS Max. .81VR-M and may not have driven the motor to give its maximum power output. It was therefore decided that the OS Max. .81VR-M should be ordered as it comes with an inclusive flywheel and universal joint.

5.7 Results[ix]

The results shown in Figure 35 represent the power obtained from the Genset on one days testing, these results were obtained from the highly machined test rig and with the OS Max. .81 VR-M engine. The Genset did not become reliably operational until near the end of the project and the results obtained are therefore sparse.

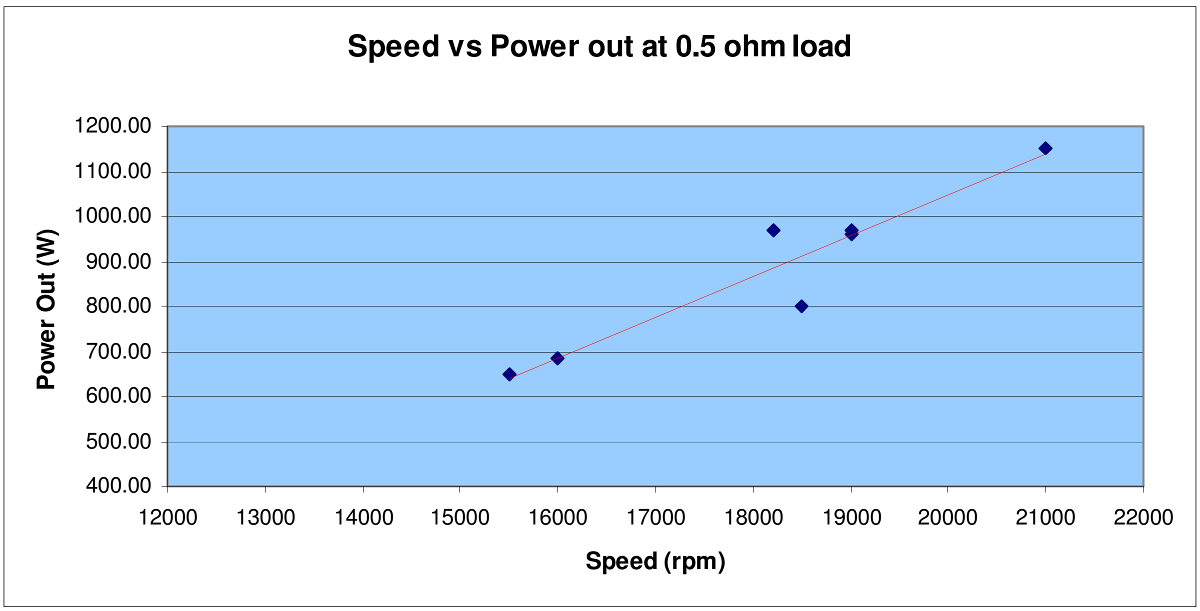

Figure 35 - Power output of Genset[27]

From Figure 35 it can be seen that the relationship between the rotational speed of the shaft (IC engine and motor) and the power output from the generator appears to be linear. Without more extensive testing this relationship cannot be checked. The maximum power output achieved is just below 1.2 KW, which is 400 watts less then is required to power the 4 outer fans if they are required to provide 1Kg of lift each. However, during the testing process it was apparent that the IC engine was not running at its maximum, as the throttle was only 2/3 open. It was therefore decided that the motor should be wired across a ¼ ohm load to see if the power output would increase. When this was done the results were inconclusive due to inaccuracies in the load resistance.

[ix] Detailed results of testing can be found in appendix E

5.8 Conclusions and Recommendations

More conclusive Genset results could have been obtained if the initial test rig designed had been designed to the lower tolerances used for the second test rig. This could have prevented the catastrophic engine failure and saved the project time and money. More time should have been spent ensuring that the IC engine shaft and motor shaft were in alignment. The flexible couplings should not have been expected to remove such substantial misalignment, up to 0.25 mm. Initial tests with the highly machined Genset rig showed that the torque between the two shafts was greater than was calculated in section 5.5.3. If this had been realised earlier in the project then a silver steel coupling could have been developed this would have allowed more results to be obtained. It may also have prevented the catastrophic failure detailed in section 5.6.1. Any unbalanced loading on the engine or motor shaft can lead to failure, this is most apparent when the imbalance is large and the speed is high but could also be significant if the Genset is to be run for long periods of time with a small unbalanced loading. When the Genset is to be mounted onto the structure great care should be taken to ensure that the shafts are aligned to as high a tolerance as is possible. The tolerance should be less than 0.1 mm in total misalignment. The mounting for the Genset will also need to be very stable and well secured to ensure that the engine and motor cannot become misaligned during operation. It may be advisable when the Genset is to be mounted onto the Flying Platform to either; turn down the engine shaft so that it no longer has a thread on it or to make a new smooth engine shaft. This would help to reduce the imbalance that can be caused by the coupling screwing onto the shaft.

The water cooled cylinder head on the OS Max. .81VR-M engine makes the engine much more reliable then the OS Max. .91VR-DF engine. The engine ran for several 15 minute time periods without needing a new glow plug, and without the cylinder head becoming too hot. It was initially thought that it may not be possible to include this engine on the platform because of the amount of water required to cool the head. It has since been realised that a very small amount of water could be carried and that this water could just be cycled through a radiator located in the airflow of one of the fan units. If the weight is still too great then the cylinder head could be replaced by the large cylinder head of the OS Max. .91VR-DF engine, since this head was fitted to the propulsion engine its reliability has increased dramatically.

From the results obtained it appears likely that the Genset will be able to produce the 1.6 KW that is currently required of it. The Genset may even be able to produce an excess of power that would enable the outer control fans to be run at a higher speeds and hence producing more thrust. In order to test whether the Genset can produce the power required to power the four control fans a test rig will need to be designed to accommodate the four fans taking all their power from the Genset. Figure 36 shows how this could be done using the same base rig as was used for the thrust testing.

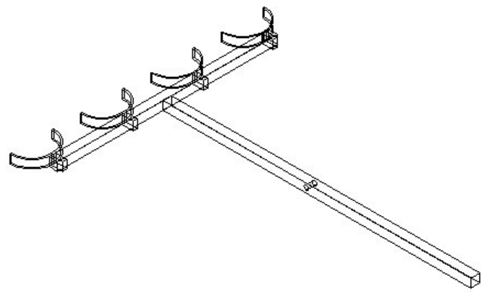

Figure 36 - Moment arm for Genset Thrust testing

If the IC engine does not have enough power to allow the motor to produce the power required, then a larger IC engine could be purchased. This may involve an engine that was not designed to run at high speeds and testing it to see how fast it can operate. If a larger IC engine cannot be found that can run at the speeds required then a gear box could be purchased or manufactured. An alternative option, if a Wren turbine turbo propeller was used for the propulsion unit, would be to use the power take off point from the turboprop to drive a gearbox. This would give a decreased rotational output to the generator thus allowing it to produce the power required without running to fast. The gearbox would be required because the turbo propeller is designed to run at approximately 100,000 rpm whereas the motor is designed to run at 19,000 rpm. It has however been speculated that the motor can be rotated at up to 80,000 rpm without it becoming dangerous, so a gearbox may not be necessary[3].

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Appendix A

Technical drawings for thrust test rigs

Appendix B

Thrust results including duct testing

Results of testing with no extra duct

Date	Thrust	Strobe	RPM
27/02/2004	4.1	100	20000
	1.34	60	12000
	3.9	100	20000
	4	104	20800
09/03/2004	3.8	100	20000
10/03/2004	3.46	96	19200
	2.94	82	16400
	3.7	99	19800
	3.2	90	18000
	3.5	96	19200
	0.26	24	4800
	3	87	17400
	3.63	100	20000
	3.2	92	18400
	0.7	50	10000
	0.805	52	10400
	3.7	98	19600
	3.8	100	20000
19/03/2004	3.8	100	20000
23/03/2004	4	100	20000
04/05/2004	3.345	100	20000
04/05/2004	3.26	100	20000
06/05/2004	3.72	100	20000
06/05/2004	3.76	100	20000
14/05/2004	0.855	50	10000
	0.705	50	10000
	1.245	61	12200
	2.335	80	16000
	0.34	33	6600
	0.58	41	8200
	0.95	50	10000
	1.335	60	12000
	1.68	67	13400
	2.5	81	16200
	3.63	99	19800
	1.57	68	13600

Results of testing where air to fuel ratio was changed

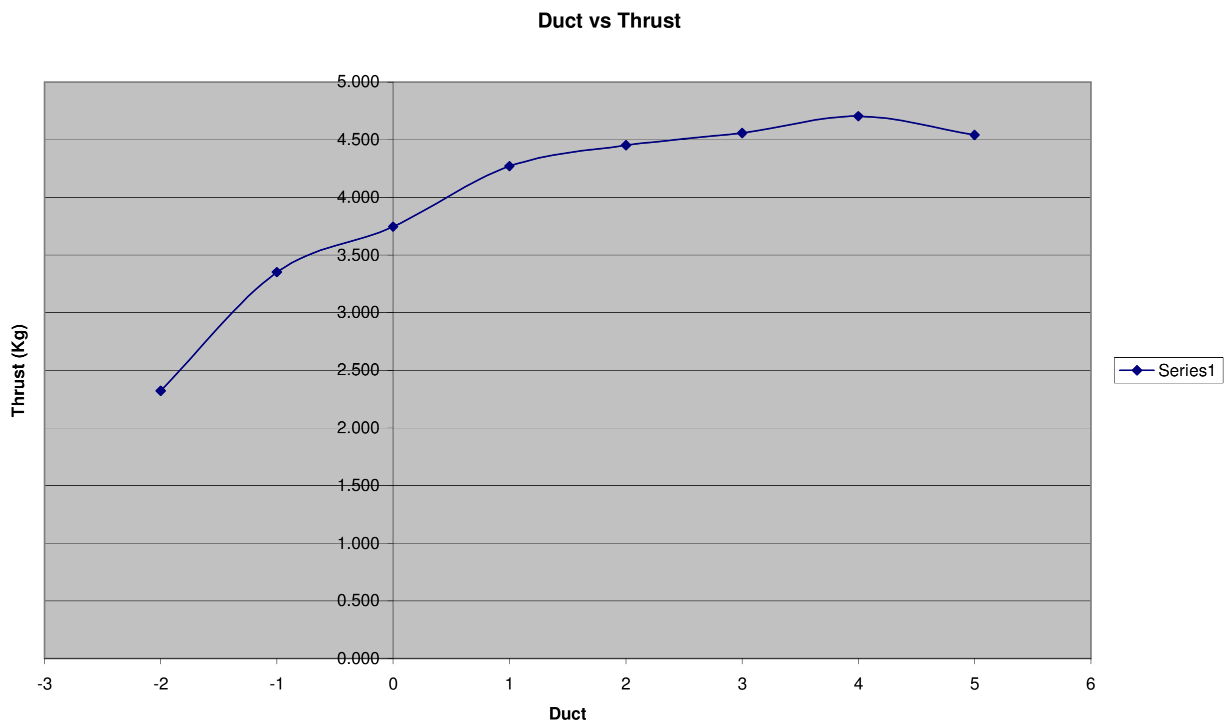
Mixture	Thrust	Throttle
-8	3.4	98
-4	3.62	102
-2	3.2	96
0	3.26	101
2	3.53	100
4	3.73	102
6	3.94	102
8	3.82	103

Results of all duct tests

16/03/2004	18/03/2004	23/03/2004	27/03/2004	04/05/2004	06/05/2004

Duct	Thrust	Strobe	RPM	Average Thrust (Kg)	Average RPM
-2 (represents largest bottom duct)	2.5	98	19600		
	2.8	104	20800		
	2.65	100	20000		
	0.6	49	9800		
	2.475	91	18200		
	2.9	99	19800		
	2.8	98	19600	2.320833	18033.33
-1 (represents smallest bottom duct)	3.1	100	20000		
	3.3	100	20000		
	3.6	99	19800		
	3.4	100	20000	3.35	19950
0	4.000	100	20000		
	3.900	99	19800		
	3.345	100	20000		
	3.740	100	20000	3.74625	19950
1	4.800	100	20000		
	4.400	98	19600		
	4.550	97	19400		
	3.335	99	19800	4.27125	19700
2	4.600	98	19600		
	4.350	97	19400		
	4.550	100	20000		
	4.600	103	20600		
	4.400	101	20200		
	4.200	100	20000	4.450	19966.667
3	4.645	97	19400		
	4.745	100	20000		
	4.445	99	19800		
	4.560	97	19400		
	4.400	99	19800		
	4.550	98	19600	4.558	19666.667
4	5.100	100	20000		
	4.545	96	19200		
	4.600	98	19600		
	4.720	100	20000		
	4.550	101	20200	4.703	19800.000
5	4.745	102	20400		
	4.600	100	20000		
	4.500	99	19800		
	4.400	100	20000		
	4.450	102	20400	4.539	20120.000

Graph showing thrust vs. Duct



Appendix C

Technical drawings for Genset Test rigs including flywheel and coupling designs

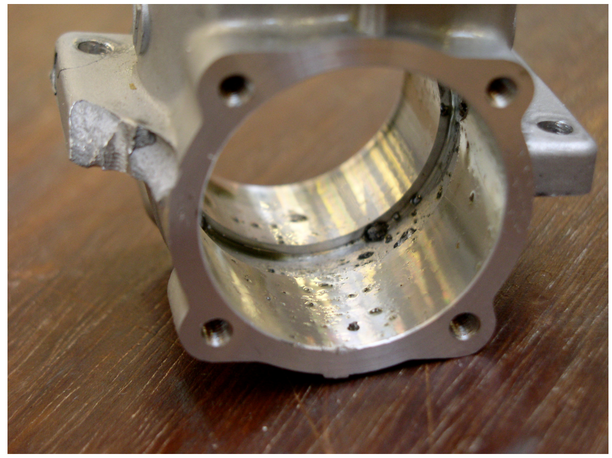
Appendix D

Photographs of the failed Genset


Detached servo arm


Screws showing stripped aluminium thread

Disintegrated Piston



View showing inside of crankcase

Bent Connecting rod

Appendix E

Genset Test Results

Results from Gen-set Testing

Date: 08/05/2004

Test completed by: RH
JMB
LD

Room: Test Bay

Strobe Reading	Speed (±100) (rpm)	Load Resistance (Ω)	V out (V)	I out (A)	Electrical Power Out (W)	Integrity of result
155	15500	0.5	18.0	36.0	648.00	Good
160	16000	0.5	18.5	37.0	684.50	Good
182	18200	0.5	22.0	44.0	968.00	Good
185	18500	0.5	20.0	40.0	800.00	Good
190	19000	0.5	21.9	43.8	959.22	Good
190	19000	0.5	22.0	44.0	968.00	Good
210	21000	0.5	24.0	48.0	1152.00	Good

180	18000	1.0	2.4	2.4	5.76	Poor
150	15000	5.0	20.7	4.1	85.70	Good
183	18300	5.0	25.0	5.0	125.00	Good
170	17000	Open Circuit	30.0	0.0	0.00	Good
190	19000	Open Circuit	33.0	0.0	0.00	Good

Appendix F

Test Rig Cost Breakdown

Cost Breakdown of all Test Rigs

Test Rig	Use	Material	Amount (Inches)	Unit Price (£)	Cost (£)
Vertical Thrust Rig	Arm	Steel Box section (3/4)	28	0.05	1.40
		Aluminium Flat ($1^1/_4*^1/_8$)	17	0.10	1.70
Vertical Thrust Rig	Counterbalnce	Steel Round (3)	2	1.00	2.00
Horizontal duct Run in/Vertical Duct	Support for duct, support for fuel tank	Aluminium Flat ($2*^1/_2$)	20	0.20	4.00
Verticla Thrust Rig	Duct Clamp	Steel Flat (1*1/8)	8	0.07	0.56
		Aluminium Flat (2*3/4)	4	0.30	1.20

Initial Motor Test Rig, genset	Motor Supports	Steel Angle (2*1/8)	8	0.40	3.20
Genset, Prop run in	Engine Supports	Aluminium Angle (2*3/8)	5	0.25	1.25
Genset	Transistor heat sinks(not used)	Aluminium Sheet (1/8)	144	0.03	4.00
Prop Run in, Duct Horizontal	Fuel Tank Support	Wood (21/2*7/8)	15		0.00
Genset	Coupling	Aluminum Round (5/8)	2 1/2	0.10	0.25
		Steel Round(5/8)	3 1/2	0.06	0.21
Vertical Thrust Rig	Duct Clamp Flanges	Steel Flat (13/4*1/8)	1	0.07	0.07
Vertical Thrust Rig	Duct 1	Card A2 thin	1	1.00	1.00
Vertical Thrust Rig	Duct 2	Card A2 Thick	2	1.50	3.00
				Total (£)	23.84