ABSTRACT

The Versatile Air Transport System (VATS) is an important step towards the autonomous precision delivery of high-valued payloads. The lack of access to remote and dangerous areas where high-valued items are needed is not a new problem. Previous research has been focused on large systems which have required the utilization of costly transport vehicles. Through extensive prototyping and iterative development, a more compact design has been conceived for a vehicle which can carry out similar missions with small to moderate size payloads (0-2 kg). The VATS is an agile and user-friendly alternative. A system for its autonomous control has been developed and verified through field experimentation. Thorough aerodynamic analysis has allowed for the creation of a non-linear theoretical model of the system’s flight, which accounts for several variable external conditions. This model has been confirmed by extensive field testing of the critical aspects of the airfoil. Results suggest the value of the VATS as a method for accurate delivery of a high-value payload by an unmanned vehicle of small size and cost.
hour missions while collecting data. Notably, both these systems are used for large capacity tasks and require the placements of expensive technical equipment on board for their intended purposes. For this reason, the VATS targets a different area of this field. The first principle for the VATS: small payloads. While there seem to be several options for larger payloads (though they may not be accessible to the common citizen), there are few small unit paragliders and none at the scale of our target payload. Originally basing our target payload on the weight of a standard survival kit (5 kg), we began reaching for a product that could be used as a small, individual unit; easily deployable and very inexpensive.

Moreover, we began forming the idea for a product that could be used for the delivery of small, valuable payloads such as would be needed in dire situations, particularly in a medical one. While there is the relatively common concept of an airdrop, we wanted to ensure that the package would reach its target hence the need for autonomy. Imagining a situation in which a person is trapped in a remote location and in need of medical supplies, the VATS would be relatively inexpensive and precise way to reach the location and deposit a payload.

With these thoughts in mind, we began designing the product.

2. REQUIREMENTS AND OBJECTIVES

Primary Goals:
- An actuated control lines system such that turning, braking, and accelerating can be done electronically and with reasonable precision
- Has the potential to autonomously navigate and propel itself to a target
- A control processing unit (black box)
- Geo-location (i.e. on-board GPS capability)
- A propulsion system with the capability of lengthening flight time by increasing the glide ratio of the vehicle
- Operable in wind-speeds of up to 5 mph
- Safe landing conditions for payload (vertical landing speed of less than 10 mph)
- A high level re-usability
- Can accommodate a small payload of up to 5” x 6” x 7” in size.

Additional Goals:
- Low cost (under around ~$1000 parts cost once fully developed)
- Higher landing precision through the use of a higher accuracy relative location system (this could be visual tracking of a ground “blob” or infrared beacon, radio location, or any other relative location system which could be used to guide the package closer to the target than traditional GPS transceivers could reliably do)
- Safe landing conditions for the surrounding environment (other people, trees, windows, etc.) as well as the payload
- Operable in less than ideal weather conditions (sustained wind speeds greater than 5 mph, and temperatures of -10 to 40 °C
- A power supply that will support propulsion, steering, and processing for several 20 minute long flights. Power supply should also turn itself off when airfoil collapses
- Will successfully avoid obstacles.

3. CANDIDATE CONCEPTS

Our process of design was a continuous one. Even after the first prototype was built, redesign continued to improve upon its performance. Our design process began with defining and clarifying the problem that we hoped our product would address. We were able to break our overall goal of creating an autonomous aerial package delivery system into smaller tasks which could be accomplished individually to ensure the success of the system. This led us to identify the four subsystems which we would be designing solutions for: the transportation system, controls system, package-carrying system, and guidance system. After a process of concept generation which involved brainstorming, reviewing prior art in the field, and consulting with advisors, we developed a list of candidate design concepts for each of these subsystems. These lists, with the design concepts eventually chosen through the process of downselection in bold, are shown in Table 1:
Table 1: Candidate Design Concepts (* propulsion system incorporated into current design)

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Design Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation System</td>
<td>Circular Parachute with Ducted Fans*</td>
</tr>
<tr>
<td>Paraglider</td>
<td></td>
</tr>
<tr>
<td>Lighter-than-air Vehicle</td>
<td></td>
</tr>
<tr>
<td>Autoglider</td>
<td></td>
</tr>
<tr>
<td>Rigid Glider</td>
<td></td>
</tr>
<tr>
<td>Rigid Airfoil</td>
<td></td>
</tr>
<tr>
<td>Controls System</td>
<td>Arduino Nano Microcontroller with Servomotor</td>
</tr>
<tr>
<td>Package Carrying System</td>
<td>Box constructed of carbon fiber reinforced plastic</td>
</tr>
<tr>
<td>Guidance System</td>
<td>WAAS GPS</td>
</tr>
<tr>
<td></td>
<td>INS</td>
</tr>
<tr>
<td></td>
<td>Differential GPS</td>
</tr>
</tbody>
</table>

Our process of downselection was an important step in the overall design of our system, but by no means the final step. The choices that we made guided us in our pursuit of an optimal design for achieving our ultimate goals. The pursuit continued with iterative testing of preliminary designs, continued brainstorming to solve problems that arose, open dialogue with our adviser, and ongoing research of the state of the art. For our final design, we adjusted our materials used based upon literature in the field of impact analysis as well as general trends in like products. The final configuration of our package-carrying system, or trike, was decided in an iterative design-and-improve method where we made necessary minor adjustments to the design selected in downselection based on what we saw through testing.

Our selection of a paraglider with servo-controlled risers pulling its lines as the primary system of transportation as well as the incorporation of a motorized propeller, a feature of our “circular parachute with fans” concept was influenced by evidence from the hobby community of the use of these systems to create the type of results we were looking for as well as our own testing. This testing was done by dropping the paraglider from altitude with a payload of a water bottle filled with water and then with an RC trike and propeller as a payload. In order to attain the glide ratios we set out to achieve, we realized we would need to incorporate a system for propulsion into our transportation system. This has created a need for motor and propeller characterization and sizing.

The level of technological development in the area of guided flight also helped us greatly in selecting our controls and guidance system concepts. Upon first consideration of the open source ArduPilot MEGA system, we saw its potential for helping us achieve our goal of autonomy. The ArduPilot MEGA is an autopilot system using an IMU which can be paired with a GPS, magnetometer, airspeed sensor, barometric altitude correction system, and two-way telemetry to detect a craft’s location, velocity, orientation, altitude, and gravitational forces and output the readings in a usable form. These sensory devices are the core of our guidance system as they interact with the servomotor and motor, controlling the paraglider’s risers and the propeller, respectively. All together, these subsystems make up our controls system.

The trike was the system which benefited most from an iterative design process and got better at fulfilling our objectives as the rest of our system’s needs became clearer. The trike is the element of our product which needed the most design attention as it brought together all other subsystems to give us our desired results. The basic function of the trike is to solve the problems listed in our essential requirements and tie the other subsystems major operations together so that the overall system functions smoothly. The essential requirements of the project which the trike is attempting to meet are:

- safe landing conditions for the payload
- a high degree of re-usability
- ability to accommodate a package at least 5”x6”x7” in size
- maintenance of a light weight

An important element of the trike is the payload box itself which we choose to leave loosely defined anticipating that the optimal design for this element would change with the specific needs of each individual user, the payload he/she chooses to drop,
and the conditions that he/she faces.

4. DESIGN DESCRIPTION

The final project design would combine several integral features. The first major component is an airfoil capable of supporting payloads on the order of a few kilograms and accomplishing high glide ratios (well in excess of 1:1) and tight turns (below 20 meters radius). These features, as well as general robustness, are required for the whole system to meet its accuracy and capacity goals. Parafoils are not easy to assemble and even more difficult to design for efficiency, so this component of the design will almost certainly be a commercial off-the-shelf product. This does not mean that intense study into the characterization of the selected foil will not be necessary.

The physical trike will serve the purpose of containing the payload, protecting that payload as well as the electronics and drive train, providing easy maintenance, and providing durability and high impact resistance. Starting with containment of the payload, this in combination with the ultimate selection of a 10”x7 in propeller dictates the minimum overall size of the trike. At this size, and with consideration to impact and durability, ABS plastic was selected as the natural choice for structural material because of its ability to handle large strains elastically. ABS plastic may not have the same strength to weight ratio as aluminum but will be easier to manufacture. In order to satisfy the requirement for easy assembly and low maintenance, the entire frame will be composed of laser cut 2D parts which will be slotted and assembled into a 3D structure bonded with a solvent-based cement (which chemically fuses the two pieces of plastic into one, with a slight reduction in elastic strength). Overall the frame has a trapezoidal shape so as to be extremely rigid along its base, the point of contact for most impacts. Additionally, a viscoelastic material with good absorption/damping properties will be mounted along these edges in sufficient quantity to reduce the intensity of impact loads and to over-damp the impact to the point where a bounce and second impact is unlikely to occur (with an emphasis on preventing the trike from inverting itself on landing).

However, the trike will be constructed as if an inversion on landing is still a possibility. The control actuators in the design will need to be capable of applying reasonably large loads at the end of a lever several inches long. There is also the possibility of high dynamic loads upon these actuators as wind gusts, ground impacts, sudden turns, and other unexpected disturbances are translated through the wing to the trike. For this reason, despite the increased weight, large format servos rather than micro aerial servos were selected as control actuators. The resolution of these servos is more than adequate to provide the turning accuracy needed; most parafoils are marginally sensitive to control line differentials on the order of a few inches. Scaled full size to the more typical 2-3m span parafoil we may use, we can expect control surfaces to be sensitive on the order of centimeters (well within servo resolution with a ~4 inch lever).

Finally the control electronics, avionics, motor, motor controller, and battery, because their development is not a main focus of this project, will all be commercial off-the-shelf components as well. The obvious selection for a power source is lithium polymer battery chemistry. They offer the highest energy density commercially available in a chemical battery. This battery was sized to provide a life of at least 30 minutes under maximum demand. The control electronics, avionics, and battery power management can then be easily combined into a single product, the ArduPilot MEGA from the DIY-drones community. This device comes equipped with a full IMU including WAAS GPS transceiver as well as a full control software suite and integrated Kalman filter. The result is accurate state estimates at the rate of 50 Hz which using pre-written reconfigurable onboard control algorithms can be translated directly into servo signals for both parafoil elevons and the motor. The selection of this device also allows for easy code modification, logging, and fly-by-wire teleoperation from a wirelessly connected laptop at ranges up to 10 miles in normal conditions and 40 miles through clear air (using a 1-Watt, 900 MHz band XBee transceivers). Providing acceptable GPS reception, pressure measurements for airspeed estimations, and ground communication required mounting the full electronics suite in the nose of the trike. The ArduPilot MEGA actually implements
control on the orientation, overall bearing, and descent rate using separate PID negative feedback loops (using its own state estimate to obtain current error in all three system outputs) with gains that can be easily adjusted before flight or in real time remotely.

It was determined early in the process that the motor would need to be brushless in order to be efficient at very high rotational speeds. To that end, the proportional throttle command sent from the ArduPilot MEGA was converted to a commutated electrical signal for the motor by a standard 25 Amp RC hobby speed controller. This controller would serve the dual purpose of providing 5V regulated power to the ArduPilot MEGA. Ideally, the perfect design would have separated these power sources in order to ensure that the ArduPilot MEGA would continue to have control of the parafoil elevons even after the main power source is depleted. Yet, this could be approximated using the ArduPilot MEGA’s voltage monitoring circuitry by imposing a limit at which point throttle to the motor would be cut, preserving the last ~10% of main battery life for passive control.

5. PROTOTYPE REALIZATION

The structural design of the final prototype is dictated by the systems vital to the functioning of the prototype. The trike, built out of ABS, is the central piece of the structural design Figure 1. It supports and connects all of the subcomponents that make up the overall prototype. It is designed around the least flexible components first and then accommodates the more flexible ones. The most expensive piece of hardware is the ArduPilot Mega and, considering how vital it is to the success of the system, the primary function of the trike is to protect it against any impact that the system could be subjected to. This component was thus double-boxed in an area enclosed by the main structure of the trike. In addition, the base of the trike was protected by a layer of memory foam and pipe foam.

The hobby community once again aided us with an open source CAD drawing of the components of a box custom-made for protecting the ArduPilot MEGA and its corresponding components (Koppendorfer, 2010). A variation of this box, shown in Figure 2 was then designed into the structure of the trike, screwed to the center of its bottom panel.

Figure 1: 3D Model of Trike

Figure 2: Trike with 5”x6”x7” payload

Another essential feature of the final trike is to support the risers which pull the control lines of the paraglider. The microcontroller sends voltage signals to two servo motors. These servo motors adjust the position of the two paddles, each of which is attached to one of the parafoil’s control lines. Adjusting the relative height at which each control line is attached to the payload causes the system to turn and brake. The risers are supported by two paddles that are integrated in the main structure. The trike of the final prototype also provides space within the structure for a payload of any size up to 5”x6”x7” (Figure 3). The memory foam and pipe foam protections are designed to absorb impacts thanks to their viscoelastic properties. These are purposely surrounding the box for more efficient protection.
This payload is rigidly connected to the trike by a bar that can be slid through holes in the trike and at the top of the payload box when aligned. The package holding system is placed high on the structure in order to avoid being exposed to the set of forces that it will have to sustain upon its impact with the ground.

The final prototype of this paraglider uses a propulsion system. It consists of a DC brush-less motor that outputs 7 N of thrust supplied by a 3-cell LiPo battery pack. This system is connected to a 10”x7 single propeller. The propulsion system increases the glide ratio and makes the distance and time the paraglider can stay in flight longer. This enables the system to reach targets further away. The rotational speed of the propeller is controlled by an electronic speed control which was programmed to slowly throttle up from zero to full power in order to avoid any instability at the beginning of the flight. The propulsion and control system are run on separate batteries so that if the LiPo batteries are depleted unexpectedly, the system can still be partially functional.

The final prototype’s control system has three modes. Fly by wire, which enables a user to directly control the paddles via a controller, stabilized flight, which automatically compensates for any turbulence or any input that would disturb the system from straight and level flight. The third one is autonomous waypoints for which waypoints can be pre-selected and the control system would send inputs to the paddles in order to steer towards each of these waypoints.

6. EVALUATION AND TEST

Our system consisted of two distinct components, which – due to restricted time and resources – we decided to test separately. The first component is the trike, which includes all navigation, propulsion, and control. The second component is the parafoil itself.

The parafoil was modeled in CAD as a rigid body. Using SolidWorks Simulation Suite, we ran basic aerodynamic analysis on this rigid body for various air speeds at 75 different angles of attack. With this analysis, we were able to generate lift, drag, and moment data for each of the points. Figure 3 is a screenshot of streamlines representing air over the parafoil during one of our flow simulation iterations.

![Figure 3: Streamlines over parafoil](image)

The data was then used to create a lookup table, which was imported to MATLAB, where we created a 2-dimensional non-linear dynamic simulation of the parafoil. This simulation takes inputs such as payload weight, initial mounting angle, and thrust. It then models the path of the system based on these conditions and on the aerodynamic data generated in SolidWorks. Figure 4 is a graph of the all of the lift data we were able to generate.

![Figure 4: Lift Force Data](image)

The next step was to validate our dynamic simulation with experimentation. During this step of the testing process, we dropped our parafoil from various heights in a series of about thirty “drops”. Most of these drops were accomplished from the upper tier of Franklin Field at the University of Pennsylvania, at about 65 feet from the ground. This
provided a controlled environment: protected from the wind and without trees or obstacles. See Figure 5 for an image of our system falling from Franklin Field:

![Figure 5: Franklin Field Drop Test](image)

However, according to our dynamic simulation, we predicted very short flight times and very poor glide ratios for Franklin Field. Figure 6, which is a screen shot from our simulation with a 1.4 kg payload, shows that an optimal glide ratio is retained only after 100 feet of falling:

![Figure 6: Dynamic Simulation with 1.4 kg weight](image)

Thus, for the safety of our trike, we chose to use deadweights when testing our parafoil. Despite this drawback, we were able to validate our dynamic simulation for very short flights. We determined that any payload weights below about 1kg were in fact too light, preventing the parafoil from filling out properly. This can be seen in Figure 7.a, which compares a 0.7kg drop to our dynamic simulation for that weight. Any weights between 1-2 kg, however, seemed to properly match with our dynamic simulation--as shown in Figure 7.b for our 1.1 kg deadweight:

![Figure 7.a: Dynamic Simulation with 0.7 kg weight](image)

![Figure 7.b: Dynamic Simulation with 1.1 kg weight](image)

The second stage was to test our navigation and controls system, as well as the propulsion. Because our flights were not long enough to implement any of these components, we were unable to test the entire system as a whole. However, we were able to implement and test three modes of control on the trike: fly-by-wire, stabilization, and fly-to-destination. Fly-by-wire was tested using an XBox controller and observing the direct effect of human
control. The latter two modes were tested by physically maneuvering the trike, and observing the response of the two servo motors, which are designed to rotate to adjust the effective lengths of the control lines on the parafoil. After running these tests several times and under several different conditions, we are confident that this subset of the system is fully functional.

Finally, in order to test propulsion, we hung our trike from a string. At numerous throttle increments, we measured the rotational speed of our propeller using a high speed camera, and calculated a static thrust value using the string’s angle with respect to a vertical reference. Figure 8 shows a figure of our thrust data directly compared to data gathered by UIUC, which was used as a preliminary assumption of our system’s thrust capabilities.

![Figure 8: Thrust versus propeller speed](image)

7. DISCUSSION

Although we were unable to test our system as a whole, we are confident of its functionality based on simulations and observations throughout our experimental process. The immediate next step in realizing this system would be to drop the full system from a structure of at least 300 feet, in order to test and characterize the functionality of all components together. We have identified a collapsed railroad bridge in Kinzua State Park in Pennsylvania as an ideal location for this.

Ultimately, our design has fulfilled the beginning stages of an effective small-scale product that could be very useful in the delivery of emergency supplies to remote locations. With a unique method of flight that capitalizes on the passive glide ratio of a parafoil, it requires little energy input in order to function. Many of the components – including the physical payload box, the wiring setup, and the graphical user interface – are very intuitive and user-friendly. Its small scale not only allows for easy maneuvering to a target, but it also keeps costs down and provides convenience for ground transport and/or disposal.

Additionally, the VATS has a very effective navigation system with state-of-the-art electronics equipment, and enough thrust to increase the glide ratio significantly. One area for further research would be to test the effect of the propeller’s thrust on the moments of the system. As explained above, applying a force to the mass of the inverse pendulum has the potential to destabilize the system. Our dynamic simulation indicates that with a constant or slowly changing thrust, any oscillations caused by its initial onset will be damped by air resistance during flight. However, we have not tested this during experimental flight, and it would be telling to do so.

Because if its size, the VATS is easily affected by large gusts of wind, which it often cannot recover from. For any further development in this project, we recommend using a larger parafoil (at least 3 meters across) in order to better accommodate payloads of 5kg and to avoid disruption. In general, adding an extra meter to the parafoil size would offer a lot more stability without sacrificing too much maneuverability or convenience. We have also found that the system requires at least 75 feet of vertical displacement in order to gain significant forward momentum and reach an ideal glide ratio. Thus, this system is not appropriate for short drops or for windy days.

While our dynamic simulation reveals many behaviors of our system, many of which have been verified by experimental tests, it would be highly beneficial to run more extensive tests in the future. Developing a way to drop the parafoil in a consistent manner is crucial, as is finding a location of more than 100 feet in height. Controlled tests from larger heights will enable the system to reach its full
potential, and give enough drop time to adequately test steering and propulsion during flight. Similarly, a strategic deployment method would be invaluable to the potential of the VATS as a marketable product. It would help avoid deployment in undesirable wind velocities caused by planes or helicopters, making the system much more practical.

Finally, it would be interesting, in the development of this prototype into a marketable product, to experiment with ways of reducing cost or implementing the re-usability of the system. The VATS is made of strong yet inexpensive materials, which promote its reuse. However, we would aim for a more intuitive recycling process for a final product.

8. ACKNOWLEDGEMENTS

We would like to acknowledge our faculty advisor, Dr. Vijay Kumar, for all of his guidance and support of our project. We would also like to thank Bruce Kothmann for his help in the beginning stages of our project. Finally, we would like to acknowledge Dr. Robert Jeffcoat—our senior design instructor—and the other members of our MEAM 445/446 class.

9. NOMENCLATURE AND DEFINITIONS

VATS: Versatile Air Transport System
ArduPilot MEGA: Arduino Nano Microcontroller for Flight Systems
GPS: Global Positioning System
RC: Remote Controlled
IMU: Inertial Measurement Unit
ABS: Acrylonitrile Butadiene Styrene
DIY: Do It Yourself
WAAS: Wide Area Augmentation System
PID: Proportional-Integral-Derivative
CAD: Computer-Aided Design
LiPo: Lithium-ion Polymer
DC: Direct Current
UIUC: University of Illinois at Urbana-Champaign

10. REFERENCES


APPENDIX A – Materials and Cost Summary

The materials and expenses for the development of the VATS was approximately $1395. However, All costs listed below are estimates. Please contact team members for a more detailed cost summary.

Table A1: Embedded, Expended, and Consumed Charges

<table>
<thead>
<tr>
<th>Qty</th>
<th>Item</th>
<th>Source</th>
<th>Cost (ea.)</th>
<th>Cost (total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Parafoil</td>
<td>HobbyKing</td>
<td>$37.50</td>
<td>$150</td>
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<td>1</td>
<td>RC Paraglider for Reverse Engineering</td>
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<td>3</td>
<td>ABS sheets for trike body</td>
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<td></td>
<td>Miscellaneous</td>
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Table A2: Recoverable Items and Charges

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<th>Qty</th>
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<td>Additional Sensors</td>
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</tr>
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<td>Lipo Battery with Charger</td>
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<td>Servo Motors</td>
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$795