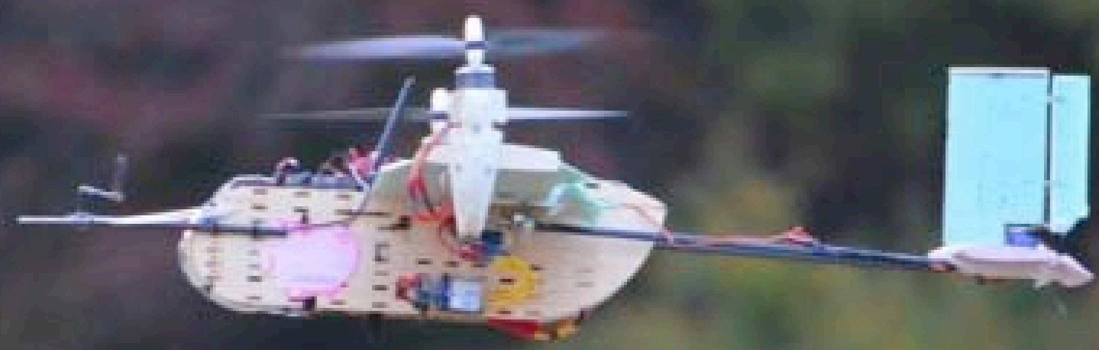
“Tiltrotor 1”



APM powered Tiltrotor

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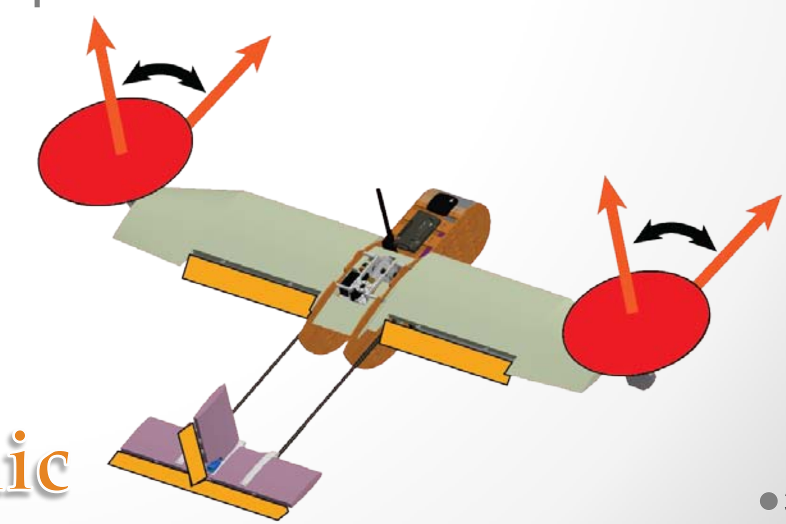
Outline

- Tiltrotor Fundamentals
- Combining The Strengths of “ArduPilot”
- Tiltrotor Challenges
- Testing
- Tiltrotor Road Map

Fundamentals of Tiltrotors

- Tiltrotors are <u>planes</u> that can hover, NOT copters that fly like planes!
- A tiltrotor uses combination of ***thrust vectoring*** and traditional ***aerodynamic surfaces*** to maintain stability while transitioning between hovering and forward flight "modes".
- Exchanging the thrust from a ***lift force*** to ***propulsion force*** while using a wing to replace the lift can greatly increase the range and efficiency compared to vertical thrust aircraft.



Thrust Vectoring

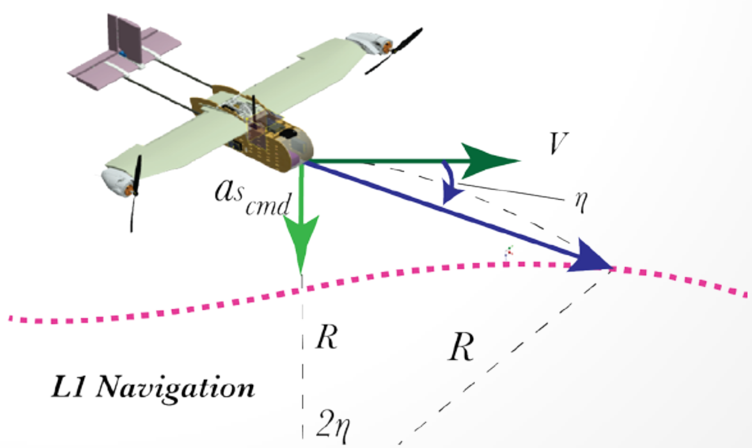
Aerodynamic

Missions of Tiltrotors

- Tiltrotors have "Plane" like range and speed capabilities without the need for runways, launchers, captive devices.
- Costly UAV external sensors / equipment can be mounted beneath the aircraft to maximize ground visibility without fear of damage during a plane-like controlled crash landing.
- Unlike other VTOL concepts, the fuselage and wing orientation is unchanged.
  - Reduced exposure to high winds in hover
  - The orientation of cargo and sensor's are unaffected

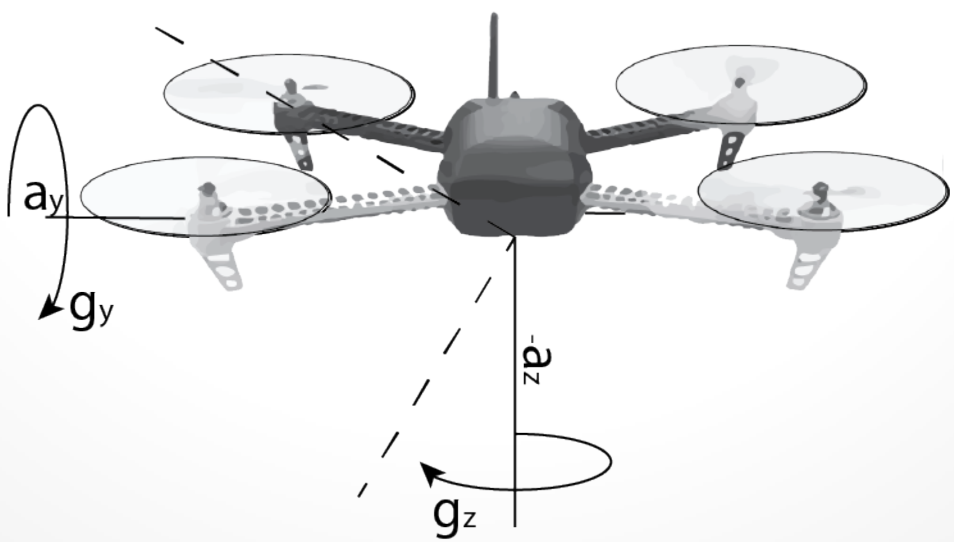
Combining the Strength's of "ArduPilot"

- Ardu**<u>Plane's</u>** Strengths
  - Attitude control with Emphasis on ***Aerodynamics***
    - Airspeed Sensor with "airspeed" sensitive control (speed scalar).
    - Attitude controllers (PID's) are designed for deflecting aerodynamic surfaces to control rates and attitudes.
    - Navigation Controllers (L1 & TECS) are great for vehicles that are in *continual motion* with the body frame always in the direction of travel (Unlike quad navigation which can separate heading and direction of travel).
    - Stall Prevention



Combining the Strength's of "ArduPilot"

- Ardu**<u>Copter</u>** Strengths
  - Attitude control with Emphasis on ***Thrust***
    - Thrust linearization of pilot input.
    - Attitude controllers (PID's) are designed for thrust changes to evoke attitudes and rates.
    - Heading target is fixed (unlike plane).
  - The most challenging flight regime for a tiltrotor is low speed. The Ardu**Copter** attitude architecture simplifies stability.



Tiltrotor Challenges

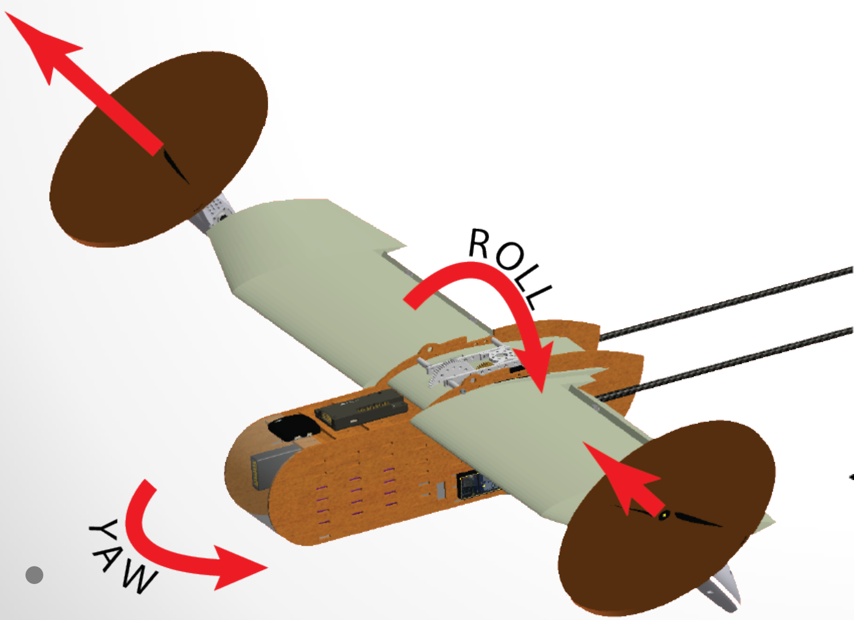
- Mixing and exchanging aerodynamic controls and thrust vectoring forces.
  - A handoff must occur between ***thrust*** based commands and ***aerodynamic surfaces.***
  - Tiltrotor control requires seamlessly bridging the gap between low speed ***thrust*** control and high speed ***aerodynamic*** control.
  - Flight control outputs that are a function of thrust vector or airspeed must be suppressed if they are redundant.
    - Tiltrotor 1 – Pitch from thrust and elevator
    - Fire Fly 6 – Rear motor set and elevons

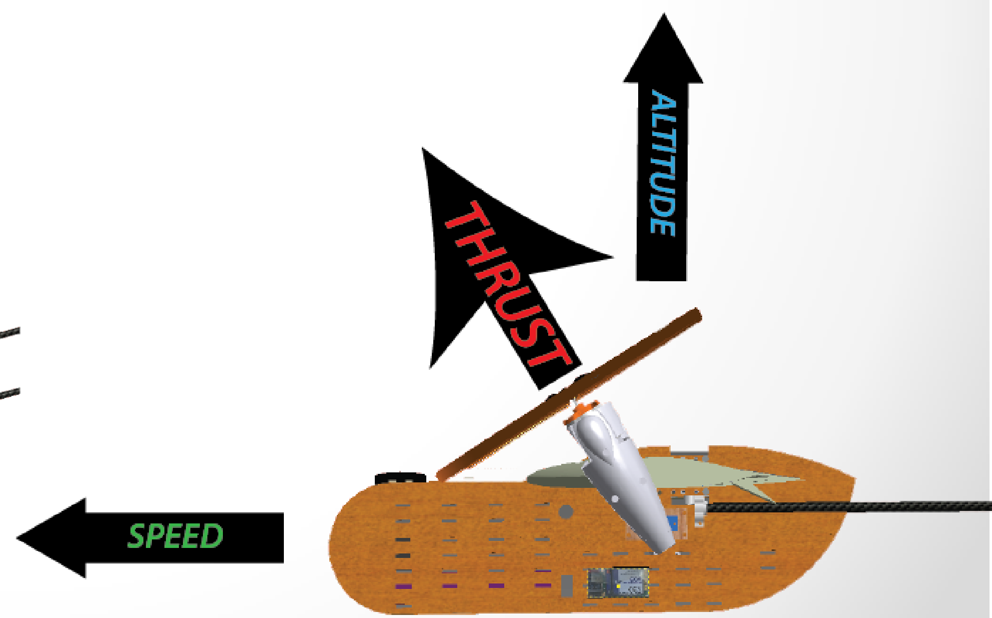
The Combined Result

- We have successfully demonstrated using the combined attitude controllers from plane and copter.
  - It took several failed attempts to truly appreciate and understand the nuances of plane and copter attitude controllers.
- When the aerodynamic surfaces and thrust are in harmony, the result is very stable and predictable attitude control at ANY thrust angle.

Tiltrotor Challenges

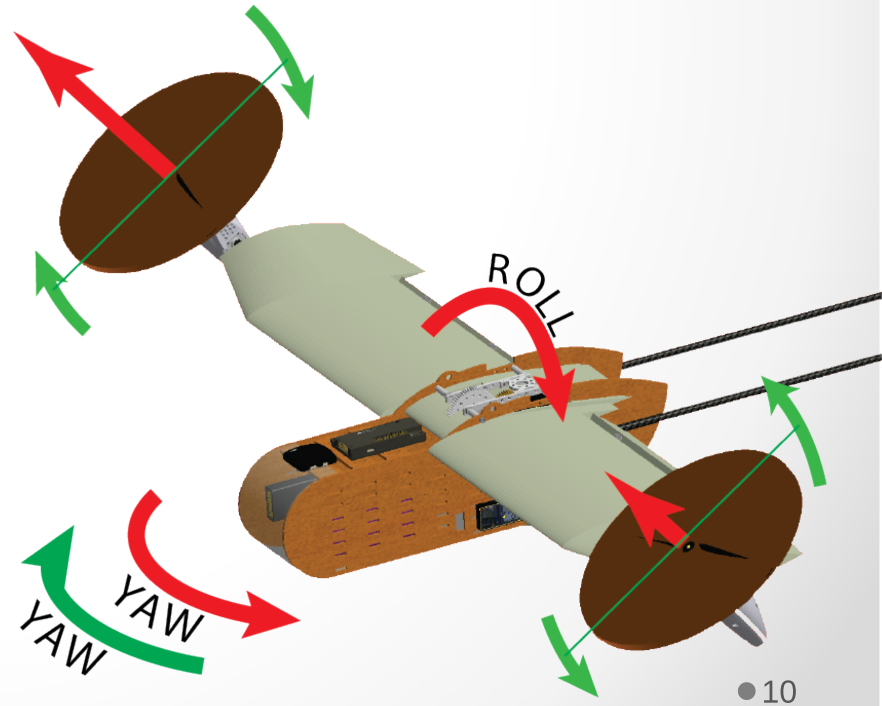
- What makes the changing the thrust vector so challenging?
  - Once the thrust vector is anywhere between 90º(vertical) and 0º (horizontal), a *DIFFERENTIAL* thrust change results in roll and yaw axis coupling.
  - A *SYMETRIC* thrust change will result in altitude and airspeed coupling.





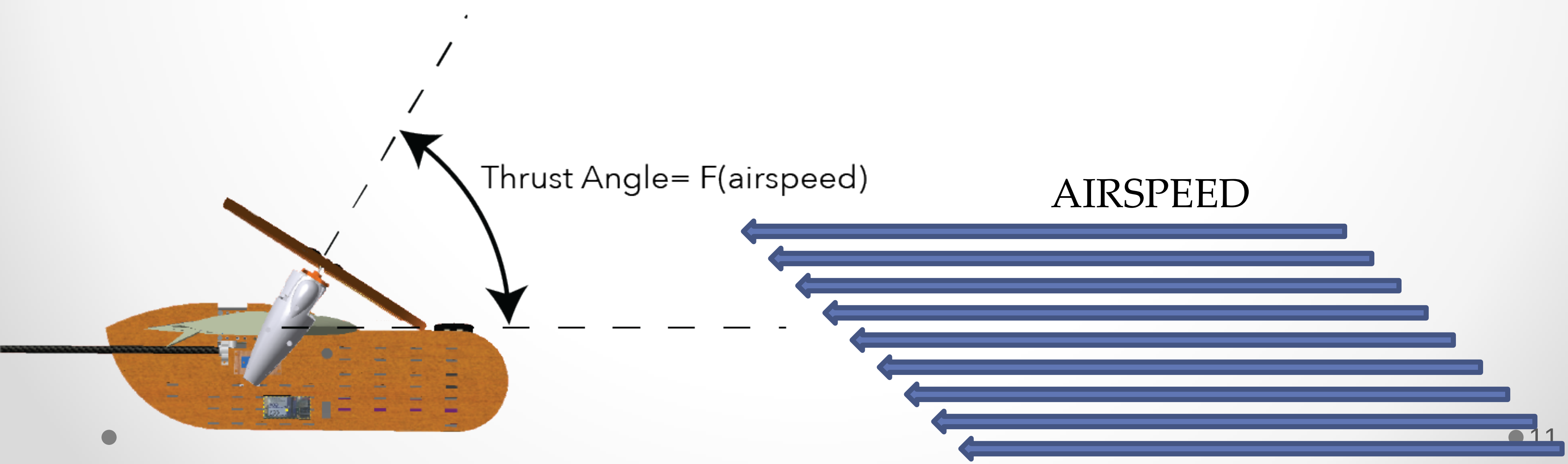
Tiltrotor Thrust Angle Controller

- Thrust angle controller commands 2 outputs (Yaw + Roll) that result in a single axis response (Roll) when the thrust axis is not in alignment the body axes.
- Cross coupling is mitigated / eliminated by manipulating the rate errors that the attitude controller operates on.



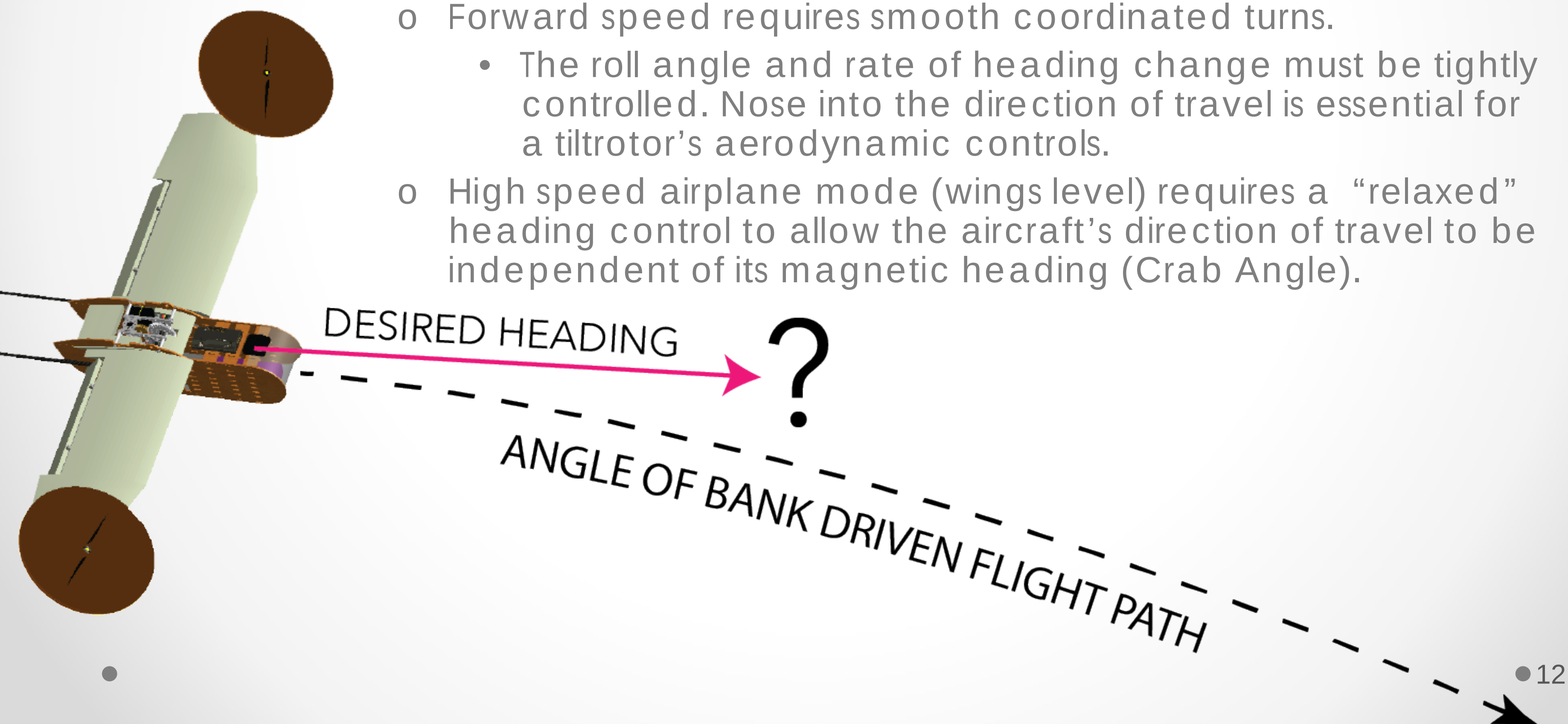
Tiltrotor Challenges

- Thrust Vector Angle Limiting
    - Use vector analysis to determine the lowest thrust angle allowed for a given speed.
        - i.e. ensure net aircraft lift (wing + thrust) preserves positive climb capability.
    - The thrust vector is rate limited to prevent abrupt center of gravity and aerodynamic changes.



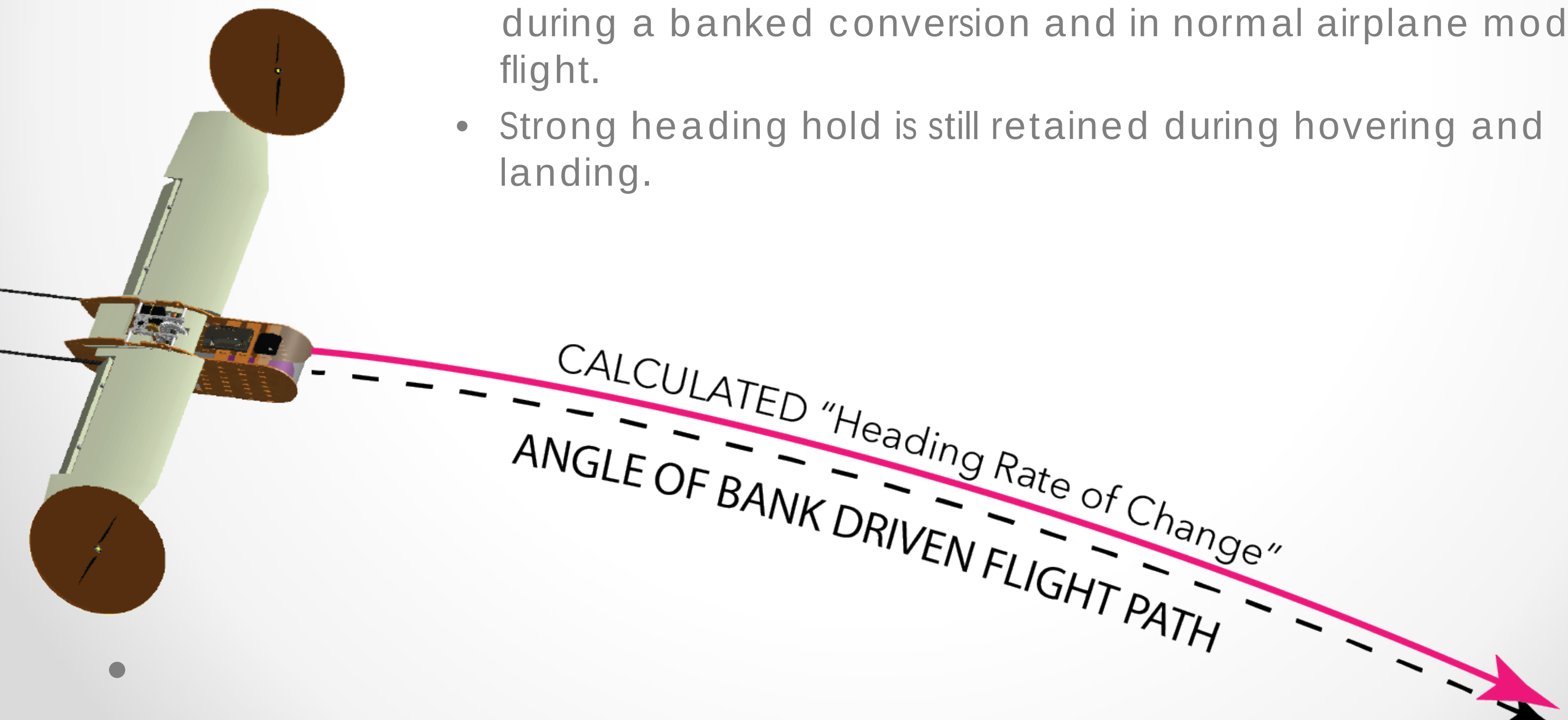
Tiltrotor Challenges

- Tiltrotor Heading control requires 3 unique "Yaw" modes
  - Slow Speed / Hovering flight requires the desired heading must be strictly maintained.
    - *Copter* Heading Control ("Heading Hold").
  - Forward speed requires smooth coordinated turns.
    - The roll angle and rate of heading change must be tightly controlled. Nose into the direction of travel is essential for a tiltrotor's aerodynamic controls.
  - High speed airplane mode (wings level) requires a "relaxed" heading control to allow the aircraft's direction of travel to be independent of its magnetic heading (Crab Angle).



Tiltrotor Yaw Controller

- A unique tiltrotor heading function was created to manage the heading rate of change for a given airspeed and bank angle.
  - The result is a smooth aerodynamically coordinated turn during a banked conversion and in normal airplane mode flight.
  - Strong heading hold is still retained during hovering and landing.



Tests and Results

- In less than 1 year we designed, tested, and flown a custom tiltrotor using an APM 2.5 .
- We have successfully flown 19 Hover, 21 Conversion Mode, and 2 Airplane Mode Test flights in the summer of 2014.
- Thorough analysis, test, and evaluation have successfully combined the major components of ArduPilot to stabilize a tiltrotor at any discrete thrust vector.

Future Tiltrotor Design Considerations

- Flight Mode Behavior
  - STABILIZE- Functions Similar to Airplane and Quad "Stabilize"
    - Manual Thrust Vector Control?
  - FBW (A/B)- User inputs are similar to conventional aircraft control
    - Maintaining desired response with any thrust vector angle
  - RTL- Plane RTL vs Copter RTL?
    - Aircraft state at moment of "RTL" command requires careful logic to protect from undesired behavior.
  - LOITER- Plane "Loiter" with exception of hover
  - AUTO- Full Mission execution from take off to landing
    - Way point commands: Airspeed / Thrust Vector Targets?

Tiltrotor Road Map

- Last Test flight of "Tiltrotor 1" November 2014 ✔
- Upgraded Hardware to a Pixhawk (December 2014) ✔
- Acquired a "Fire Fly 6" (Craig Elder) Tiltrotor (February 2015) ✔
  - Expedite Tiltrotor software development
- Merge our existing software to ArduCopter 3.2.1 (March 2015) ✔
- ArduPilot Master software Merge (March 2015) ✔
- Aircraft Regression Testing ☐ **PLANNED APRIL 2015**
  - Significant Code Restructuring for Pixhawk / Master
  - New Hardware
  - New Airframe (FireFlY6) with new attitude controllers for Y6 Configuration
- Implement Navigation Controllers ☐ **PLANNED SUMMER 2015**
  - L1 Navigation
  - Auto Thrust Vector
  - TECS Vertical / Speed Navigation
- Vehicle Expansion ☐ **AFTER AUTONOUMOUS CODE COMPLETE**
  - Make this code flexible and expandable for new airframes