PROTECTIVE SHROUD FOR AN AUTONOMOUS UNMANNED AERIAL VEHICLE

A Thesis by

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the requirements for the degree of
  Master of Science

December 2006
I have examined the final copy of this thesis for from and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a Major in Mechanical Engineering.

______________________________
Brian Driessen, Committee Chair

The following faculty members have read this thesis and recommend its acceptance:

______________________________
Behnam Bahr, Committee Member

______________________________
Asraf Teshomi, Committee Member
DEDICATION

To my parents and brother
ACKNOWLEDGMENTS

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Unmanned aerial vehicles are high in demand for various purposes such as surveillance and reconnaissance in military applications. They are also widely used for civilian applications in fire monitoring and analysis, coffee harvest optimization, irrigation, crop management and other applications. Damage to UAVs is common due to the absence of an onboard pilot. One of the steps involved in reducing damage to UAVs is protecting the rotors from damage during collision with obstacles.

In this thesis the design and development of a protective shroud for a quadrotor vehicle which will enable it to continue flight even after collisions with obstacles has been achieved. The shroud will protect the rotors from any kind of damage during collisions with obstacles during flight.

Work has been done on the development of Differential Global Positioning System for position control of the quadrotor vehicle.
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LIST OF SYMBOLS

\( \mathbf{e}_N \)  Inertial axis in the North direction
\( \mathbf{e}_E \)  Inertial axis in the East direction
\( \mathbf{e}_D \)  Inertial axis in the Down direction
\( \mathbf{x}_b \)  Body axis in the X direction
\( \mathbf{y}_b \)  Body axis in the Y direction
\( \mathbf{z}_b \)  Body axis in the Z direction
\( \varphi \)  Roll angle
\( \theta \)  Pitch angle
\( \psi \)  Yaw angle
\( \mathbf{r} \)  Position vector from the inertial origin to the vehicle center of gravity (CG)
\( \omega_b \)  Angular velocity in the body frame
\( \mathbf{e}_v \)  Current velocity direction
\( \mathbf{Q}_i \)  Aerodynamic torque
\( \mathbf{T}_i \)  Thrust
\( \mathbf{u}_i \)  Voltage applied to the motors
\( \mathbf{D}_b \)  Body drag force
\( \mathbf{m} \)  Vehicle mass
\( \mathbf{g} \)  Acceleration due to gravity
\( \mathbf{F} \)  Total force
\( \mathbf{M} \)  Total moment
\( \mathbf{R}_r \)  Rotation matrix for roll
\( \mathbf{R}_p \)  Rotation matrix for pitch
\( \mathbf{R}_y \)  Rotation matrix for yaw
\( \mathbf{I} \in \mathbb{R}^{3\times3} \)  Inertia matrix
1.1 Overview:
Unmanned aviation had its beginnings with the models built and flown by Cayley, Stringfellow, Du temple, and other aviation pioneers as precursors to their attempts at manned flight in the first half of the nineteenth century. These models were used as the technology testbeds for larger, man-carrying versions, and in this sense they were the forerunners for manned aviation. The child’s rubber band powered toy of today represented the leading edge of aeronautics in that era, and through such models the advantages of wing dihedral and camber were revealed and studied. [1]

In its broadest definition unmanned aviation encompasses a wide range of flying devices. The geology of unmanned aircraft is depicted in the following figure.

**FIG 1.1 [1]**
Starting from its roots as an “aerial torpedo,” the forerunner of today’s cruise missiles, its family tree has branched out to include guided glide bombs, target drones, decoys, recreational and sport models, research aircraft, reconnaissance aircraft, combat aircraft and even exotic astroplanes-aircraft designed to fly in the atmospheres of the other worlds. Unmanned aircraft in these last four branches are widely referred to today as unmanned aerial vehicles.

1.2 Definition of UAVs:

The term unmanned aerial vehicle came into general use in the early 1990s to describe robotic aircraft and replaced the term remotely piloted vehicle (RPV), which was used during Vietnam War and afterward. Joint publication 1-02, the Department of Defense Dictionary defines a UAV as, “A powered, aerial vehicle that does not carry a human operator uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or non-lethal payload. Ballistic or semi-ballistic vehicles, cruise missiles, and artillery projectiles are not considered unmanned aerial vehicles”.

1.3 Literature overview:

Cruise missiles were the first unmanned aircraft built to destroy themselves along with their targets, such as the Kettering Aerial Torpedo, a 240-kg (530-lb) flying bomb developed for the United States Army in 1918. Target drones were the first radio-controlled UAVs used during World War II (1939-1945) to train antiaircraft gunners.

The first reconnaissance UAV was a modification of the FirebeeU.S which was USA Air Forces jet powered drone. The Air Force used these for spy flights over North Vietnam and China during the Vietnam War (1959-1975).

In the early 1970’s the modern UAV originated. Smaller, cheaper UAVs were started by designers in the United States and Israel. They resembled large model airplanes, with power provided by motorbike or snowmobile engines. The most important feature of these UAVs was that they used new, small video cameras which could send pictures in real time to the operator.
“Mini-UAVs” in combat were first used by Israel. In 1982 Scout and Pointer UAVs destroyed Syrian air defenses in Lebanon in advance of Israel’s air attack, and helped Israel achieve a crushing victory. In the 1991 Persian Gulf War, the Israeli-designed Pioneer was the UAV used by allied forces.

UAVs had a widespread usage in the 1999 Kosovo war. Various UAVs were employed by United States and 4 allied nations to help commanders in difficult terrain and poor visibility identify possible targets.

During the 2003 U.S.-British invasion of Iraq that ousted President Saddam Hussein’s regime, Predators were extensively used. The low-flying Predators were primarily used to detect antiaircraft fire so that those positions could be pinpointed and then bombed. The Joint Chiefs of military Staff cited the higher-flying Global Hawk for its ability to provide 24-hour, all-weather surveillance for an area the size of the state of Illinois. Totally, ten different types of Predators were used by the Army, Air force and the Marines during the war.

Most current UAVs are simple, conventional aircraft, but new technologies are used in some experimental UAVs. Reliability is one important issue in UAV development. As UAVs become more reliable, they may be allowed to fly in the same airspace as civilian aircraft, which they cannot do currently.

The Backpack UAV

In 2003, the Marine Corps adopted the Dragon Eye UAV (Fig 1.2), the smallest functioning unmanned aerial vehicle, in an effort to minimize friendly casualties and maximize pre-movement surveillance. It is a 1.9-kg (4.3-lb) battery-powered UAV with a 114-cm (45-in) wingspan. The Dragon Eye can be carried in a backpack and is hand-launched. The Dragon Eye is primarily used in missions to take pictures of supposed improvised explosive device strips and bunkers on buildings invisible from the ground. [8]
Civilian UAVs

Other UAVs are used for scientific research or civilian uses. Helios Prototype (Fig 1.3) is the name of a solar- and fuel cell system-powered unmanned aerial vehicle that NASA tested. AeroVironment, Inc. developed the vehicle under NASA's Environmental Research Aircraft and Sensor Technology program. On 13 August 2001, it set an altitude record for a propeller-driven aircraft, reaching at 96,863 feet (29,511 m). [7]

Combat UAVs

For the sole purpose of carrying weapons some UAVs are used. These aircraft are known as unmanned combat aerial vehicles (UCAVs). The X-45A (Fig 1.4) is a 1,000km/h (600-mph) jet made by Boeing Company and first flown in June 2002 is designed to transport eight 250-lb small diameter bombs. It is known as a “stealth” fighter because it is designed in a way to make it difficult to detect by radar and made of special materials. [6]

Figure 1.2: Dragoneye [3]
Figure 1.3: Helios [4]

Figure 1.4: X-45 A [5]
1.4 Objective:
The objective of the research work carried out at Wichita State University was the “Design of a Protective Shroud for a quadrotor vehicle”. We plan to develop a cluster of fully autonomous mini UAVs which have the capability of flying without touching each other and continue successful flight even during inter vehicular collisions.

The thesis work is divided into 2 parts. Part 1 involves the building of a protective shroud for the UAV and testing it by collisions with the wall.

Part 2 involves developing the position control for the UAV using Global Positioning System.
CHAPTER 2.0

Quadrotor history:

Four years after the Wright brothers’ first successful powered flights in fixed-wing airplanes at Kitty Hawk in the United States, in 1907 a French bicycle maker named Paul Corneo designed and developed a vertical flight machine which was said to have carried a human off the ground for the first time. Boulet (1984) gives a good account of his work. The airframe was quite simple, with a rotor at each end. Power was supplied by a gasoline motor and a belt transmission to each of the rotors. The rotors rotated in opposite directions to cancel torque reaction. A primitive means of control was achieved by placing auxiliary wings in the slipstream below the rotors. The machine was supposed to have made several tethered flights of a few seconds at low altitude, but this has never been recorded. [9]

Fig 2.1 Vertical Flight machine [9]

In 1904 French academician and scientist Charles Richet built a unpiloted small helicopter. While the machine was unsuccessful, one of Richet’s students was the future famous aviation pioneer, Louis Breguet. During the latter part of 1906, the brothers Louis and Jacques Breguet had begun to conduct helicopter experiments of their own under the guidance of Professor Richet. The Breguet Brothers were a famous affluent clock making family, and they later became pioneers in French aviation. Louis Breguet made meticulous tests of airfoil shapes, paralleling those of the Wright Brothers [see Anderson (1997)], and understood the essential aerodynamic theory of the helicopter. The Breguet Brothers built their first helicopter in 1907.
Their quad-rotor Gyroplane No.1 consisted of four long girders made of steel tubes and arranged in the form of a horizontal cross. A rotor consisting of four biplane blades was placed at each of the four corners of the cross, giving a total of 32 separate lifting surfaces. The pilot would sit in the center of the cross next to a 40-hp engine. The machine is recorded to have carried a pilot off the ground, though briefly. Photographs showed several men assisting, stabilizing and perhaps even lifting the machine. The machine never flew completely freely because, like the Cornu machine, it lacked stability and a proper means of control.

In the early 1900s, Igor Ivanovitch Sikorsky and Boris Yur'ev started to design and build vertical lift machines in Czarist Russia independently. By 1909, inspired by the work of Cornu and other French aviators, Sikorsky had built a nonpiloted coaxial helicopter prototype. This machine did not fly because of the lack of a powerful enough engine and vibration problems. Sikorsky (1938) stated that he had to await "lighter materials, better engines and experienced mechanics." His first design, the S-1, was unable to lift its own weight, and the second machine, the S-2, only made short (nonpiloted) hops even with a more powerful engine.

Although he never gave up his vision of the helicopter, it was not until the 1930s after he had immigrated to the United States that he again pursued his ideas of vertical flight.
Boris Yur'ev had also tried to build a helicopter around 1912 in Russia. This machine had a very modern looking tail rotor configuration and single rotor. The large diameter, high aspect ratio blades suggested that this was the configuration for high aerodynamic efficiency. However like Sikorsky's S-1 and S-2, Yur'ev's aircraft lacked a powerful enough engine. The helicopter never flew properly, being pulled down with mechanical failures. Yet, besides being one of the first to use a tail rotor design, Yur'ev was another one of several firsts to propose the concepts of cyclic pitch for rotor control.

Crocco, who pioneered the ideas of hydrofoil boats, recognized that if a helicopter in forward flight was to work properly, a means of changing the pitch on the blades would be needed to account for the dissymmetry in the aerodynamic loads between the side retreating away from the wind and side of the rotor advancing into the relative wind. The concept of cyclic pitch was one key to attaining full control of the helicopter as mentioned earlier. [9]
It was not until the 80’s that interest in quadrotor vehicles was rejuvenated. Now many researchers are working on the quadrotor vehicles for UAV applications for their simplicity in design, low cost and higher payload capacity.

2.1 X-4 FLYER [10]

The X4 FLYER is a quadrotor helicopter purchased from a Canadian based company, RC TOYS.
FIG 2.6 Detailed components of Dragonflyer V Ti [10]

The above figures show the detailed assembly of an X4 flyer.
**Components of X 4 Flyers**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Dragonflyer V Ti circuit board</td>
</tr>
<tr>
<td>2</td>
<td>Dragonflyer V Ti carbon fiber frame</td>
</tr>
<tr>
<td>3</td>
<td>Carbon fiber base plate</td>
</tr>
<tr>
<td>4</td>
<td>Clear dome canopy</td>
</tr>
<tr>
<td>5</td>
<td>4-channel digital proportional FM transmitter</td>
</tr>
<tr>
<td>6</td>
<td>3 cell 11.1 volt Lithium Polymer battery</td>
</tr>
<tr>
<td>7</td>
<td>Set of 4 rotors (2 clockwise 2 counter clockwise) and decal sheet</td>
</tr>
<tr>
<td>8</td>
<td>120 volt AC peak charger for Lithium Polymer battery pack and transmitter</td>
</tr>
<tr>
<td>9</td>
<td>Set of Velcro tape for flight battery</td>
</tr>
</tbody>
</table>

**Dragon flyer V Ti small parts pack for main frame:**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>5/64” allen key wrench</td>
</tr>
<tr>
<td>4</td>
<td>6/32” Nylon nut caps for carbon fiber bottom plate</td>
</tr>
<tr>
<td>12</td>
<td>2-56*3/8” hex socket cap bolt for main frame bolts</td>
</tr>
<tr>
<td>12</td>
<td>#2-56 3/16”*1/16” hexagon nuts for main frame</td>
</tr>
<tr>
<td>8</td>
<td>#4-40*3/8” nylon mounting screws for main rotors</td>
</tr>
</tbody>
</table>
**X4 FLYER CONTROLS**

Aileron operation (Left/Right- Roll)
The Dragonflyer V Ti will tilt to the right when the aileron stick is moved to the right. The right motor speed reduces and the left motor speed increases. The Dragonflyer V Ti tilts to the left when the aileron stick is moved to the left. The left motor speeds down and the right motor speed increases.

![Aileron operation (Left/Right- Roll)](image)

**FIG 2.7 Aileron operation (Left/Right- Roll) [10]**

Elevator operation (forwards/ backwards- pitch)
When the elevator stick is pulled back, the Dragonflyer V Ti will tilt in a backwards direction. The front motor speed increases and the rear motor speed decreases. When the elevator stick is pushed forward, the Dragonflyer V Ti will move forward. The front motor slows down and the rear motor speed increases.

![Elevator operations (forwards/ backwards- pitch)](image)

**FIG 2.8 Elevator operations (forwards/ backwards- pitch) [10]**
Rudder operation (Rotating clockwise/counter-clockwise-Yaw)

When the rudder stick is moved to the left, the speed of the counterclockwise turning rotors slow down while the speed of the clockwise rotors increases. This makes the Dragonflyer V Ti rotate to the left. When the rudder stick moves towards the right, the clockwise rotors slow down while the counterclockwise rotors speed increases. This will cause the Dragonflyer V Ti to rotate to the right.

![Diagram of rudder operation](image)

FIG 2.9 Rudder operation (Rotating clockwise/counter-clockwise-Yaw) [10]

X4 FLYER FACTS:

- The maximum payload capacity of X4 flyer is 0.25 pounds.
- The total weight of the protective carbon tubing comes to 0.2323 pounds, which is just below the X4's payload of 0.25 lbs

Advantages of X4 flyer over conventional 1 rotor helicopters

<table>
<thead>
<tr>
<th>X4 FLYER</th>
<th>SINGLE ROTOR HELICOPTER</th>
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<tr>
<td>Short assembly time</td>
<td>Longer assembly time</td>
</tr>
<tr>
<td>Few components</td>
<td>More number of components</td>
</tr>
<tr>
<td>Easier to fly</td>
<td>Difficult to fly</td>
</tr>
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</table>

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2.2 Previous work on X-4 Flyer

**Motivation:**

Extensive research has been made on UAVs in the recent past. Many universities have been involved in the work on autonomous flight of unmanned aerial vehicles. Some of the works are

**STARMAC project (Stanford Testbed for Autonomous Rotorcraft for Multiagent Control) [11]**

The Stanford Testbed of Autonomous Rotorcraft for Multi-Agent Control (STARMAC) is a multi-vehicle test bed used to demonstrate new concepts in multi agent control on a real-world platform. For the success of such a testbed, the focus was on developing a small and light, low-cost design, which presented numerous opportunities for innovative work. STARMAC consists of up to eight quadrotor vehicles that autonomously track a given waypoint trajectory and the main goals of the project lie in two phases:

- Phase 1: Vehicle and Testbed Design and Flight
- Phase 2: Multi Agent Control Demonstration

![STARMAC PROJECT](image)
The Quattrocopter [12]

The EADS Quattrocopter is a quadrotor unmanned aerial vehicle capable of flying autonomously for more than 20 minutes within a range of about a kilometer. It weighs 550 grams and spans 65 centimeters in its flight configuration (and 35 folded). By controlling the speed of the rotors which steer it, the operator can launch it into the air at the speed of about 15 meters per second. The onboard electronics include a micro avionics autopilot that has 6 degrees of freedom MEMS inertial measurement unit (IMU), air data sensors, and a GPS receiver, an R/C receiver, a 16 bit analog to digital converter, and power amplifiers to power the motors.
CHAPTER 3

Dynamics of an X-4 Flyer [13]

“The derivation of the nonlinear dynamics is performed in North-East-Down (NED) inertial and body fixed coordinates. Let \( \{ \mathbf{e}_N, \mathbf{e}_E, \mathbf{e}_D \} \) denote the inertial axes, and \( \{ \mathbf{x}_B, \mathbf{y}_B, \mathbf{z}_B \} \) denote the body axes, as defined in Figure 2. Euler angles of the body axes are \( \{ \phi, \theta, \psi \} \) with respect to the \( \mathbf{e}_N \) and \( \mathbf{e}_D \) axes, respectively, and are referred to as roll, pitch and yaw. Let \( \mathbf{r} \) be defined as the position vector from the inertial origin to the vehicle center of gravity (CG), and let \( \mathbf{\omega}_B \) be defined as the angular velocity in the body frame. The current velocity direction is referred to as \( \mathbf{e}_v \) in inertial coordinates”.

Fig 3.1 Free body diagram of X-4 Flyer [13]

“The rotors, numbered 1-4, are mounted outboard on the \( \mathbf{x}_B, \mathbf{y}_B, - \mathbf{x}_B \) and \( - \mathbf{y}_B \) axes, respectively, with position vectors \( \mathbf{r}_i \) with respect to the CG. Each rotor produces an aerodynamic torque, \( Q_i \), and thrust, \( T_i \), both parallel to the rotor’s axis of rotation, and both used for vehicle control. Here,
\( T_i = u_i \cdot \left( \frac{k r / 1 + 0.1 s}{1 + 0.1 s} \right) \), where \( u_i \) is the voltage applied to the motors, as determined from a load cell test. In flight, \( T_i \) can vary greatly from this approximation. The torques, \( Q_i \), are proportional to the rotor thrust, and are given by \( Q_i = k r T_i \). Rotors 1 and 3 rotate in the opposite direction as rotors 2 and 4, so that counteracting aerodynamic torques can be used independently for yaw control.

Horizontal velocity results in a moment on the rotors, \( R_i \), about \(-e_z\), and a drag force, \( D_i \), in the direction \(+e_z\).

The body drag force is defined as \( D_B \), vehicle mass is \( m \), acceleration due to gravity is \( g \), and the inertia matrix is \( I \). A free body diagram is depicted in Figure 2. The total force, \( F \), and moment, \( M \), can be summed as,

\[
F = -D_B e_z + m g e_y + \sum_{i=1}^{4} (-T_i e_y - D_i e_z) \quad (1)
\]

\[
M = \sum_{i=1}^{4} (Q_i e_y - R_i e_z - D_i (e_y \times e_z) + T_i (e_y \times e_x)) \quad (2)
\]

The full nonlinear dynamics can be described as,

\[
m \ddot{r} = F
\]

\[
I \ddot{\omega} + \omega \times I \omega = M \quad (3)
\]

where the total angular momentum of the rotors is assumed to be near zero, because they are counter-rotating. Near hover conditions, the contributions by rolling moment and drag can be neglected in Equations (1) and (2).

Total thrust is defined as \( \sum_{i=1}^{4} T_i \). The translational motion is defined by,

\[
m \ddot{r} = -R_y \cdot R_x \cdot R_z e_y + m g e_y \quad (4)
\]

where \( R_y, R_x, \) and \( R_z \) are the rotation matrices for roll, pitch, and yaw, respectively. Applying the small angle approximation to the rotation matrices

\[
\begin{bmatrix}
\dot{\theta} \\
\dot{\phi} \\
\dot{\psi}
\end{bmatrix} =
\begin{bmatrix}
1 & \psi & \theta \\
\psi & 1 & \phi \\
\theta & -\phi & 1
\end{bmatrix}
\begin{bmatrix}
0 \\
0 \\
-T
\end{bmatrix} +
\begin{bmatrix}
0 \\
0 \\
m g
\end{bmatrix} \quad (5)
\]
Finally, assuming total thrust approximately counteracts gravity, \( T \approx T = mg \), except in the \( e_p \) axis,

\[
\begin{pmatrix}
\dot{\phi} \\
\dot{\theta} \\
\dot{\psi}
\end{pmatrix} = \begin{pmatrix}
0 & 0 & -T \\
0 & T & 0 \\
mg & 0 & 1
\end{pmatrix} \begin{pmatrix}
\phi \\
\theta \\
T
\end{pmatrix}
\]  \hspace{1cm} (6)

For small angular velocities, the Euler angle accelerations are determined from Equation (3) by dropping the second order term, \( \omega \times I \omega \), and expanding the thrust into its four constituents. The angular equations become,

\[
\begin{pmatrix}
\ddot{I}_x \\
\ddot{I}_y \\
\ddot{I}_z
\end{pmatrix} = \begin{pmatrix}
0 & l & 0 & -l \\
l & 0 & -l & 0 \\
kr & -kr & kr & -kr
\end{pmatrix} \begin{pmatrix}
T_1 \\
T_2 \\
T_3 \\
T_4
\end{pmatrix}
\]  \hspace{1cm} (7)
CHAPTER 4
SHROUD DESIGN

Design issues:

Initially a shroud was designed for the X-4 flyer using music wires. This design was successfully implemented on the X-4 flyer. The design was satisfactory in protecting the rotors without affecting the flight time of the X4 flyer. However during collisions the wires would snap off sometimes which was dangerous for the people around due to the sharp wires that may poke in the eye. Frequent snapping of wires would occur during collisions with walls. This resulted in wastage of time for replacing the wires.

FIG 4.1
X4 flyer shroud with music wires

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So we replaced the music wires with carbon fiber tubes which proved to be an excellent replacement option. These tubes are highly effective in protecting the rotors from damage during impact collisions. They also suffer minimal damage; as a result considerable time is saved for any replacement of these tubes. The below figure shows the shroud design for inter vehicular collisions.

FIG 4.2 X-4 flyer with carbon fiber shroud
Shroud specifications:

Length=Breadth=27.5 inches
Height=10.5 inches.
Diagonal length=38.89 inches (Using Pythagoras formula)
Another shroud was designed for the collisions with obstacles only. (Fig 4.4)

![Second X-4 Flyer shroud](image)

**FIG 4.4 Second X-4 Flyer shroud**

Statistics for shroud design

The below table gives the statistics for the flight of X-4 flyer in the Wallace hallway (in front of room 116)

<table>
<thead>
<tr>
<th>Flight times</th>
<th>Number of rotors Damaged(X-4 Flyer)</th>
<th>Number of rotors damaged(X-4 flyer with shroud)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 minutes</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>5 minutes</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

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• The maximum payload capacity of X4 flyer is 0.25 pounds.
• The total weight of the protection-carbon-tubing comes to 0.2323 pounds, which is just below the X4’s payload of 0.25 lbs (the original shroud-along with music wires).

Factors taken into consideration during design:

• Weight of the shroud being designed
• Toughness of the shroud to withstand impact collisions with the wall.
• Simplicity for easy replacement of shroud in case of damage.

CARBON FIBRE [14]

It is twice as stiff as high-strength aluminum alloys with an ultimate tensile strength that exceeds that of steel, yet it is the weight of plastic. Due to its very high strength to weight ratio, carbon fiber materials are uniquely qualified for high performance structural components in R/C aircraft, robotics, and other demanding applications.
Sandwich Structure = Lighter & Stiffer Plate

DragonPlate™ carbon fiber laminate is an engineered sandwich structure. When a panel is flexed, at the outer surfaces of the panel, the majority of the stresses are created. This is explained by engineering beam theory which shows the distribution of stress as a function of the distance from the center of the panel. It can be seen from the illustration that as one approaches the center of the beam the stresses reduce rapidly. This is why I-beams have thin center panel and wide flanges. It is why surf boards have a foam core and fiberglass skin.

The highest strength to weight structure takes advantage of this phenomenon and places lower density structural material internally as core and high strength carbon fiber at the outside skins of the panel.
DragonPlate CF Laminate utilizes aircraft-grade birch plywood as its core material. Birch is a fine-grained hardwood of exceptional toughness. It is the material of choice for wooden aircraft propellers. Aircraft-grade plywood is a very special material. Absolutely no knots or voids are allowed. Special waterproof glue is used and the plywood must be able to withstand a 24-hour boil test in water without delaminating.

Birch plywood laminate is approximately ½ the density of carbon fiber laminate, so DragonPlate is lighter weight than a 100% carbon fiber laminate of the same thickness. Because the bending strength of a plate is related to the square of its thickness, DragonPlate is stronger than a solid carbon fiber plate of the same weight.

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>ULTIMATE TENSILE STRENGTH(KSI)</th>
<th>TENSILE MODULUS E(MSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4130 STEEL</td>
<td>125</td>
<td>30</td>
</tr>
<tr>
<td>2024-T 3 ALUMINIUM</td>
<td>65</td>
<td>10</td>
</tr>
<tr>
<td>CARBON FIBER</td>
<td>200</td>
<td>20</td>
</tr>
</tbody>
</table>

**Comparison Tests**

We performed bending deflection tests using our own Dragonplate carbon fiber laminate and solid carbon fiber. The test samples were identical in length/width and similar in weight per square inch. The test procedure consisted of hanging weights from the end of the material and measuring the amount of deflection that occurred (see test set up below).
FIG 4.6 Bending Test [14]
The graphs below show a significantly higher strength to weight ratio, proving that Dragonplate laminate is stronger in bending than solid carbon fiber of the same weight.

FIG 4.7 Comparison graph [14]
FIG 4.8 Comparison graph [14]
Regarding Quality

- High quality carbon fiber laminates can be distinguished by their absolute flatness and lack of voids or surface bubbles.
- Dragonplate Carbon Fiber Laminates are manufactured by skilled technicians under rigid process control to exacting specifications.
3/16 inches right angled elbow hose fittings used for the design purpose. These are made of natural polypropylene material. [15]
Thrust calculation

The thrust of the rotors for a given motor speed was required to be calculated for our experiment.
The above figures show the experimental setup done in room 125(Wallace hall). A metallic fishing pole was used for this purpose. The motor was taped at one end of the tube. It was placed on a weighing scale and taped. Then the motor was powered with a 12 V battery. The rotor had a clockwise motion which resulted in the exertion of force on the weighing scale. This gave the thrust value in terms of grams. Also the RPM (Revolutions per Minute) of the rotors was noted using a photo tachometer. A piece of reflective tape was stuck on the rotor and the tachometer was aimed at the rotating rotor. The RPM reading was displayed on the tachometer.
Thrust data

Weight of X4 (grams): 610 grams
Rpm of rotors near hover: 2050 rpm
Voltage across motor (volts): 12.28 volts
Rotor thrust (grams) 210 grams
Rpm 2770 rpm

Thrust v/s RPM graph:

![Thrust v/s RPM graph](image)

Fig 4.13 Thrust v/s RPM graph

The above graph shows a lot of thrust v/s rpm. As the RPM of the rotor increases the thrust also varies almost linearly.
Thrust v/s voltage graph:

![Thrust v/s voltage graph](image)

**Fig 4.14 Thrust v/s voltage graph**

In the above graph it can be observed that as the voltage increases the thrust also increases gradually.
Impact collision calculations

The impact collisions of the X4 flyer with the wall has been recorded on a video camera. The speed of collision has been determined based on the frames of the video.

Speed calculations:

Preliminary results using the preliminary shroud in Figure 4.15 below are shown. It demonstrates the ability of the vehicle to continue successful flight following a collision with a brick wall at 2.3 mph. (The complete set of frames (not shown here) of the video are 0.07 seconds apart; this allows us to estimate the velocity at which the vehicle is hitting the wall.)

Figure 4.15. Preliminary shroud, allowing collisions with obstacles but not vehicle-to-vehicle collisions
Collision velocity calculations:

According to "Windows-Movie-Maker."

Second collision clocked occurs at: $t_2 = 12.7s$
Vehicle was one vehicle-width from wall at $t = 11.98s$.
So, the second collision's velocity estimate is, using 29" as the width of the vehicle:

\[
29\text{inches/} (12.7-11.98 \text{ sec}) \times (1\text{foot/12 inches}) \times (1\text{mile/5280feet}) \times (3600\text{sec/hour})
\]

\[= 2.3 \text{ mph}\]

(Hovering follows this collision.)

First collision clocked occurs at: $t_1 = 5.55s$
Vehicle was one vehicle-width from wall at $t = 4.89s$.
So, the second collision's velocity estimate is, using 29" as the width of the vehicle:

\[
29\text{inches/} (5.55 - 4.89 \text{ sec}) \times (1\text{foot/12 inches}) \times (1\text{mile/5280feet}) \times (3600\text{sec/hour})
\]

\[= 2.3 \text{ mph}\]
Figure 4.16. Collision at 2.3mph with wall, followed by vehicle hovering, frames at 0.2 second intervals (continued in Figure 4.16 b)
Figure 4.16b. Collision at 2.3mph with wall followed by vehicle hovering, frames at 0.8 second intervals (continued from Figure 4.16a).

The wires in Figure 4.16a and 4.16b are all just for convenience of controls development and testing and of course will not be in the final product.

In Figure 4.16, the wires are present simply for convenience. The wires do not provide any more rpm to the rotors than the on board flight battery’s rpm-capacity.

This on-board flight-battery is on the vehicle in Figure 4.16a. It is simply not providing any power to the vehicle in Figure 4.16. Also, only for convenience, the microchip computer on the vehicle is momentarily not being used in Figure 4.16a, although it could be. Temporarily, instead, Lab View, running on a PC, is being used for the real-time controls. These real-time controls are a PD control on the roll and pitch angles and a yaw-holding control which is almost a PD control except that the proportional term is purposely saturated to prevent it from causing saturation of the roll/pitch PD controls.

The PD controls on the roll/pitch provide an automatic self-leveling which allows the user to be momentarily distracted without a subsequent crash of the vehicle. The yaw-holding control is an automatic control that holds the vehicle at the currently requested vehicle heading. Both of these automatic controls make the vehicle much easier to control with a joystick. At the default user joystick inputs of zero for roll and pitch, the vehicle self-levels. Presently, the only additional hardware/sensors on the vehicle are a gyro and a power circuit.
To allow inter-vehicle collisions, the shroud from Figure 4.16a was modified as shown in Figure 4.16c below.

Figure 4.16c. Modified Shroud to Allow Inter-Vehicle Collisions

It is easily verified that the modified shroud allows rotor contact from a neighbor vehicle only when the two vehicles are tipped by almost 45 degrees relative to each other, as shown in Figure 4.17 below, in which contact between a shroud corner and the blue rotor occurs.
This sole means of possible rotor contact can also be eradicated by adding four short cross-bars on the top of the shroud.

For this configuration (in Figures 4.16 and 4.17), two Lithium batteries are used in series for extra thrust.

Preliminary results using the shroud of Figures 4.16 and 4.17 are given in Figures 4.18a and 4.18b below. These two figures demonstrate the vehicle colliding with the wall at 2.8mph and then continuing to fly in a stable manner after the collision.
Figure 4.18b. Collision at 2.8mph with wall, followed by vehicle hovering, frames at 0.8 second intervals (continued from Figure 4.18a), larger shroud that allows inter-vehicle collisions

Additional preliminary results are as follows. Figure 4.19a shows a successful inter vehicle collision in which the two faces of the vehicles collide. The relative velocity between the two vehicles was estimated to be about 3.5mph in Figure 4.19b.

Figure 4.19a. Successful face to face collision between two vehicles, relative impact velocity of 3.5mph, frames shown at 0.2 second intervals. Note: in the first frame, e.g.: one sees the bottom of the closer vehicle.
Figure 4.19b shows a successful inter vehicle collision in which the corner-edge of the first vehicle collides with the face of the second vehicle. In Figure 4.19b, the relative impact velocity is estimated to be 2.7 mph.

Using this same shroud, we are able to successfully collide the vehicle’s face head-on into the corner of a building, as illustrated in Figure 4.20 below, in which the collision velocity was estimated to be about 2 mph. Subsequent successful vehicle hovering is also shown.
Figure 4.20a. 2mph head-on collision of vehicle's face with the corner of a building followed by successful hovering, frames at 0.2 second intervals (continued in Figure 4.20b.)

Figure 4.20b. 2mph head-on collision of vehicle's face with the corner of a building followed by successful hovering, frames at 0.8 second intervals (continued from Figure 4.20a.)
Figure 4.21a shows successful 2mph collision of the vehicle’s corner edge with the face of a brick wall.

Figure 4.21a. 2mph collision of vehicle corner edge with face of brick wall, frames at 0.8 second intervals (continued in Figure 4.21b).

Figure 4.21b. 2mph collision of vehicle corner edge with face of brick wall, frames at 0.8 second intervals (continued from Figure 4.21a).
GPS (Global Positioning System): [16]

Global positioning system (GPS) is a satellite navigation system capable of providing continuous highly accurate global navigation service without help of other positioning aids. GPS provides worldwide 24 hr all weather coverage with timing, position and velocity information.

The system uses the NAVSTAR (Navigation Satellite Timing and Ranging) satellites which consist of 24 operational satellites with at least 6 satellites in view at all times for a GPS receiver. 4 satellites are required at a minimum in view to allow the receiver to compute its current altitude, latitude, longitude with reference to GPS system time and mean sea level.

GPS System Design:

The GPS design consists of 3 parts:

- The space segment.
- The control segment
- The user segment

The space segment:

The space consists of 24 NAVSTAR GPS satellites. Totally the system contains 24 satellites in six 55 degrees orbital planes; 4 satellites in each plane (plus additional extra room for spares). The total orbital period of each satellite is approximately 12 hours at an altitude of 20,183 kilometres. This would provide the GPS receiver with at least 6 satellites in total viewing scenario at any from any point of viewing..

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The GPS satellite signal provides the data of positioning, ranging, timing, satellite status and the corrected ephemeris (orbit parameters) of the satellite to the users after identifying the satellite. The satellites can be identified either by the Pseudorandom Code Number(PRN) or the space vehicle number(SVN). The PRN is generally used by the Novatel receiver.

The GPS satellites always transmit on 2 L-band frequencies, one centered at 1227.60 MHz(L2) and 1575.42MHz(L1). The L1 carrier is modulated by the C/A code(Coarse/Acquisition) and the P code (Precision) which is encrypted for military and other authorized users. The L2 carrier is modulated only with P code.

**The Control Segment**:

The control segment consists of a master control station, 5 base stations and 3 data up-loading stations in locations all around the globe.

The base stations track and monitor the satellites via their broadcast signals. The broadcast signals contain the ephemeris data of the satellites, the clock data, the ranging signals data, and the almanac data. The signals are passed to the master control station where the ephemerides are re-computed. The resulting timing corrections and ephemerides data are transmitted back via the data up-loading stations to the satellites.
The User Segment:

The user segment contains equipment which tracks and receives satellite signals such as Novatel receiver. The user equipment is capable of simultaneously processing signals from a minimum of 4 satellites to obtain accurate timing, position and velocity measurements.

GPS positioning

GPS positioning can be categorized as follows:

- Single point or relative
- Static or kinematic
- Real time or post mission data processing

Single point vs. Relative positioning

In single-point positioning, coordinates of a GPS receiver are obtained with respect to the earth’s reference frame by using the known positions of GPS satellites being tracked at an unknown location. The final position solution generated by the receiver is initially developed in earth-centered coordinates which will subsequently be converted to any other coordinate system. With even four GPS satellites in view, the absolute position of the receiver in three-dimensional space can be
determined. One receiver is sufficient. For our project we focused on single point positioning. In relative positioning, the coordinates of a GPS receiver at an unknown point (the “rover” station) are required with respect to a GPS receiver at a known point (the “base” station). The concept is illustrated in Figure 4, Example of Differential Positioning on Page 51. The relative-position accuracy of two receivers locked on the same satellites and not far removed from each other - up to tens of kilometers - is extremely high. The largest error contributors in single-point positioning are those associated with atmospheric-induced effects. These errors, however, are highly correlated for adjacent receivers and hence cancel out in relative measurements. Since the position of the base station can be determined to a high degree of accuracy using conventional surveying techniques, any differences between its known position and the position computed using GPS techniques can be attributed to various components of error as well as the receiver’s clock bias. Once the estimated clock bias is removed, the remaining error on each pseudorange can be determined. The base station sends information about each satellite to the rover station, which in turn can determine its position much more exactly than would be possible otherwise.

The advantage of relative positioning over single point positioning is much greater precision (presently as low as 2 cm) depending on the method and environment) can be achieved.

Static vs. Kinematic Positioning

Static and kinematic positioning refer to whether a GPS receiver in moving or stationery at a point during collection of GPS data.

Real-time vs. Post-mission Data Processing

Real-time or post-mission data processing refer to whether the GPS data collected by the receiver is processed after the entire data gathering session is complete or as it is received.
Differential Global Positioning System

Differential Global Positioning System (DGPS) is an enhancement to Global Positioning System which utilizes a network of fixed ground based reference stations to broadcast the difference between the positions indicated by the satellite systems and the actual known fixed positions.

In the US and Canada, these system commonly use long wave radio frequencies between 285 kHz and 325 kHz.

FIG 5.3 [16]  Example of differential positioning
GLOBAL POSITIONING SYSTEM SPECIFICATIONS

SUPERSTAR 2 FLEXPACK UNIT

HARDWARE SPECIFICATIONS
Size: 45x 147x123 mm
Weight: 307 Gms
Input voltage: +6 to +18 volts
Power consumption: 0.9 W (typical)

Communication ports:
- 1 RS-232 serial port capable of 19,200 bps
- 1 RS-232 DGPS port capable of 19,200 bps

Connectors
- Power: 3 pin waterproof Deutsch
- Antenna input: Waterproof TNC female
- COM1, COM2: 13-PIN waterproof Deutsch

Operating temperature: -30 deg C to 75 deg C
Humidity: 95% non-condensing
SUPERSTAR 2 CARD

HARDWARE SPECIFICATIONS

Size 46x71x13 mm
Weight 22 g
Input voltage +3.3 to +5V DC

Power consumption

3.3 V version 0.5 W (typical)
5 V version 0.8 W (typical)

Communication ports

- 2 TTL serial ports capable of 19,200 bps

Connectors

Main 20 pin dual row male header
Antenna input MCX female
Operating temperature -30 deg C to +75 deg C
Storage temperature -40 deg C to +45 deg C
Humidity 5% to 95% non-condensing to 60 deg C
STARVIEW software:

STARVIEW is the software used for getting the GPS data into the computer. It provides information about the receiver position and velocity information. It can be used to send and receive commands to the GPS receiver.

LABVIEW SOFTWARE: [19]

National Instruments LabVIEW is an industry-leading software tool for designing test, measurement, and control systems. LabVIEW has the flexibility of a programming language combined with built-in tools designed specifically for test, measurement, and control, to create applications that range from simple temperature monitoring to sophisticated simulation and control systems.

For our application we have used LabVIEW 8.0 version. The binary data generated from the receiver was acquired in LabVIEW software. The data analysis was done from the data obtained.

Steps involved in setting DGPS system

- The initial connections were made
- Data was acquired in Starview software. Required messages were selected for this purpose.(Message ID 20 AND 21)
- A code in Labview software was generated for data acquisition purpose.

TYPES OF PROTOCOLS USED [16]

Binary format

Binary messages are meant strictly as a machine readable format. They are also ideal for applications where the amount of data being transmitted is quite high. Due to the inherent compactness of binary as opposed to ASCII data, the messages would be smaller. This allows a larger amount of data to be transmitted and received by the GPS receiver’s communication ports. The standard message block structure of binary messages from a SUPERSTAR II-based receiver are noted here:

Byte 1: Start of Header (SOH)
Byte 2: Message ID#
Byte 3: Complementary ID#
Byte 4: Message Data Length (0...255)
Byte 5 ... n: n-4 Data Bytes
Byte n+1... n+2: Checksum

StarView allows you to view binary messages in ASCII format. Saved data is stored in its original Binary format.

NMEA FORMAT

NMEA log structures follow format standards as adopted by National Marines Electronics Association.
Challenges faced during GPS programming:

The basic idea of the GPS design was to obtain position control for the X4 flyer. In order to get the GPS position data it was required to generate a code in Labview software. Labview software provides the interface for the existing controller and the GPS system.

Labview V 8.0 was used for this purpose. Data outputted from the GPS system was in the form of binary code. First the protocol of the code was studied. Next the required bytes were separated. (X, Y, Z coordinates). The values were in the binary form initially. These values were then converted to decimal form. To check if the position values generated were the right ones the values were compared with the position values obtained in STARVIEW software. Accuracy of the values was in the order of 0.0001 m. The CEP of the GPS system was 1.8 m. However we faced signal loss problems due to obstruction from the surrounding buildings. There was a lot of delay in getting the signals from the GPS system due to the signal loss most of the time.

The same program with some changes has been used for getting the position and velocity data(X, Y, Z) from the centimeter GPS system. The accuracy of the data has been verified from the GPSolution software that came with the GPS system. The same issues of signal losses continue here as well.
Following are the position data values (x, y, and z) of the Superstar 2 Flexpak unit.

**FIG 6.1 Position (X direction)**

**FIG 6.2 Position (Y direction)**
FIG 6.3 Position (Z direction)

Position data in x, y, z directions of the bare card:

FIG 6.4 Position (X direction)
The above graphs indicate the meter level accuracy of the Superstar 2 GPS card.
Position data obtained from the Centimeter GPS Base unit:

FIG 6.7 Position (X direction)
FIG 6.8 Position (Y direction)
FIG 6.9 Position (Z direction)
Conclusion

The successful design and testing of the protective shroud for the X-4 flyer has been achieved. Also the basic programming for the GPS system has been done.

Future work:

• Vibration analysis of the shroud during flight can be done
• The actual implementation of the DGPS system on the X-4 flyer can be made.
• Interfacing of the DGPS system with the PIC microcontroller chip can be done.
• Position control of the X-4 flyer during flight can be tested
• Development of suitable mathematical models for further research on the X4 flyer can be achieved.
REFERENCES
LIST OF REFERENCES


[16] www.novatel.ca: Date found July 2006

