Autonomous Aerial Vehicle:
SADTU

(Self Automated Dynamic Thrust Unit)

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Abstract

This experiment incorporates both autonomous and manual control of SADTU (Self Automated Dynamic Thrust Unit). A single ducted fan propulsion unit is used to maintain uniform levitation. Stability and control is maintained by usefp of simple electronics and the fundamental principles of aerodynamics and fluid mechanics. This research will prove that a free-floating body can maintain controlled, stable levitation through changing gravitational environments; and compensate for external factors using a single propulsion unit. This research can be applied to VTOL craft and can be appreciated by those who challenge the daunting aspects of Vertical Take-Off and Landing.

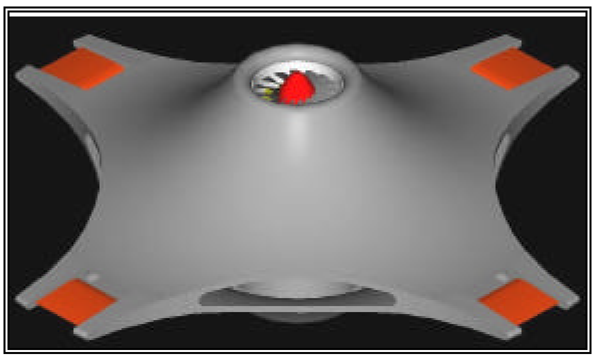

Figure 01 – SADTU (Self Automated Dynamic Thrust Unit)

1. Motivation

A club with the acronym MAFIA (Micro-gravity Association For Innovations in Astronautics) at Embry-Riddle Aeronautical University inspired this research through a program sponsored by NASA.

> Sponsored by NASA and administered by the Texas Space Grant Consortium, this program provides a unique academic experience for undergraduate students to successfully propose, design, fabricate, fly and assess a reduced-gravity experiment of their choice over the course of eight months. That experience includes scientific scholarship, hands-on test operations and education/public outreach activities.
>
> www.tsgc.utexas.edu/floatn/

I was interested. Later I found a few others interested, and the development process began. As the story goes SADTU was born. Little did I know it would be so consuming in time and responsibility. As I now look back, I am grateful for all of the experiences that I have made, the people whom I have met, and the skills that I have learned in the mean time as the project is in full swing. I have come a long way in understanding what it takes to conceptualize, propose and believe in a new idea. Important lessons every Aerospace Engineer will doubtlessly need to learn.

2. Purpose

In addition to the valuable lessons learned, there are many applications for such research. The way I see it, going to the moon was one of the most significant waypoints in our history. Yet, what is even more important is how we got there. It truly was ". . . a giant leap for mankind.", but greater is the knowledge that we learned from the endeavor. I like to look at this research in a similar manner.

2.1. Principle & Usage

Quite honestly, it is simply everywhere around you. Similar research has gone directly into dynamic motion control in some of today's automobiles. The control system compensates (through hydraulic actuation) for *pitch*, *roll* and *yaw* of the automobile, be it braking or corning "hard". The consumer therefore can experience a smooth, safer ride. The automobile becomes safer to drive because better control can be maintained. It is a perfect example of how autonomous computer control and manual (human) control can seamlessly coexist. Another example of course, lies in today's modern fighter planes. An example that I will not delve into, but considering with out computer assisted autonomous control systems, they simply would not fly. So as one can see from the outside, one may simply see a neat toy, while the knowledge learned may go un-noticed.

2.2. Applications

The research and development of autonomous aerial vehicles such as SADTU could find its niche in various areas. Applying an autonomous hover control system to platforms varying from helicopters to VTOL crafts such as SADTU would be very valuable. Let's examine a rescue situation where a person(s) is stranded upon their car in the middle of a flash flood. Such control systems applied appropriately to aerial rescue vehicles of today (helicopters) could reduce the pilot demand/fatigue; especially if there are severe external factors such as heavy winds, or precipitation etc. Benefits exist in applications or situations where more sophisticated control is required. If hover can be maintained autonomously, simply tell the craft to go forward, backward, left or right. The pilot load is lessened, so he/she can tend to other tasks that cannot be admitted to computer control. Manual control and computer control can seamlessly coexist in this manner.

Great opportunities exist for remotely controlled piloted vehicles. Reconnaissance, military intelligence (target acquisition), or surveillance are simple a few examples. It is small and hopefully quite stable; suitable for urban usage as well, such as crowd control or in hostile situations such as riots. This R&D can easily find numerous applications in society. Many of the functions of not just aerial vehicles, but any form of locomotion today could benefit from such a form of automation. From planes, trains, automobiles to submarines, similar technology keeps developing through similar inspirations.

3. Conclusion

Originally conceptualized for micro-gravity in an atmospheric environment, SADTU would show controlled, stable flight in varying gravity using ducted fan propulsion. Later research and rationalization decided to focus on the earth's reference frame for initial phases of testing. Experimental goals included solving the problem of autonomous, stable levitation in dynamic micro/macro-gravitational environments. Experimental goals now include a much broader spectrum including a more efficient hypothesized form of stabilization, vertical take off, and hovering. The innovation, design, and execution of the knowledge developed in the creation of SADTU are truly the primary objectives.

3.1. Cessation

By conducting this research, one gains a greater understanding about the intrinsic nature of engineering. From planning to construction, to the testing of the craft, NASA introduces the lifecycle of a concept/project to students with the ambition to innovate. Much has been learned, and much still needs to be learned in the creation of a craft like SADTU and its control dynamics. Areas of interest lie in aerodynamics, fluid dynamics, microprocessors, robotics, computer integrated manufacturing, and pretty much anything and everything necessary to successfully engineer my dreams. Special thanks goes to Dr. Antonio Arroyo, Dr. Schwartz, and the National Science Foundation (NSF). I was able to continue my research at the University of Florida during their summer 2000 Research Experience for Undergraduates (REU).

4. Aerial Vehicle Description

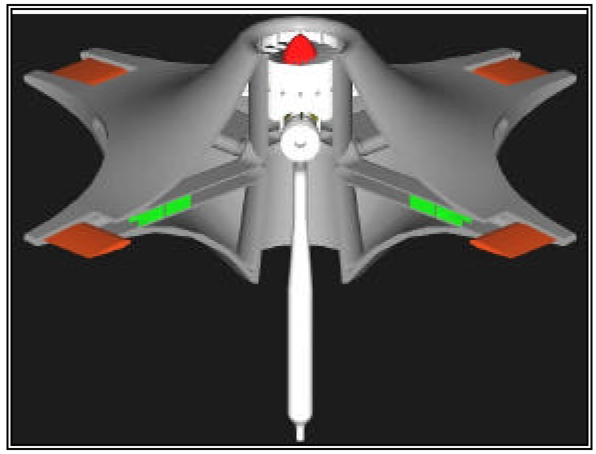

Figure 02

SADTU is ultimately a control system utilizing simple, manageable electronics. Onboard sensors interpret changing gravity and voltages, and induce the necessary thrust and control compensation to maintain levitation. The shape of the craft is designed to maintain the flow and aerodynamic characteristics, yet minimize weight. Processing and data acquisition is accomplished through a micro-controller. “Bleeding” the compressor section of the ducted fan provides control. Vectoring a portion of the overall thrust through ducts over airfoils provides additional lift and axial control. The airfoils are servo-controlled.

4.1. “Road Map”

SADTU revolves around standard aerodynamic and fluid dynamic principles. (The whole concept parallels nicely with the current education I’m receiving at Embry-Riddle.) I did not realize how many factors must be addressed with such aerial vehicles. This research can be divided equally into aero-design, and control system development. I will touch on the aero-design of each topic lightly in the test objectives, and later go more into depth. Following, I will discuss the control system objectives.

5. Design and Control System Development

5.1. Test Objectives

The object is to design a platform for which accessories can be adapted to perform multifunctional operations (in situations regardless of outside influences such topography, wind, etc. on a prototype scale). Test objectives are valid upon final construction of the craft. Much is still being researched and performed to finalize the design. New technology and software enables much more accurate representations of the flow and control dynamics which could not have previously been determined. Due to the complexity of a craft such as SADTU, much time will be spent here to "virtually" simulate these characteristics. Learning to use the software will take some time in itself. This allows for very accurate engineering of SADTU prior to any prototyping. This ultimately saves time, money, and manufacturing costs. Many aspects will be experimented and their importance is briefly discussed below.

5.2. Inlet Diameter

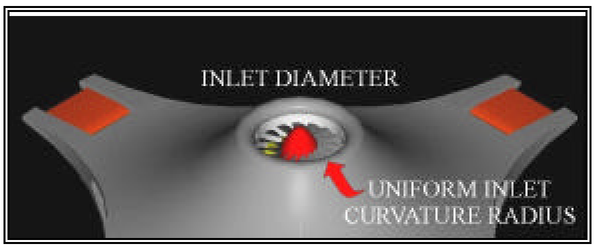

Figure 03

Characteristics of the inlet diameter and uniform inlet curvature radius need experimentation to create smooth flow and maximum efficiency of the ducted fan. The exit area, efficiency, and static thrust are highly dependent upon the inlet portion of the craft. The exit diameter must be approximately 75-80% of the inlet diameter to reach maximum efficiency. Due to the fact that there is a tuned exhaust protruding the exit, the exit diameter and exit area must be constant, based off of the inlet diameter dimensions. (It also deems necessary to "lampshade" the exit.) This equates to an efflux exit diameter of 4.21 in. to 4.46 in. This of course will be tested to achieve a constant exit area.

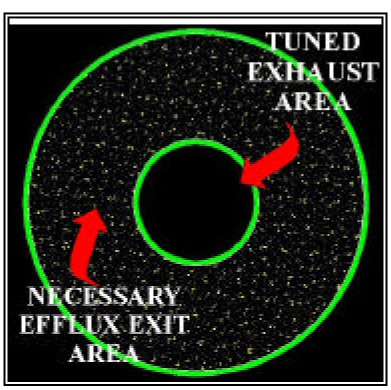

Figure 04 – Efflux Exit Area

<u>75% Inlet Area</u>

$$5.25in \times 0.75 = 3.937in$$

$$area = \frac{pD^2}{4} = 12.176in^2$$

$$12.176in^2 = \frac{pD_{exit}^2}{4} - \frac{pD_{exhaust}^2}{4}$$

$$12.176in^2 = \frac{pD_{exit}^2}{4} - \frac{p\left(1.5^2\right)}{4}$$

$$D_{\min} = 4.21in$$

<u>80% Inlet Area</u>

$$5.25in \times 0.80 = 4.20in$$

$$area = 13.854in^2$$

$$13.854in^2 = \frac{pD_{exit}^2}{4} - \frac{p\left(1.5^2\right)}{4}$$

$$D_{\max} = 4.46in$$

5.3. Exit and Efflux flow

Static thrust is a primary concern. It dictates many physical aspects of SADTU such as the overall dimensions, and of course the weight. I don't feel at the moment that the nature of the flow (being turbulent, laminar or transient) through the exit is as important as it is through the "channels" or "ducts". A flow control aperture or flow control leaders (discussed later) control static thrust.

5.4. Compressor Section

The "compressor section" is obviously a key area of interest. It is the location of the flow control. The purpose and function of the flow control is described in 7.1. Pressure gradients will exist that need to be analyzed and predicted in order to predict flow rates through the ducts. This will largely constitute airfoil characteristics and lift dynamics. These in turn dictate moment dynamics of the craft as well. Rough approximations have currently been made using the efflux velocity developed from the engine and fan specifications. This information along with overall dimensions will not be included in this paper.

5.5. Ducts & Flow Analysis Assumptions

Duct or channel dimensions are also of concern. Different shapes exist that may enhance flow conditions. Duct dimensions partially control flow rate; again affecting airfoil, lift and moment characteristics. One assumes the ducts to be completely filled with air (unlike a drain pipe). The finish of the ducts should be as smooth as possible in order to fully develop the flow, if fully developed flow is at all possible. The ducts may not be long enough or flow may simply be too turbulent. The flow over a body, through a tube of any shape does not lend itself to precise mathematical description except under very unusual circumstances. It is usually necessary to implement assumptions, and simplifying factors relating to the geometry of the structure or to the physical properties of the fluid. These assumptions dictate the use of the mathematical expressions. Fundamental simplifications include: that steady motion is assumed, temperature, pressure, density, velocity, and acceleration at a point (past which a fluid is flowing) are all independent of time. Another approximation of fluid mechanics is in the idea of a "perfect fluid". A perfect fluid is assumed to be homogeneous, continuous, incompressible, and inviscid. Compressible effects take place at pretty high velocities, around 350 mph or higher. The maximum velocity reached in SADTU is 170 mph. Assuming the air to be incompressible and invicid, no significant error result. Therefore, the continuity and Bernoulli equations may be appropriately used.

5.6. Free Jets

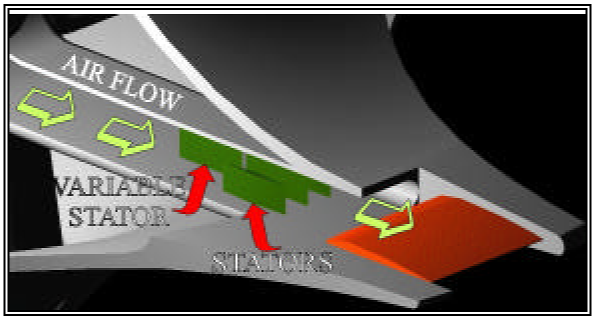

Figure 05

Attention must be paid to jet exit characteristics such as exit area and flow velocity. The distance the airfoil should be located to the jet is important as to not "choke" the flow of air over the airfoils. Undesirable effects could be generated such as poor lift components if the airfoils are located too closely.

5.7. Variable Control Vanes

The variable control vanes (refer to figure 05) are still in the initial design stages. They lie in the duct in front of a series of stators. These variable vanes will negate the torque generated by the engine when spinning up or spinning down. The purpose for the stator vanes is to again, smooth the flow before exiting the jets, and then out over the airfoils. The location from the center axis is still to be determined. The moment must equal the torque transferred on the craft. Finding that distance is not difficult.

5.8. Airfoil Analysis

5.8.1. Airfoil Fundamentals

Aerodynamic forces arising from relative motion between an airfoil and the surrounding air are dependent upon three separate influences:

1. Angle of attack
2. Camber
3. Airfoil thickness

These three influences are additive. Since the lift coefficient due to (1) acts at the 25 percent chord, the moment coefficient about the 25 percent chard due to (1) is zero. (It is not zero for any other point on the chord). Since the moment coefficient due to (2) is the same for any point on the chord, it may be chosen to act at the 25 percent chord. There is no moment or lift associated with (3); thus it may be discarded from present considerations.[1]

5.8.2. External Factors

Magnitude of the relative velocity, and size and shape of an airfoil are subject to air density, compressibility, and viscosity of the air. The engine and ducted fan performance will also be influenced by these external factors.

5.8.3. Airfoil Characteristics

Airfoil characteristics are simplified due to the symmetric nature of a bisymmetrical airfoil. Separation of flow is minimized at small angles of attack and zero lift is generated at zero angle of attack. Airfoil thickness and chord length need to be finalized. Around a 12% thickness airfoil will most likely be used leaving approximate airfoil dimensions to have a span of 3.71 in, a thickness of .45 in, and a chord length of 3.75 in. This airfoil produced the following results at the two given jet flow rates.

Lift (lbs.) vs. Angle				
Velocity (mph)	Angle (degrees)			
	1	5	10	15
50	0.075	0.376	0.750	1.118
60	0.108	0.542	1.080	1.610

Figure 06 - Lift Generated Per Airfoil

Relative velocity is used to determine these characteristics. The pressure or force developed on the surface is dependent upon the velocity relative to the point or body considered, not upon the absolute velocity. That's partially why such a concept is feasible. For example, the aerodynamic force on an airfoil is found using the air velocity relative to it; it makes no difference whether the air passes over the wing or the wing passes through the air.

5.9. Lift & Moment Generation

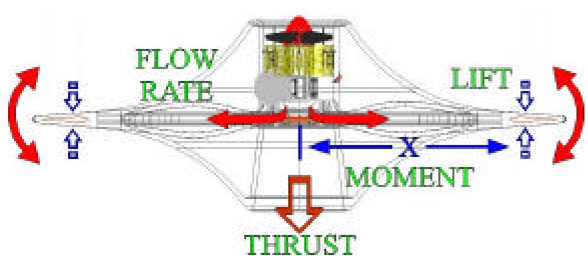

Figure 07

The predominant thrust is down through the main exit. What is "bleed" from the compressor section flows over the airfoils. Lift is generated when the airfoils rotate causing a moment to be generated ultimately compensating for any tilt the craft may incur, both in pitch and roll. What lift is generated per degree of rotation must be approximated. From this, one can accurately predict the moment generated and can more appropriately determine the overall diameter of the craft.

6. Power Plant

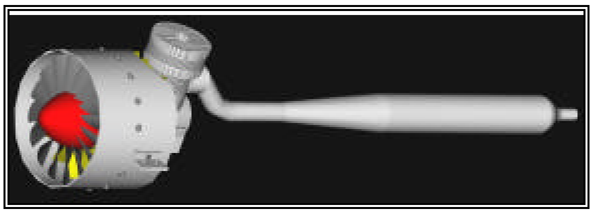

Figure 08 – Dynamax Fan and O.S. Max .77 engine

The power plant used is a Dynamax Ducted Fan Unit Originally designed for model aircraft use; I decided to test its performance in a different application. I paired the Dynamax Ducted Fan Unit with an OS max .77-size engine. The pair should produce approximately 10 lbs. of static thrust according to factory specs. Currently the craft is being designed to approximately 8 lb. limit. Due to the fact that this engine is new, but currently approximately 12-15 years discontinued, I was able to receive a practical price. Incorporation of an OS .91 can easily be adapted at a later point (providing approximately 2-5 more lb. of thrust) when more funding is available. This combination (Fan/engine/glow plug/carburetor) weighs 1.190 kg. The tuned exhaust pipe, necessary for maximum engine performance and efficiency, weighs 0.154 kg. With 24oz of fuel, one can expect approximately seven minutes of flight time. Total capacity of the fuel cells will be 32 oz, but most likely not all will be used. Vibration will be a serious concern in this case due to the sensitivity of some of the sensors. I'm hoping they can be filtered out successfully. I was unsuccessful in finding exact specifications, but I managed to speak with a technical representative at OS engines. Together we predict the engine horsepower to be anywhere between ≈ 3.5 hp to ≈ 4.2 hp. The engine rpm is approximately 5,000 to 22,000 rpm. To regulate the engine rpm and fuel/air mixture is a flight governor. It has three programmable rpm settings and can be remotely turned on and off. It utilizes a Hall effect sensor. This combination constitutes the static thrust predictions needed for sustained hover.

Figure 09 –Ducted Fan Unit & GV1 Flight Governor

6.1. Rotation About a Central Axis

This is a discussion concerning performance of torque and angular momentum generated by the engine and fan. The blade exerts a tangential force component on the fluid (air) in the direction of motion of the blade. The tangential force component and blade motion are in the same direction. The engine and fan together, basically act as a pump. The torque originates from the engine and performs work on the fan, and then the fan to the fluid. This is an important consideration and must be addressed. If not addressed, this induced torque will be transferred to the entire craft, causing it to spin and to be virtually uncontrollable due to the symmetric nature of the craft.

6.1.1. Torque Approximation

Due to the unpredictable nature of fluid dynamics, one can only accurately predict a range for the torque generated by the engine. The torque on the system may be more. Calculating torque can be accomplished a number of ways. Probably the easiest way to calculate the torque on a shaft generated by an engine would be to utilize the horsepower approximations.

$$Range: [3.50\,hp - 4.20\,hp]$$

$$W = T_s \times w$$

$$3.50\,hp \times \frac{550\,\frac{ft \cdot lb}{\sec}}{hp} = T_s \times 21000\,\frac{rev}{\min} \times \frac{2p}{rev} \times \frac{1\min}{60\sec}$$

$$T_{s(3.5hp)} = 0.875\; ft \cdot lb$$

$$T_{s(4.2hp)} = 1.05\; ft \cdot lb$$

For the system, torque on the shaft must equal the external resulting forces on the system. Angular momentum states:

The net torque on a control volume assumes:

1.) Conservation of mass
    a. Steady flow
    b. Velocity normal to surfaces
    c. Velocity and density are constant
    d. There exists one inlet and one exit to the control volume.
2.) Neglecting:
    a. Bearing friction
    b. Drag of the fluid on outside of rotor
    c. Fluid shearing stress

$$T_z = \int_{cs} (r \times V_z)(rV \cdot \partial A)$$

$$T_z = \dot{m}(r_2 V_{t2} - r_1 V_{t1})$$

7. Flow Analysis

Flow is an important consideration in many senses. As to whether and where the flow will be turbulent, laminar or fully developed can really only right now be hypothesized. (I would like to inspect these attributes more.) Establishing some flow rate calculations aid in possible predictions. Again, due to the many factors included in flow analysis, the mathematical descriptions are used to give a good approximation of what to expect. The first analysis is based on flow directly from the fan unit. (Following will be flow analysis from the exit of the craft and the exit of the ducts). The flow from the duct exits basically acts as jets. The flow out of the jets will partially govern the amount of lift generated by the airfoils. What's more important is to analyze how the flow will change while constricting the flow with the flow control aperture.

7.1 Flow Control (Aperture)

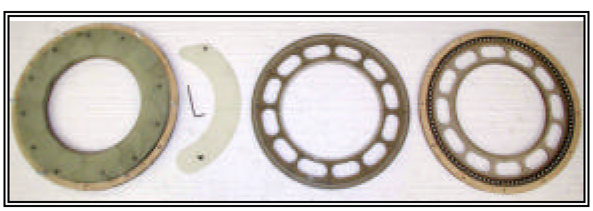

Figure 10 – Aperture Design

Flow control is very important, especially at zero altitude or take-off. The idea is to minimize ground effects. So on take-off, when the aperture is partially closed (basically stalling the fan), the engine can maintain it's maximum rpm where it is most efficient, and generate more flow through the ducts. This will establish more flow over the airfoils creating more precise control on take-off and landings (maximum control, zero lift). Once the aperture opens, the craft instantly experiences the thrust necessary for take off. It takes a lot more effort [time] to control spin up and spin down of the fan and engine rpm (which obviously governs the amount of thrust) than it does to open and close an aperture. The thrust control is greatly affected by this concept; the craft will have a higher response and should prove to be effective. Although this prototype will not be used, its principles will be.

8. Manufacturing

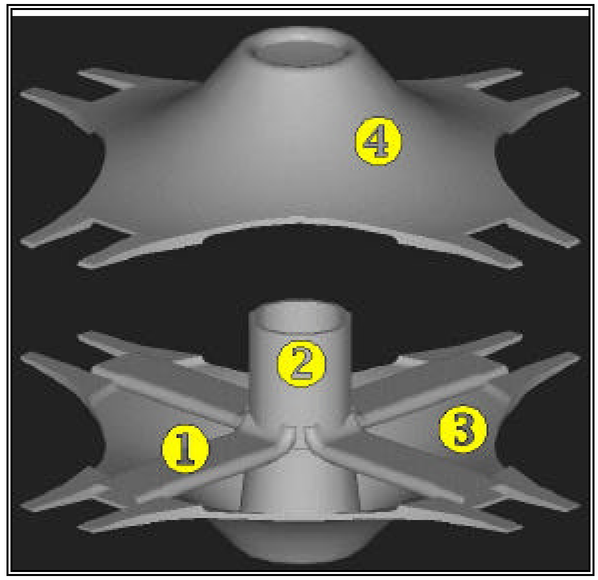

Figure 11 – Individual Molded Components

8.1. Materials & Construction

The composite structure is carbon fiber. The first prototype may use a polystyrene foam mold. Then vacuum mold it with ¾ oz fiberglass and epoxy resin. It is cheaper, more readily available, and does not need to be baked. The next prototype will definitely be a vacuum molded carbon fiber shell. It will be very strong and very light. Drawbacks are that it costs more and the process is different due to having to bake the carbon fiber and mold. It can be done. The mold will be cut using a process called Computer Numeric Control (CNC) manufacturing. This greatly simplifies the task of creating the molds in order to vacuum mold with fiberglass or carbon fiber. The whole process will consist of four molds (refer to figure 11): the main duct, auxiliary ducts, top, and bottom. Creating these four individual pieces greatly simplifies construction. Simple landing gear and the necessary accessories will be adapted later.

9. Stability and Control

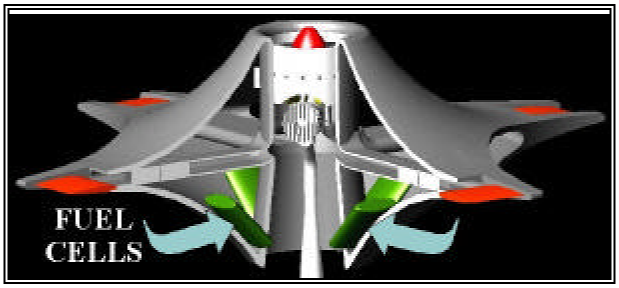

Figure 12 – Concentration of Weight Location

Stability and control is closely linked to the physical design and the control system. Physically, the craft itself is designed to be inherently stable due to the location of the fuel cells and electronics. The objective is to try and orient the "movable" components as close to the bottom as possible in order to create a "pendulum" effect. In other words, orient the center of gravity (cg) as low as possible. A beneficial, though not too significant, aspect concerning the fuel cells is that, as the fuel is consumed, the cg actually gets even lower. In this manner, the craft will naturally want to "right" itself, aiding the control system. This way, there are both physical and electrical aspects to this control system, both assisting each other. One does not on the other hand, what to make the craft too stable either. That would also make the craft difficult to control defeating the whole purpose. I really don't foresee that being a problem.

10. Control System Description

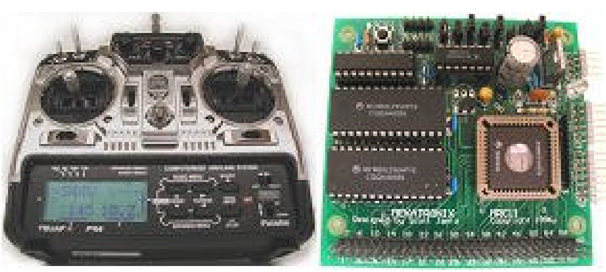

Figure 13 –Computer Radio & HC11 Micro Controller

Motor and sensor control revolves around a Motorola MC68HC11 (fondly known as the HC11) micro controller on a MRC-11 board (designed at University of Florida's Machine Intelligence Lab). The HC11 is responsible for sensor inputs and for decoding pulse-width-modulated (PWM) signals from the radio's receiver. The receiver receives RF input from Futaba's T8UAF computer controlled radio. Autonomous level flight is maintained, however, any user input can override the control system. It is important to note that the computer always assists the remote pilot. Essentially, any user input will control the sensitivity of the sensors. This is a dynamic system. This creates a smooth transition between maneuvers. Manual control will be powered by the receiver batteries incase the computer batteries fail. For any reason, one will always have manual control. An emergency cut-off switch will be located on the radio should a situation deem necessary.

10.1. Dynamic Multi-axis Motion

10.1.1. Sensors

Sensors consist of the following:

1. Accelerometers, or three axis accelerometer
2. Angular rate sensors
3. HeliMax Heading hold piezo gyros
4. Futaba Pilot Assist Link (horizon sensor)
5. Solid state compass
6. Futaba GV1 Flight Governor

10.1.2. Liquid vs. Solid-State

There are several possible choices of sensors to provide pitch, roll, and yaw data. Some choices are naturally better than others due to some concerns with vibration and the level of accuracy necessary. Consequently, any mercury or liquid-level based tilt sensors will not do. That casts out the inexpensive method of dynamic motion measurement. The most probable of all sensors would be something like the Analog Devices ADXL202 accelerometer paired with angular rate sensors, a solid state sensor system. A low pass filter, 100 Hz or lower cutoff frequency (a single pole RC filter), must be generated to lessen the "noise" generated from engine vibrations. The sensors must be soft mounted. They are very accurate and quite susceptible to vibration. Dampening will be tricky. A promising sensor is the horizon sensor. It manages to find a horizon using light. It can distinguish the difference between the sky and the horizon (ground). One major drawback is that it must be a "nice day" outside.

10.1.3. Gravity & Rotation Rate

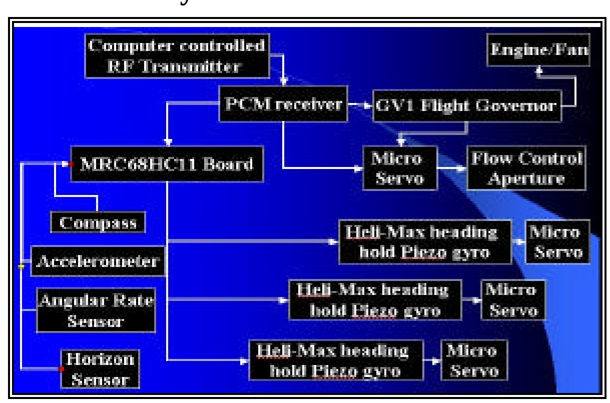

Figure 14 – Control System Flow Chart

The dynamic motion measurement necessary will consist of a pair of sensors, each compensating for the others weaknesses. As a pair they provide redundancy. The horizon sensor will prove interesting to experiment with and will definitely be explored. Accelerometers measure changes in gravity (tilt), while angular rate sensors measure rotation rate (roll, pitch, and yaw) around a certain axis. This is a problem considering rotation angle is needed, not rotation rate. One must integrate the rate over time for each axis (x-axis; pitch, y-axis; roll, z-axis; yaw) to get the crafts angle for each axis as a function of time. Any error produced with time may be ignored due to the very short, continuously changing periods of tilt. The servo controlling the variable stator vanes (compensates for torque of engine) will have its own channel that will be able to be fine tuned in flight by the pilot's radio. A simple algorithm can be developed to relate the accelerometers change in voltage to angle of rotation. For example, every 0.1 g acceleration in any axis would be $\sin^{-1}(0.1) = 5.7^o$ on that axis.[4] A similar algorithm can be modified (add parameters such as gain and error reduction) to suit specific demands.

10.1.4. Gyros & Stabilization

Figure 15 – Heading Hold Piezo Gyro

Gyros are a special addition to SADTU. They play several important rolls. Conventional gyros make use of a spinning flywheel powered by a small electric motor. A piezo gyro uses a piezoelectric crystal that uses no moving parts. The Heli-Max Heading Hold piezo gyros are more durable and compact than conventional gyros. They are also more accurate and more reliable. Gyros sense motion about the axis it controls, and sends a PWM signal to the servo, steering it in the opposite direction preventing unwanted rotation. Theoretically, gyros may be all that's needed to physically stabilize SADTU. It will be nice to achieve harmonious control amongst these sensors due largely to their quality. In standard mode, the gyros act as a conventional gyro. When set in heading hold mode, a neat feature of the HeliMax gyros, the servo is held in the last position set by the pilot's transmitters last stick movement, until another is given. This is great when facing unexpected events, such as a gust of wind. They gyros will compensate nicely for such external influences. The mode between conventional and heading hold can be remotely switched on the transmitter. The PC board has an anti-vibration design to absorb shock and vibration. It has built in drift and temperature compensation, a servo speed selector, and a throw expander and limiter. It will be a fancy, unique, little control system.

10.1.5. Sensor Location

Acceleration must be measured along each orthogonal axis. Therefore, accelerometers must be affixed as closely to the crafts cg in order to minimize rotational or centripetal accelerations. The heading hold gyros can be mounted almost anywhere (on it's axis of course). The remaining components should be placed low, and in balanced positions, which will be determined later.

11. Acknowledgements

I would like to thank the following companies for their generous support and student aid regarding components and hardware.

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Paneltech
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Dow Chemical
Florida Fasteners & tool CO., INC.
Analog Devices

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