An Autonomous Autopilot Control System Design for Small-Scale UAVs

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Introduction
This paper describes the design and implementation of a fully autonomous and programmable autopilot system for small scale autonomous unmanned aerial vehicle (UAV) aircraft. This system was implemented in Reflection and has flown on the Exploration Aerial Vehicle (EAV) platform at NASA Ames Research Center, currently only as a safety backup for an experimental autopilot. The EAV and ground station are built on a component-based architecture called the Reflection Architecture. The Reflection Architecture is a prototype for a real-time embedded plug-and-play avionics system architecture which provides a transport layer for real-time communications between hardware and software components, allowing each component to focus solely on its implementation. The autopilot module described here, although developed in Reflection, contains no design elements dependent on this architecture.
The UAV system is composed of two main components: a ground station component which provides telemetry feedback for the operator and allows for control of the aircraft, and a flight system component onboard the vehicle. The component details are shown in Table 1.

Table 1. System Hardware

<table>
<thead>
<tr>
<th></th>
<th>Ground Station</th>
<th>Flight System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform/Airframe</td>
<td>Dell Mobile Workstation</td>
<td>Hanger 9 Quarter Scale Cessna 172</td>
</tr>
<tr>
<td>CPU</td>
<td>DELL Precision M70 Workstation, Pentium M 770, 2.13GHz, 2GB RAM</td>
<td>Digital Logic MSMP3SEV, Pentium-III, 700MHz, 256MB RAM</td>
</tr>
<tr>
<td>Operating System</td>
<td>Windows XP Professional</td>
<td>Windows XP Embedded</td>
</tr>
<tr>
<td>Real-Time Infrastructure</td>
<td>Reflection Architecture</td>
<td>Reflection Architecture</td>
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<tr>
<td>Communications</td>
<td>Microhard Spectra 910, 1W 902-928MHz RF Modem</td>
<td>Microhard MHX-910, 1W 902-928MHz RF Modem</td>
</tr>
<tr>
<td>Avionics</td>
<td>Athena Guidestar GS111m INS/GPS</td>
<td>Pontech SV203 Servo Controller</td>
</tr>
<tr>
<td></td>
<td>Custom Servo Switching Board</td>
<td></td>
</tr>
</tbody>
</table>

**Ground Station Monitoring and Control**

With the Reflection plug-and-play architecture, simulation and hardware can be mixed on the fly for in-situ simulation testing of hardware components at any level of granularity. When implementing the final ground station controller, several simulation components were reused to provide telemetry data back to the ground station. A screenshot of the ground station is shown in Figure 2 below.
The bottom left window provides a graphical interface for configuring and manipulating waypoint commands. Waypoints can be manipulated on a 2D representation of the terrain; waypoints are overlaid on GPS-localized 2D bitmap images. Once a mission is programmed, the user can ‘upload’ the commands to the aircraft. The ground station generates remote method invocations on the remote autopilot module, and passes these invocation requests to the Reflection distributed transport layer (RDTL). The RDTL converts the invocation requests into Reflection Virtual Machine byte-code commands and sends the commands over to the autopilot component via the 900 MHz communications link. On the flight computer, the RDTL receives and assembles the invocation requests, then executes the commands on the autopilot module.

**Autopilot System Overview**

The autopilot system is implemented as a stand alone plug-in component in the Reflection Architecture. Data flow through the system conceptually follows the diagram shown in Figure 3. Command objects generate FMS lateral and longitudinal mode instructions for the FMS. The FMS in turn generates controller mode instructions, which are used by the controller to command the actuators of the vehicle. The state information and the actuator commands are generated by external plug-and-play Reflection modules.
The top-most object in the control system is an instance of the AutopilotSystem class, as shown in Figure 4. The AutopilotSystem class is responsible for communicating with the rest of the Reflection system and maintaining the two main objects in the system: the FMS (flight management system) and the Controller. The FMS is responsible for maintaining the list of commands which specify FMS mode instructions. The mode instructions are used by the FMS to provide targets to the controller. The controller is responsible for implementing the control loops which control the aircraft through the vehicle’s actuators.

Commands in the Flight Management System

The flight management system class is a state machine that controls the continuous feedback control system in the controller object. The FMS is responsible for maintaining a database of mission program, keeping track of the mission program execution, and setting the modes of the controller object’s feedback loops.

The mission program is implemented Command objects, which are stored in a programmable list in the FMS. The command list is an ordered list of commands that can be programmed on the ground, or reprogrammed while the aircraft is in the air. In implementation, the Command class is a virtual interface class, from which specific types
of command classes inherit. All commands implement the interfaces defined by the base class, which includes methods to initialize their internal state, update their internal state at each OnComponentUpdate() callback, and to notify the FMS when the command objectives have been met.

Controller commands can be programmed through the ReflectionScript language, which interprets text-based commands into binary code which is passed to the Reflection Virtual Machine. The following scripts are examples of programmed routes for the Reflection component.

```plaintext
// Program the Autopilot System.
objAutopilot.ClearCommandList();
objAutopilot.AddCommand_Takeoff ( 4500.0, -2000.0, 500.0, 80.0, 1000.0, -0.34907, 50.0 );
objAutopilot.AddCommand_FlyToTrack ( 8070.9, -6009.7, 500.0, 80.0, 1000.0 );
// Following heading until specified altitude is reached.
objAutopilot.AddCommand_SetFMSMode ( HEADINGHOLD, 0.0, ALTCMD, 400.0, SPDCMD, 80,
ALTITUDE, GT, 300 );
objAutopilot.AddCommand_FlyToTrack ( 10127.0, -1390.7, 500.0, 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( 8904.5, -902.8, 500.0, 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( 6919.8, -5568.9, 500.0, 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( 3357.4, 1364.9, 500.0, 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( -3319.9, 4457.2, 500.0, 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( -5436.1, 3960.7, 500.0, 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( -4371.0, 1696.2, 200.0, 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( -741.1, 182.6, 50.0, 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( 2522.8, -1267.5, -10.0, 80.0, 1000.0 );
objAutopilot.AddCommand_Jump ( cmd );
```

**Figure 5. Sample Control Program.**

At the start of the mission, the controller activates the first command, which might be a *Takeoff* command for an autonomous takeoff. The update sequence, shown in Figure 6, is very simple sequence of steps; the FMS object is only responsible for maintaining the current state, transitioning between states at the appropriate time. At each component update callback, the FMS calls the Update() method of the active command, which updates its internal state. The FMS then checks the IsComplete() method of the command; when *TRUE* is returned, the FMS transitions to the next command, and signals a Reflection event in case any other Reflection component is monitoring autopilot state transitions.
The FMS internally maintains three different FMS control modes, an FMS lateral mode, FMS longitudinal mode, and FMS speed mode. The active command object internally maintains a state machine which outputs FMS mode commands and targets appropriately to meet the objectives of each command.

Command Types

Command: Direct To Waypoint

The DirectToWaypoint class controls the vehicle mostly through heading commands towards a specified 3D waypoint. When initiated, the DirectToWaypoint stores the initial position of the aircraft and the position of the next waypoint (if there is one). Depending on the transition mode, the command uses this information to determine the size of the waypoint radius based on current aircraft speed to allow a turn to the next waypoint without overshoot, and to determine if the aircraft has passed the waypoint based on a 2D axis perpendicular to the line from the initial position to the waypoint position, and passing through the waypoint.

In implementation, the DirectToWaypoint class inherits from the Command base class, as shown in Figure 8.

The DirectToWaypoint command sets the lateral FMS mode to ‘FlyToWaypoint’, and outputs a heading command. The longitudinal mode and speed mode are selected based on the waypoint command; the longitudinal controls or the speed controls can be used to
control either airspeed, altitude, or follow the vertical track between waypoints. Having throttle control altitude is the default, for safety if the engine fails.

<table>
<thead>
<tr>
<th>Command</th>
<th>Lateral</th>
<th>Longitudinal</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct To Waypoint</td>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

### Command: TrackToWaypoint

The TrackToWaypoint command is similar to the DirectToWaypoint command, except that the aircraft is controlled to fly the track from the previous waypoint to the next waypoint, rather than heading straight to the waypoint. Similar to the DirectToWaypoint command, the transition to the next waypoint can be triggered by penetration of the perpendicular axis or the transition radius, which can be calculated based on the current aircraft state and the performance characteristics of the aircraft (turning radius).

![Diagram](image4.png)

### Figure 10. TrackToWaypoint Diagram

The TrackToWaypoint commands the TrackToWaypoint lateral FMS mode. The longitudinal mode is set to AltitudeCommand.
The manner in which the altitude is captured can be set by the waypoint. Immediate altitude capture is the default, where the aircraft is controlled within the safety limits of the controller to attain the altitude as soon as possible. The glideslope mode will have the aircraft follow the slope between waypoints, and is used for instance in the final approach leg during a landing.

**Command: Jump**

The Jump command instigates an immediate transition to another command in the list. This control is used for instance to repeat a sequence of commands. There are no FMS modes associated with the Jump command.

**Command: Circle**

The Circle command controls the aircraft to fly a circle pattern of a given radius about a waypoint. The lateral PID mode is set to ‘Circle’, the longitudinal mode set to AltitudeCommand.

**Command: TakeOff**

The TakeOff command provides commands for an autonomous takeoff sequence. The FMS modes are set to a dedicated ‘TakeOff’ mode, which provide full throttle to the aircraft while maintaining heading on the runway based on steering and rudder inputs, as rudder and steering inputs are ganged together on the same servo command line. Once the rotation takeoff speed is reached, the aircraft performs a climb longitudinal maneuver while maintain lateral wings level, until a safe turning altitude is reached.
Command: Landing
The Landing command is used for automated landings. The aircraft is commanded to maintain a track between waypoints and command a constant descent rate until the ground sonars pick up a reading from the ground, and the aircraft attains the specified distance to the ground. Note that position information based on pressure and GPS may not be accurate enough to determine the flare maneuver, so the flare command will institute this command based on an ultrasonic altimeter located on the bottom of the aircraft. When the flare mode is executed, the elevators are used to command a nose up attitude of the aircraft while power is reduced, until the altitude notifies that the rear wheels are on the ground. The power is cut while the elevator is used to drop the front wheel.

Command: SetFMSMode
The FMSModeTimed will command the specified FMS mode until a transition condition is realized. This command’s class structure is shown in Figure 15.
Flight Management System Modes

The FMS receives command modes and targets from the active command, and outputs command instructions to the autopilot. The list of FMS modes currently implemented is shown in Table 2.

Table 2. List of FMS Modes

<table>
<thead>
<tr>
<th>Lateral Mode</th>
<th>Longitudinal Mode</th>
<th>Speed Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>DirectToWaypoint</td>
<td>CmdSpeed</td>
<td>CmdSpeed</td>
</tr>
<tr>
<td>TrackToWaypoint</td>
<td>CmdAltitude</td>
<td>CmdAltitude</td>
</tr>
<tr>
<td>Circle</td>
<td>CmdVertTrack</td>
<td>CmdVertTrack</td>
</tr>
<tr>
<td>TaxiTrack</td>
<td>AltitudeAttain</td>
<td>AltitudeAttain</td>
</tr>
<tr>
<td>CmdRoll</td>
<td>AltitudeHold</td>
<td>AltitudeHold</td>
</tr>
<tr>
<td>CmdAileron</td>
<td>CmdElevator</td>
<td>CmdThrottle</td>
</tr>
<tr>
<td>Disabled (PilotCmd)</td>
<td>CmdPitch</td>
<td>Disabled (PilotCmd)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Disabled (PilotCmd)</td>
</tr>
</tbody>
</table>

Each mode is associated with one or more commands to the controller, and modes can be implemented as state machines. For instance, the CmdAltitude mode for both the lateral and longitudinal modes contains an internal state machine shown in Figure 16.
The two state machines implementing an FMS mode and a command object could be integrated into a single machine; for instance, the DirectToWaypoint command uses the CmdAltitude FMS state, but could implement the AltitudeAttain/AltitudeHold FMS states explicitly using the same state machine model. The reason to have two state machines is to help avoid redundant code. Since many different commands require the aircraft to attain then hold an altitude, this state machine was implemented as a common FMS control mode rather than duplicating the logic in several individual command machines.

**Autopilot Controller**

The controller object is responsible for implementing the feedback control loops that command the aircraft. The FMS object commands the controller by first setting high level modes, the providing actual target data. Similar to the FMS, there are three modes associated with the controller: lateral modes, longitudinal modes, and speed modes. Lateral modes control the ailerons and rudder, longitudinal modes control the elevator and also affect the rudder, and speed modes control the throttle. The controller modes are listed in Table 3.

<table>
<thead>
<tr>
<th>Lateral</th>
<th>Longitudinal</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disengaged</td>
<td>Disengaged</td>
<td>Disengaged</td>
</tr>
<tr>
<td>Roll Cmd</td>
<td>Pitch Cmd</td>
<td>Fixed Throttle</td>
</tr>
<tr>
<td>Heading Cmd</td>
<td>Altitude Cmd</td>
<td>Airspeed Cmd</td>
</tr>
</tbody>
</table>

Table 3. Controller Modes
The controller uses a cascaded control structure mainly composed of proportional-derivative-integral (PID) controller transforms. Several different paths can lead from sensor inputs to actuator command outputs, as shown in Figure 17. Specific paths are associated with enumerated controller modes. Lateral modes control the ailerons and rudder, longitudinal modes control the elevator and also affect the rudder, and speed modes control the throttle.
Figure 17. Cascading PID Control Structure in the Controller Class


**Dependability Analysis Requirements**

**For an Electric Unmanned Aerial Vehicle (UAV)**

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**Summary**

This document specifies the dependability analysis requirements for the Swift Unmanned Aircraft System (UAS). Section 1 gives a description of the system, a high-level concept of intended operations and an overview of the autopilot software to be deployed in the airborne part of the UAS. Section 2 specifies the analysis to be performed and the expected outcome.

1 **System Description**

1.1 **The Swift UAS**

The Swift UAS comprises a single airborne system: the electrically powered *Swift* unmanned aerial vehicle (UAV), a primary and secondary ground control station (GCS) and communication links for remote control and telemetry.

A pilot on the ground can control the UAV, or can it fly autonomously by following a *nominal flight plan*. The pilot might takeoff, land, or intercept at any time during flight. There is an *off-nominal flight plan* which describes the actions of a Contingency Management System (CMS), i.e., the failsafe trajectory, the procedures to be followed on the ground, and so on. The CMS is required is to keep the aircraft on range, so that if any crash occurs, it happens on range.

The protocol for the CMS is:

1. If there is a failure of the primary pilot system, switch to the redundant secondary system, on a different channel.
2. If the secondary also fails, engage the onboard autopilot.
3. If the autopilot fails, force a spiral descent to impact.

During semi-autonomous flight, the aircraft can operate in the primary pilot in control (PIC), or secondary pilot in control (SIC) modes, or in computer in control (CIC) modes. The GCS is used to upload commands to the UAV.

Figure 1 gives a physical breakdown of the complete Swift UAS. In this breakdown, we are interested in the contributions of the Avionics sub-system (shown as enclosed by the dotted box) to UAS hazards.

This will require reasoning about hazards from several perspectives. In particular:
1. From a mission perspective, i.e., specific environmental conditions during a specific phase of flight, in which there is an increased likelihood of unacceptable loss, e.g., sudden crosswind during takeoff (landing), obstacles in the flight path, etc.
2. From the perspective of the machine (the UAS), e.g., specific machine states (such as failure states) in which there is an increased likelihood of unacceptable loss, and
3. From the perspective of states of the avionics system, e.g., flight computer failure, which can contribute to an increased likelihood of unacceptable loss. These could take the form of interactions with other subsystems, or uncovered (failure) states, or interactions (which may or may not be legitimate) with environmental conditions that contribute to system hazards.

Figure 1: Physical breakdown with Avionics subsystem highlighted
1.2 UAV Avionics

The avionics onboard the UAV is the computer-based control system that accepts pilot input (or pre-programmed / uploaded commands), processes the input, and regulates the flight control surfaces. Figure 2 shows a conceptual layout of the avionics system, in the context of the UAS.

![Avionics System Conceptual Layout](image)

Figure 2: Avionics system conceptual layout

1.3 Concept of Operations

Figure 3 shows one of the concepts of operation for the Swift UAS. As seen in the figure, there are seven distinct phases of flight:

(i) Takeoff
(ii) Climb
(iii) Cruise
(iv) Survey
(v) Return Cruise
(vi) Descent
(vii) Land
For this particular mission, the aircraft is operated out of line of sight, i.e., it will not always be within sight of the pilots or the GCS operator. However, there are safety observers stationed at pre-defined locations on range, so as to ascertain the aircraft continues to be on range, and to identify situations in the environment that are potentially hazardous.

The dependability analysis of the Swift UAS will need to take into account the notion that during the different phases of flight, not all hazards pose the same level of safety risk, e.g., loss of power is a hazard at any point during flight, whereas loss of the autopilot need not be a hazard during landing, but could be a hazard during cruise, survey, return cruise, etc.

1.4 Autopilot Software

See attached document: Corey Ippolito, “An Autonomous Autopilot Control System Design for Small-Scale UAVs”.

2 Dependability Analysis Requirements

This section specifies the analyses potentially beneficial for safety assurance of the system described in Section 1.

1. Fault tree analysis and / or Event tree analysis
   a. Generation of minimal cut sets
   b. Probabilistic analysis of failure probabilities for hazardous top events
   c. Event chains leading to system failure (or an undesirable outcome)
   d. Probabilistic analysis
2. Hazard analysis using a combination of fault trees and event trees
Overview of the NASA Swift UAS

Presentation to Professor Joanne Dugan
Dependable Computing Class
University of Virginia
April, 2012

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Presentation Outline

• Swift UAS Program Summary
• Preliminary Design Summary
• Subsystems Overview
• Autopilot System Overview
• Analysis, Modeling and Simulation
Goal of the Swift UAS

• Develop a fully autonomous, fully electric, zero-emissions human flight capable research vehicle platform using today’s technologies and applicable for next generation aircraft research

• Build on existing Bright Star Gliders SWIFT airframe, a high performance glider

• Utilizes GOTS/COTS control hardware, algorithms, and infrastructure available at NASA Ames Research Center.
Swift UAS Specifications

**Geometry**
- Wing Span: 12.8m (42ft)
- Length: 3.4m (~11ft)
- Wing area: 12.5 m² (136 ft²)
- Aspect ratio: 12.9

**Speeds**
- Speed, Cruise: 45 knots (23 m/s)
- Speed, Stall: 20 knots (10 m/s)
- Speed, $V_{NE}$: 68 knots (35 m/s)

**Weight and Payload**
- Weight, Empty: 48 kg (106 lb)
- Weight, Max Take Off: 145 kg (320 lbs)
- Payload Capacity: 100kg (220lbs)

**Performance**
- Maximum glide ratio: 27:1
- Rate of sink: 36 m/min (118 ft/min)
- Powered Rate of Climb: 2.5 m/s
- Est Max Endurance: ~7 hours
- Est Max Range: ~500 km
- Takeoff Field Length: 50m
- Service Ceiling: >7.6km (>25,000 ft)

**Control and Propulsion**
- Propulsion: Electraflyer 18hp/13.5kw
- DC Motor, 5.6KW-hr Li-Po
- Propeller: 1.5m (60") carbon-fiber

**Materials**
- All Composite Wing Structure (Aramid/Carbon)
- Steel/Aluminum Fuselage Frame
Control Surface Modifications
1. Split control surfaces for redundancy
2. Design/Install actuators on all control surfaces and controllable systems.

Avionics Installation
1. Design/Install Isolated Mounting Structures
2. Design avionics
3. Install Flight Critical Control Systems
4. Install C&DH/Avionics System

Propulsion System
1. Install engine system
2. Install batteries

Control Surfaces
• L/R Elevons
• L/R Flaps
• Engine Speed Control
• Steerable front wheel

Structural Modifications
• Tricycle landing gear structure

Sensor Installation
• GPS and DGPS Antenna Installation
• Five-Hole Pitot Probe
• Radio Antenna Pass Thru/Mounts

Installation of Wheel Tiplets (kit)
Swift’s Unique Characteristics

- Low cost reconfigurable platform with characteristics of larger aircraft
- Large flexible wing (13m/42ft span)
  - Wing structure is light-weight, flexible, simple, all-composite
- Redundant actuation
- Large payload capacity (~200lbs limited by COA)
- All-electric, zero emissions platform
- Slow cruise speeds ideal for long duration test segments
- Capable high altitude flight
- Quiet airframe structure (noise, emissions, EMI, etc.)
- Custom autopilot/navigation system
- Fully redundant and fully instrumented for local or remote autonomy
- Immediate pilot preemption over redundant links for safe/immediate termination of experiments
Control Experiment Mission Concept

1. Takeoff
2. Climb
3. Flight Test Pattern (Racetrack, Circle, Figure-8, etc.)
4. Experiment Segment
5. Final Approach
6. Descent
7. Land

Always Within Direct Pilot Control Range

FAA COA Operational Boundary

Ground Control Station and Crew

Experiment Airfield (e.g., Moffett, Crow’s Landing)
Remote Survey Mission Concept

1. Takeoff
2. Climb
3. Cruise
4. Survey
5. Return Cruise
6. Descent
7. Land

Range up to 100 km RFLOS*

Altitude up to 7.6 km MSL**

Remote Scientists/Observers
# Swift UAS Systems Breakdown

<table>
<thead>
<tr>
<th>PA.1.0</th>
<th>Complete Swift UAS System</th>
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<tr>
<td>PA.1.1</td>
<td>Flight Vehicle System (FVS)</td>
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<tr>
<td>PA.1.1.1</td>
<td>Avionics System (AVS)</td>
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<td>Flight Critical Control System (FCS)</td>
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<td>Control and Data Handling System (CDHS)</td>
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<td>CDHU (Control and Data Handling Unit) Hardware</td>
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<td>FMS (Flight Management System)</td>
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<td>Propulsion Support</td>
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<td>Avionics Mounting Structure</td>
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<td>PA.1.1.6</td>
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<td>PA.1.1.6.3</td>
<td>Actuation Power</td>
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<td>PA.1.1.6.4</td>
<td>PV Regeneration System</td>
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<td>PA.1.1.7</td>
<td>Contingency Management System (CMS)</td>
</tr>
<tr>
<td>PA.1.2</td>
<td>Ground Control System (GCS)</td>
</tr>
<tr>
<td>PA.1.2.1</td>
<td>Primary Ground Control Station</td>
</tr>
<tr>
<td>PA.1.2.2</td>
<td>Secondary Ground Control Station</td>
</tr>
<tr>
<td>PA.1.2.3</td>
<td>CPDS Payload Ground Station (PGS)</td>
</tr>
<tr>
<td>PA.1.3</td>
<td>Flight Operation and Procedures (OPS)</td>
</tr>
<tr>
<td>PA.1.3.1</td>
<td>Runway</td>
</tr>
<tr>
<td>PA.1.3.2</td>
<td>Airspace</td>
</tr>
</tbody>
</table>
Conceptual Avionics Layout
Swift UAS Actuation System
Swift UAS Landing Gear System
Actuation: Control Surface Specification

A1 3.5" Hinge, To Be Installed
A2 3.5" Hinge
B1 2.5" Hinge, To Be Installed
B2 2.5" Hinge

Swift UAS Modifications: Wing Modifications

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Swift UAS Propulsion Power

Battery System
- 144 cells (10 A-hr, 3.7 V)
- 18S, 8P Pack = 66.6V, 80 A-hr
- Unit cell = 3S, 4P (11.1V, 40 A-hr)
- 80 lbs weight
Swift UAS Avionics

Fuselage Assembly

- Payload / CPDS
- CDHS/CDHU
- FCS
- Propulsion Power Mng
FCS (Flight Critical Systems)
Instrumentation: Antennas and Probes

Antenna
Novatel DGPS

Antenna
GPS

Air Data Probe
United Sensors, Inc.

Antenna
900MHz Omni

900MHZ 5dbi Rubber Duck Antenna
http://www.l-com.com

Vertical
Horizontal
Ground Control System (GCS)

Reusing a well-tested redundant ground station configuration (EAV vehicle is shown).

Wireless Communications:
- Microhard Spectra 910 Wireless Modem (1 Watt Transmitter)

Wireless Communications:
- 6dB 900Mhz Omnidirectional Antenna, 5ft Fiberglass

CPU
- Laptop Control Station with Reflection Architecture for UAS C&C through avionics CPU.

Controllers
- USB Controller through avionics CPU
- JR DSX9 2.4GHz DSM2 (bypass CPU)

Two completely separate, identical, and redundant ground stations.
Autopilot Controller Overview

Figure. Conceptual Data Flow and Components
Sample Mission Script Commands

// Program the Autopilot System.
objAutopilot.ClearCommandList();
objAutopilot.AddCommand_Takeoff ( 4500, -2000, 500.0, 80.0, 1000.0, -0.34907, 50.0 );
objAutopilot.AddCommand_FlyToTrack ( 8070.9, -6009.7, 500.0, 80.0, 1000.0 );

// Following heading until specified altitude is reached.
objAutopilot.AddCommnd_SetFMSMode ( HEADINGHOLD, 0.0, ALTCMD, 400.0, SPDCMD, 80, ALTITUDE, GT, 300 );

// Follow a preprogrammed path.
cmd=objAutopilot.AddCommand_FlyToTrack ( 10107.0, -1390.7, 500.0, 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( 8904.5, -902.8, 500.0, 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( 6919.8, -5568.9, 500.0, 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( 3357.4, 1364.9, 500.0, 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( -3319.9, 4457.2, 500.0, 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( -5436.1, 3980.7, 500.0, 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( -4371.0, 1696.2, 200.0, 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( -741.1, 182.6, 50.0 , 80.0, 1000.0 );
objAutopilot.AddCommand_FlyToTrack ( 2522.8, -1267.5, -10.0, 80.0, 1000.0 );
objAutopilot.AddCommand_Jump ( cmd );
Autopilot Controller

Figure. Top Level Classes
Autopilot Controller Architecture

LATERAL AP Mode

Disengaged
Roll Cmd
Heading Cmd
CrossTrack
Circle
Takeoff

LONGITUDINAL AP Mode

Disengaged
Pitch Cmd
Altitude Cmd
Airspeed Cmd
Vert Speed Cmd

Note: RudderFromYacc is disengaged only when lateral mode is DISENGAGED.
Rudder from HDG is engaged only during TAKEOFF.
Autopilot Controller Architecture

SPEED AP Mode
-------------
0 = Disengaged
1 = Fixed Throttle
2 = Airspeed Cmd
3 = Altitude Cmd
4 = Glide Slope

state_PIDSpdMode: 

Fixed

Typically, full throttle (1.0)
commands_fixedThrottle_m1p1

Fixed: Glide Slope (error from FPA)
commands_speed_ktas
CurrentWP Speed

Fixed
commands_altitude_ftagl
CurrentWP Alt

Throttle from Airspeed

Throttle from Altitude

Pilot Throttle Input
commands_pilotThrottle_m1p1

Throttle Output

DesiredThrottle
Example FMS State Diagrams

<table>
<thead>
<tr>
<th>Command</th>
<th>Lateral</th>
<th>Longitudinal</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct To Waypoint</td>
<td><img src="example_diagram.png" alt="Diagram" /></td>
<td><img src="example_diagram.png" alt="Diagram" /></td>
<td><img src="example_diagram.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Track To Waypoint</td>
<td><img src="example_diagram.png" alt="Diagram" /></td>
<td><img src="example_diagram.png" alt="Diagram" /></td>
<td><img src="example_diagram.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- **Command**: Direct To Waypoint, Track To Waypoint
- **Lateral**:
  - DirectToWaypoint: Update/ calculate heading to waypoint,
  - Transition Criteria

- **Longitudinal**:
  - [Lon Mode in Waypoint]:
    - CmdSpeed
    - CmdAltitude
    - CmdVertTrack

- **Speed**:
  - [Spd Mode in Waypoint]:
    - CmdSpeed
    - CmdAltitude
    - CmdVertTrack
Example FMS State Diagrams

**Command**

**FMS Lat Mode**

- **FMSLATMODE_TRACKTOWAYPOINT**
  - AP LAT Modes
  - LATMODE_CROSSTRACK

**FMS Lon Mode**

- **FMSLONMODE_ALTITUDE_ATTAIN**
  - Top of Descent Reached

**FMSLATMODE_FLARE**

- AP LAT Modes
  - LATMODE_CROSSTRACK_NOFLYBACK

**FMLS LATMODE FLARE**

- AGLAltitude < FlareAlt
  - (m_landingflarealt_ftAGL)*

**FMSLONMODE_GLIDE**

- AP LON Modes
  - LONMODE_VERTSPEEDON
  - SPEEDMODE_AIRSPEEDON

**FMSLONMODE_FLARE**

- AGLAltitude < WheelDownAlt
  - (m_landingwheelisdownl_ftAGL)*

- Pitch controls vertical speed
  - (set in AP var)
- Throttle controls airspeed
  - (set in waypoint)

**Wing Level**

**TAXI-STOP**
Geometric Modeling

- Geometric modeling utilized to derive computational fluid models, dynamics models
- Utilized robotic FaroArm for 3D geometric data acquisition and model generation
- Error Analysis
  - Position error maximum
    +/−9.00 mm
  - Variation of the drag cross section:
    -2.78% to 2.73%
  - Variation of the lift cross section:
    -0.56% to 0.57%

<table>
<thead>
<tr>
<th>Sources</th>
<th>Low impact</th>
<th>Medium impact</th>
<th>Critical impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring of the temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monitoring of atmosphere composition</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flatness of the ground</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy of the touch probe</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy of the kinematic chain of the robotic arm</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy of the processing hardware of the controller box</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imperfections on the surface of the foil during its fabrication</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Play in the connection between the foil and the tip</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tiny damages at the extremity of the plane due to previous flights</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sources</th>
<th>Low impact</th>
<th>Medium impact</th>
<th>Critical impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imperfection in the assembly of the different parts of the plane</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexibility of the airfoil skin</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deformation of the stand supporting the foil</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy of the operator</td>
<td>✔</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Dynamic Modeling and Simulation

- Simulation studies used for dynamics and performance predictions, control law development
- Dynamic models generated from STAR Navier-Stokes analyses
  - Time consuming process, provides estimates for all major dynamic coefficients
- Lower fidelity method for comparison
  - X-Foil model using estimated properties
  - Vehicle Sketchpad / Vorview models
- Simulation Models
  - Linear model (Matlab) containing stability derivatives, control law development
  - Non-linear model for simulation testing
- Model assumptions and estimates will be continuously refined throughout development
- Flight test data will be used for parameter estimation
CFD Modeling

- CFD model and analysis performed by John Melton (ARC-AUS)
- STAR N-S analysis derived from geometry
  - Navier-Stokes drag coefficient estimates derived for small number of conditions
  - Assumed fully turbulent boundary layer
- Comparisons with lower order models
  - Airfoil derivatives from X-Foil for comparison
6-DOF Simulation Model

States:

\[ \mathbf{p_e} = [X_e \ Y_e \ Z_e]^T ; \mathbf{v}_b = [u \ v \ w]^T ; \mathbf{q} = [q_0 \ q_1 \ q_2 \ q_3]^T ; \mathbf{\omega}_b = [p \ q \ r]^T \]

Kinematics:

\[
\begin{align*}
\dot{\mathbf{p}_e} &= (\Omega_{E_e} \mathbf{p}_e) + \mathbf{R}_{b2e} \mathbf{v}_b \\
\dot{\mathbf{q}} &= -0.5 \mathbf{\omega}_b \mathbf{q} \\
\dot{\mathbf{v}}_b &= -(\mathbf{\omega}_b \times \mathbf{v}_b) - (\mathbf{R}_{e2b} \Omega_{E_e}^2 + \mathbf{R}_{e2b} \Omega_{E_e} \mathbf{R}_{b2e} \mathbf{\omega}_b) + \mathbf{R}_{e2b} \mathbf{g}_e \\
&\quad + \mathbf{m}^{-1} (F_{PR_b} + [-\text{Drag} \ Y - \text{Lift}] \mathbf{R}_{wi2b}) \\
\dot{\mathbf{\omega}}_b &= -J^{-1}_b \mathbf{\omega}_b J_b + J^{-1}_b \left( T_{PR_b} + [L \ M \ N] \right)
\end{align*}
\]

Dynamics:

\[
\begin{align*}
\text{Lift} &= \text{Q} \text{S} C_{l_{\alpha}} (\alpha, \delta_{\text{flap}}) + \text{Q} \ast \text{S}_{ht} \ast \frac{\text{d}C_l}{\text{d} \delta_{\text{ele}}} \delta_{\text{ele}} + \left( \frac{\text{Q} \overline{c}}{2V} \right) \frac{\text{d}C_l}{\text{d} \alpha} \alpha + \left( \frac{\text{Q} \overline{c}}{2V} \right) \ast \frac{\text{d}C_l}{\text{d} \mathbf{q}} \mathbf{q} \\
\text{Drag} &= \text{Q} \text{S} C_{D_{\alpha}} (\alpha, \delta_{\text{flap}}) + \text{Q} \text{S} C_{D_{\text{\delta}}_{\text{\text{flap}}} \text{\delta_{\text{\text{flap}}}}} (\delta_{\text{\text{flap}}}) + \frac{\text{Q} \text{S}_{HT}}{\text{d} \delta_{\text{ele}}} \delta_{\text{ele}} + \frac{\text{Q} \text{S}_C}{\text{d} \mathbf{p}} \mathbf{p} + \frac{\text{Q} \text{S}_C}{\text{d} \mathbf{r}} \mathbf{r} \\
\text{Y} &= \text{Q} \text{S} C_{Y_\beta} (\beta) + \text{Q} \text{S} \left( \frac{\text{d}C_Y}{\text{d} \delta_{\text{ail}}} \right) \delta_{\text{ail}} + \text{Q} \text{S} \left( \frac{\text{d}C_Y}{\text{d} \delta_{\text{rdr}}} \right) \delta_{\text{rdr}} + \text{Q} \text{S} \left( \frac{\text{b}}{2V} \right) \left( \frac{\text{d}C_Y}{\text{d} \mathbf{p}} \right) \mathbf{p} + \text{Q} \text{S} \left( \frac{\text{b}}{2V} \right) \left( \frac{\text{d}C_Y}{\text{d} \mathbf{r}} \right) \mathbf{r} \\
\text{L} &= \text{Q} \text{S} C_{l_\beta} (\beta) + \text{Q} \text{S} \left( \frac{\text{b}^2}{2V} \right) \left( \frac{\text{d}C_l}{\text{d} \mathbf{r}} \right) \mathbf{r} + \text{Q} \text{S} \left( \frac{\text{b}^2}{2V} \right) \left( \frac{\text{d}C_l}{\text{d} \mathbf{p}} \right) \mathbf{p} + \text{Q} \text{S} \text{b} \left( \frac{\text{d}C_l}{\text{d} \delta_{\text{ail}}} \right) \delta_{\text{ail}} + \text{Q} \text{S} \text{v} \text{t} \text{MA} \text{v}_t \left( \frac{\text{d}C_l}{\text{d} \delta_{\text{rdr}}} \right) \delta_{\text{rdr}} \\
\text{M} &= \text{Q} \text{S} \overline{c} \left( \frac{\text{d}C_M}{\text{d} \alpha} \right) \alpha + \text{Q} \text{S} \overline{c} C_{M_0} + \text{Q} \text{S} \overline{c} C_{M_{\text{\text{\text{flap}}}}} + \text{Q} \text{S} \overline{c} \left( \frac{\overline{c}}{2V} \right) \left( \frac{\text{d}C_M}{\text{d} \mathbf{q}} \right) \mathbf{q} + \text{Q} \text{S} \overline{c} \left( \frac{\overline{c}^2}{2V} \right) \ast \frac{\text{d}C_M}{\text{d} \alpha} + \text{Q} \text{S} \overline{c} \text{ht} \text{MA} \text{ht} \left( \frac{\text{d}C_M}{\text{d} \delta_{\text{ele}}} \right) \delta_{\text{ele}} \\
\text{N} &= \text{Q} \text{S} \text{b} \text{C}_N \beta \beta + \text{Q} \text{S} \left( \frac{\text{b}^2}{2V} \right) \left( \frac{\text{d}C_N}{\text{d} \mathbf{p}} \right) \mathbf{p} + \text{Q} \text{S} \left( \frac{\text{b}^2}{2V} \right) \left( \frac{\text{d}C_N}{\text{d} \mathbf{r}} \right) \mathbf{r} + \text{Q} \text{S} \text{b} \text{h} \left( \frac{\text{d}C_N}{\text{d} \delta_{\text{ail}}} \right) \delta_{\text{ail}} + \text{Q} \text{S} \text{v} \text{t} \text{MA} \text{v}_t \left( \frac{\text{d}C_N}{\text{d} \delta_{\text{rdr}}} \right) \delta_{\text{rdr}}
\end{align*}
\]

- Table driven coefficients
- Data filled in from NASA EAV model
Simulation
Development Status and Progress

- Preliminary Design
- Engine Integration
  - Preliminary Flight Test
- Modeling and Simulation
- Airframe Modification
  - Actuator installation, control surface splitting, landing gear installation
- Avionics Integration
  - Actuation System Integration
  - CDHS/Autopilot Integration
  - Propulsion System Integration (completed April-2012)
- Acceptance and Environmental Testing
- Flight Worthiness Statement / AFSRB
- Flight Testing and Autopilot Tuning
Introduction to the Swift UAS

Presentation to Prof Joanne Dugan
Dependable Computing Class
University of Virginia
April 16, 2012

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