Autonomous Aerobatics: A Linear Algorithm and Implementation for a Slow Roll

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Introduction

Unmanned Combat Aerial Vehicles (**UCAV**'s) are becoming common on the battlefield airspace but to date they have not been implemented in **fighters** due to the complexity of executing maneuvers required and the **nonlinearities in aerodynamics**, control response, control inputs required, and extreme attitudes.

Such maneuvers are crucial for **Air Combat Maneuvering (ACM, "dogfighting")**, low level penetration with extreme maneuvering for bombing targets, escape and evasion from missiles, and "jinking" for avoiding ground to air gunfire. Such flying is collectively known as **Basic Fighter Maneuvers** (**BFM**).

BFM is fundamentally **composed of aerobatics**, and aerobatics itself is fundamentally composed of a **few basic maneuvers**. **Humans are limited** in their biological ability to withstand extreme maneuvering, thus autonomous fighter aircraft have the capacity to **completely redefine the current mission paradigm** of dogfighting, air superiority, and maneuvering.

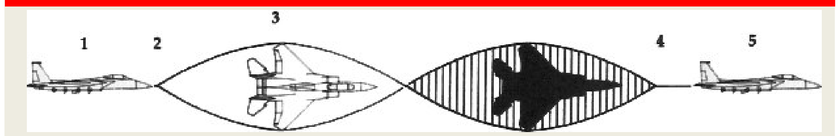
A **slow roll** is one **of three primary fundamental maneuvers**, and the objective of this research is to implement an algorithm capable of flying a slow roll and its associated variations.

The algorithm is based upon methods utilized by the author that are taught to flight students as a Certificated Flight Instructor and utilized flying multiple different powered aircraft and gliders.

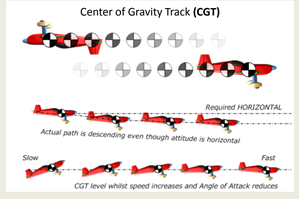
A concurrent objective is to design, fabricate, and flight test a suitable airframe capable of performing in such an extreme envelope, and implementing the necessary routines in an off the shelf autopilot. A **robust hyper-maneuverable airframe** was designed, constructed, and flight tested as a test vehicle, with the flight controls implemented on an APM Autopilot with a software bridge to MATLAB.

The algorithm will be tested by having a **fly-off** between the airframe and full-sized aerobatic aircraft with pilots, with the maneuvers judged on a standard criteria from the International Aerobatics Club. The scores of the algorithm will be **compared against human pilots** to give an assessment algorithm quality.

Flying the Slow Roll

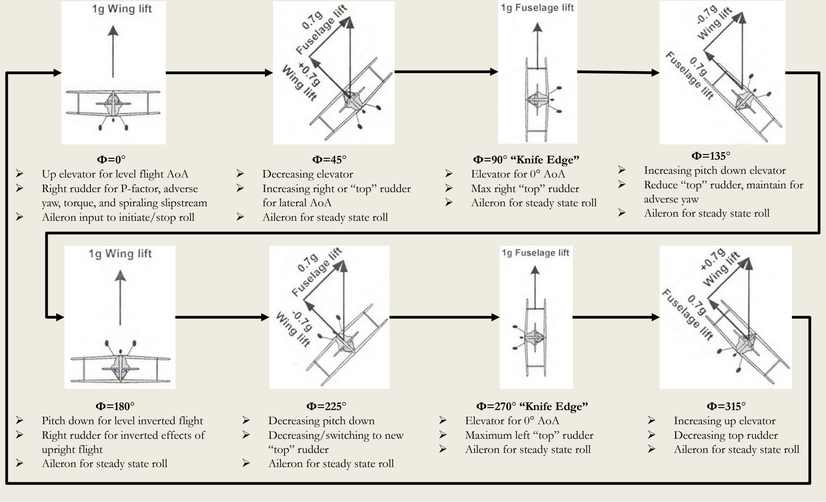


- A slow roll is one of 3 fundamental maneuvers
- 360° roll with or without hesitations along the longitudinal axis while level, climbing, or descending



Roll Criteria

- Roll rate must be constant throughout maneuver
- Roll must be in a constant plane for the Center of Gravity Track (CGT)
- No change in direction of flight during maneuver
- Accurate and crisp angle stops between elements during point rolls
- Maintain axis in level or 45° climbing or descending flight



Φ=0°
- Up elevator for level flight AoA
- Right rudder for P-factor, adverse yaw, torque, and spiraling slipstream
- Aileron input to initiate/stop roll

Φ=45°
- Decreasing elevator
- Increasing right or "top" rudder for lateral AoA
- Aileron for steady state roll

Φ=90° "Knife Edge"
- Elevator for 0° AoA
- Max right "top" rudder
- Aileron for steady state roll

Φ=135°
- Increasing pitch down elevator
- Reduce "top" rudder, maintain for adverse yaw
- Aileron for steady state roll

Φ=180°
- Pitch down for level inverted flight
- Right rudder for inverted effects of upright flight
- Aileron for steady state roll

Φ=225°
- Decreasing pitch down
- Decreasing/switching to new "top" rudder
- Aileron for steady state roll

Φ=270° "Knife Edge"
- Elevator for 0° AoA
- Maximum left "top" rudder
- Aileron for steady state roll

Φ=315°
- Increasing up elevator
- Decreasing top rudder
- Aileron for steady state roll

Control Algorithm Methodology

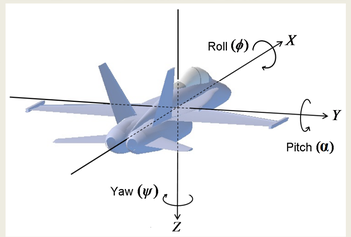
A pilot is essentially a PID Controller. The author's unique aviation experience as a Certificated Flight Instructor and competition aerobatic pilot in powered and sailplanes is applied and converted to a mathematical basis.

This reduces the control problem to a linear system, bypassing the analytical, computational, and monetary issues with a typical engineering approach.

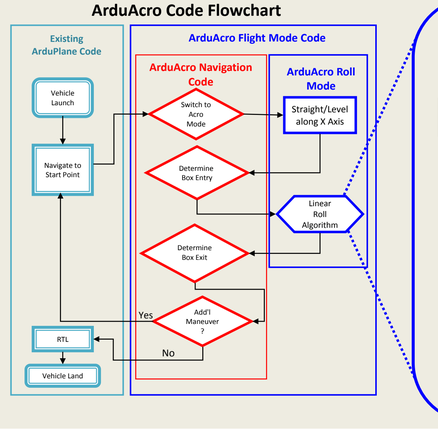
- Utilizing the existing codebase, the airframe launches and navigates to the aerobatic box and aligns for the maneuver
- Input parameters of roll rate, entry speed, altitude, heading are handed over to the algorithm, and ACRO mode is engaged
- Measure error in inertial frame, and rotate errors as a function of Φ to convert to body frame for proper control deflection direction and scaling

$$\begin{bmatrix}\Delta\alpha\\ \Delta\Psi\end{bmatrix}=\begin{bmatrix}\cos\Phi & \sin\Phi\\ -\sin\Phi & \cos\Phi\end{bmatrix}\begin{bmatrix}\Delta Altitude\\ \Delta Heading\end{bmatrix}$$

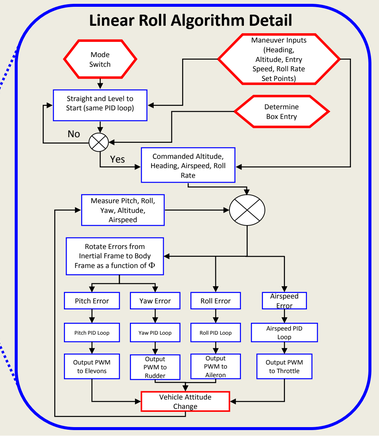
- Rotated errors are used in a standard PID loop for elevator and rudder inputs. Roll and throttle are decoupled, with throttle increases linked to altitude loss at full control deflection
- Outputs sent to servos on control surfaces



ArduAcro Code Flowchart



Linear Roll Algorithm Detail

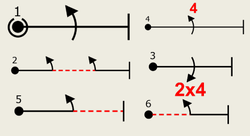


Flight Testing, Data Collection, and Fly Off

- VF-1 Valkyrie "Roy Fokker" was flight tested and found to have excellent flight characteristics and met performance requirements
- The autopilot was calibrated and utilized in a fly-by-wire mode to tune APM Control gains. Tuning and final testing will be done at Old South Aerodrome (Private Airport, K32VA)
- Final data collection will be conducted by having a "Fly-off" air show between human pilots and the Valkyrie using International Aerobatic Club scoring criteria and certified judges

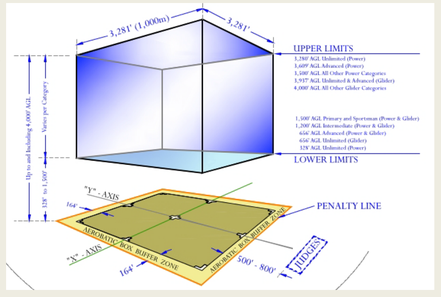
Fly-off Procedure

- Both manned and unmanned aircraft will fly a defined aerobatic sequence in a box under IAC rules
- Sequence will consist of at least 3 repetitions of various slow rolls
  - 2 point, 4 point, 2/4, 1/2, and a "long" slow roll
- Multiple pilots and planes have volunteered to give an accurate comparison to human capabilities
- Scores will be processed and compared to validate algorithm performance



Power			
Fig 1	1.1.1.1 9.1.3.4	2 8	10
Fig 2	1.1.1.1 9.1.3.2 9.1.3.2	2 4 4	10
Fig 3	1.1.1.1 9.1.3.4	2 8	10
Fig 4	1.1.1.1 9.4.3.4	2 11	13
Fig 5	1.1.1.3 9.1.3.2	2 4	6
Fig 6	1.1.1.4 9.4.3.2	2 3	7
Total K = 56			

Aerobatic Contest Box and Axes

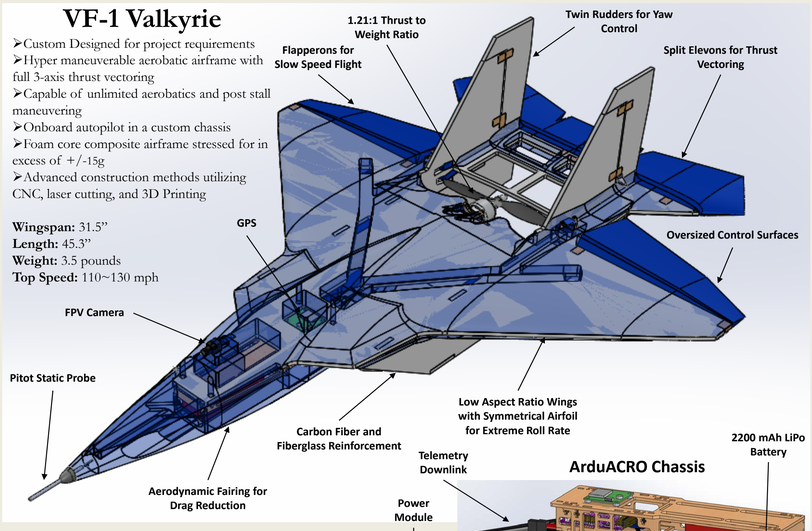


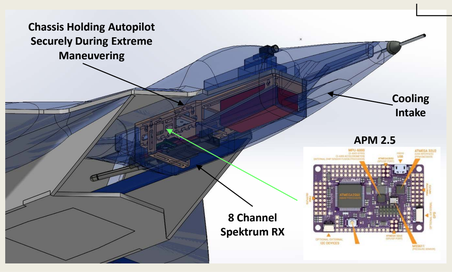
Custom Designed Airframe

VF-1 Valkyrie

- Custom Designed for project requirements
- Hyper maneuverable aerobatic airframe with full 3-axis thrust vectoring
- Capable of unlimited aerobatics and post stall maneuvering
- Onboard autopilot in a custom chassis
- Foam core composite airframe stressed for in excess of +/-15g
- Advanced construction methods utilizing CNC, laser cutting, and 3D Printing

Wingspan: 31.5"
Length: 45.3"
Weight: 3.5 pounds
Top Speed: 110~130 mph





ArduACRO Chassis

ArduACRO

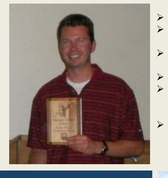
- Custom ArduACRO flight mode programmed in ArduPlane to implement autonomous roll algorithm
- Custom MATLAB/MAVLink interface for communication and telemetry
- 3-axis gyros and accelerometers
- Barometric Altimeter/Airspeed and 5Hz GPS
- Atmel ATMEGA Processor
- 915MHz telemetry downlink

MAVLINK MICRO AIR VEHICLE COMMUNICATION PROTOCOL

ARDUPLANE

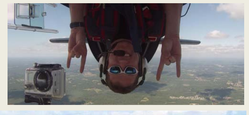
VF-1 Valkyrie – Versus- Top Aerobatic Pilots

Eric Sandifer
- 1,150 hours total time
- Earned license in 2002, started flying aerobatics 2003
- Flown in all IAC categories, currently flying Unlimited in the Pitts, 1st place wins in all categories, 2015 Northeast Series Advanced Champion
- President of IAC Club 19 and was contest director at 7 contests



John White
- ~34,000 hours total time
- Master Aerobatic CFI and Air show Pilot
- Chief Pilot for Strongwell Corp.
- Test Pilot for Piper
- Professional Aviator , including experience in an SU-25 Fighter
- Learned to fly in 1967, and was taught by his father James Franklin White

Brett Pearce
- 500 hours total time
- Represented NCSU in Collegiate Aerobatics Division, placed 2nd nationally
- Certificated Glider Flight Instructor



Pitts S-1S, N100MP

- Designed in 1943 by Curtiss Pitts
- The Smithsonian described it as "revolutionary because of its small size, light weight, short wingspan and extreme agility"

Wingspan: 17'4"
Length: 15'6'
Weight: 1150 pounds
Engine: 180hp 4 cylinder Lycoming
Propeller: 2 blade fixed pitch
Roll Rate: 180 deg/sec
G Limits: +6/-3g
Top Speed: 176 mph

Extra 300, N300XT

- Designed by Walter Extra in 1987 as a composite, unlimited class monoplane
- Started a monoplane revolution in air shows and competition aerobatics

Wingspan: 24'3"
Length: 22'9"
Weight: 2,095 pounds
Engine: 300hp 6 cylinder Lycoming
Propeller: 3 blade constant speed
Roll Rate: 400 deg/sec
G Limits: +/-10g
Top Speed: 253 mph