# CHALLENGES IN UAS:
# Design for Autonomy and Integration into the National Airspace

**Dr. Ing. Kimon P. Valavanis, John Evans Professor**
**Fellow, AAAS**
**Fellow, U.K. Institute of Measurement and Control**
**Director, Research & Innovation**
**Daniel Felix Ritchie School of Engineering & Computer Science**

**kimon.valavanis@du.edu**

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# Motivation - Rationale

- The importance of autonomy
- Integrate UAVs into the National Airspace System
- UAVs must function as if there were a pilot on-board
- UAVs must demonstrate ELOS comparable to those of manned aviation
- UAVs must have on-board sense-and-avoid/see-and-avoid systems
- UAVs must have failure recovery capabilities that go beyond the nominal/backup control system
- Goal: Manned – unmanned aviation flying / sharing the same airspace
  - Unmanned formations
  - Manned – unmanned formations
  - Mid-air collision avoidance

# UAV Industry

Fortune - "*An estimated 30,000 commercial and civil drones could be in the skies in the U.S. by 2020, according to the Federal Aviation Administration (FAA). The Association for Unmanned Vehicle Systems International (AUVSI) estimates that between 2015 and 2025, the drone industry will create 100,000 jobs and contribute $82 billion to the U.S. economy.*"





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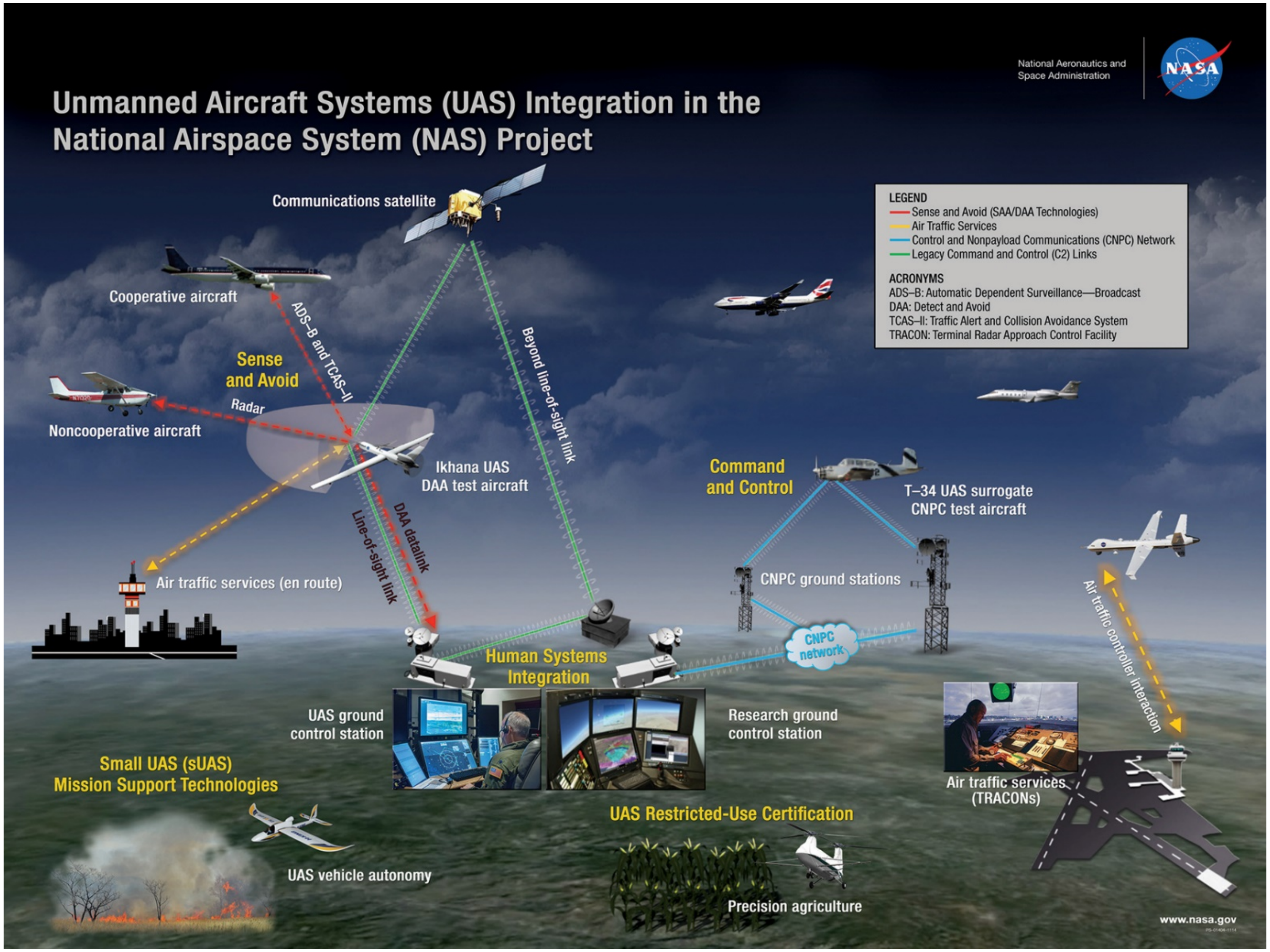
# Integration into NAS




Picture is taken from: https://www.nasa.gov

# There is Nothing "Unmanned" in UAS

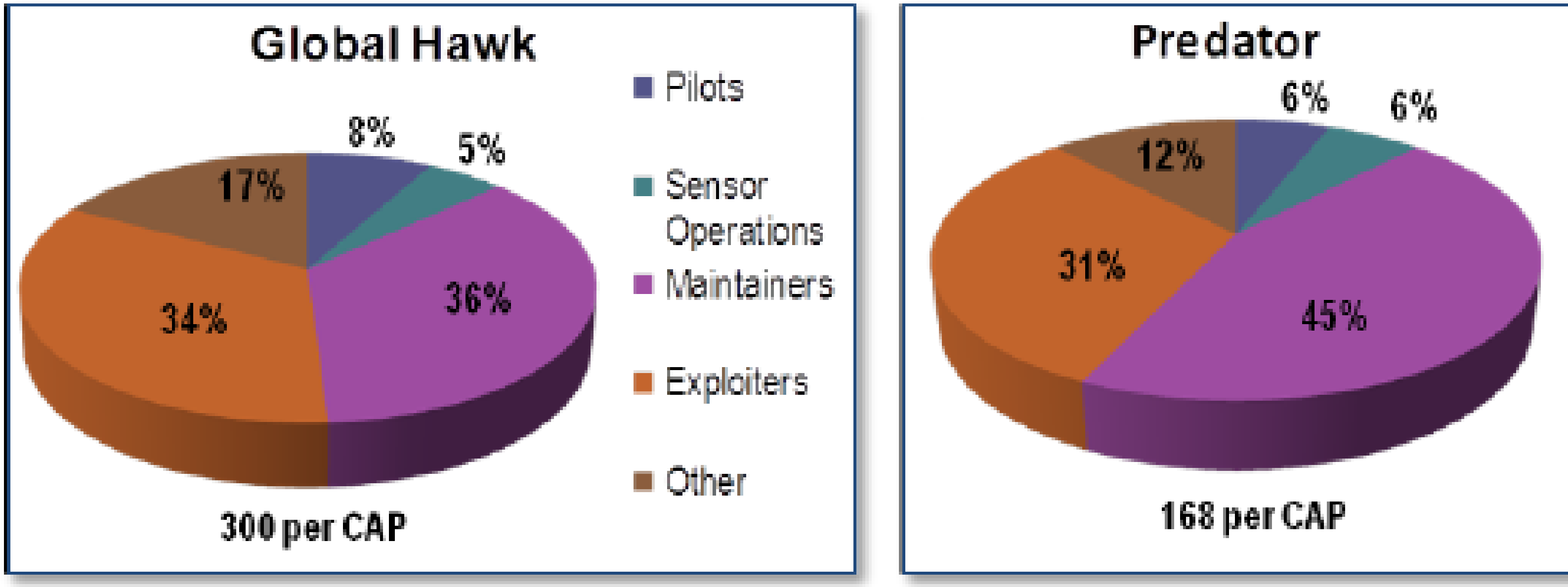



Figure 4-1 Manning Unmanned Platforms is a Key Staffing Problem

**Objective: 4-1 ratio to become 1-4, that is, one operator, 4 UAS.**
**Human-in-the-loop (U.S. Air Force)**
**Human-on-the-loop (U.S. Army)**

# There is Nothing "Unmanned" in UAS

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**MQ-9 Reaper AVOs**

- **Must design effective / efficient HMIs to reduce AVO workload.**
- **Requires automation progression - decision making shifts to the 'machine'**
- **High confidence systems**
- **Challenge: Quest for autonomy**

→ *iff (if and only if) the above is 'accepted', and if the roadmap to integration into the NAS is 'developed', then, UAS will be fully integrated into the national*

**FAA regulations for UAS operating in the NAS state that they must provide an** *"…equivalent level of safety comparable to see-and-avoid aerial requirements for manned aircraft"*. *They should function 'as if there were a pilot on-board'!!!*

**The challenge:**

"Design and build UAS that comply with VFR and later IFR requirements"

Compliance with requirements pertaining to:

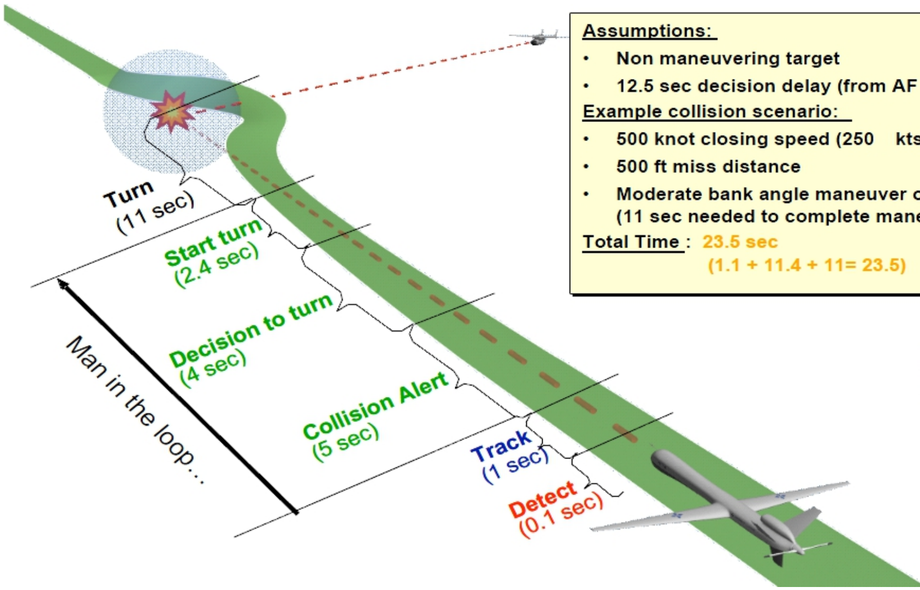
- ❑ See and avoid
- ❑ Right-of-way rules
- ❑ ATC communication
- ❑ Airspace classes
- ❑ NOTAMs

- **Use "Redundancy" to increase safety**
- **As such**:
  - *See-and-avoid*
  - *Sense-and-avoid*

*functioning as one system and also independently*

*Quote from FAA Rep: "THIS IS A NECESSARY BUT NOT SUFFICIENT CONDITION"*

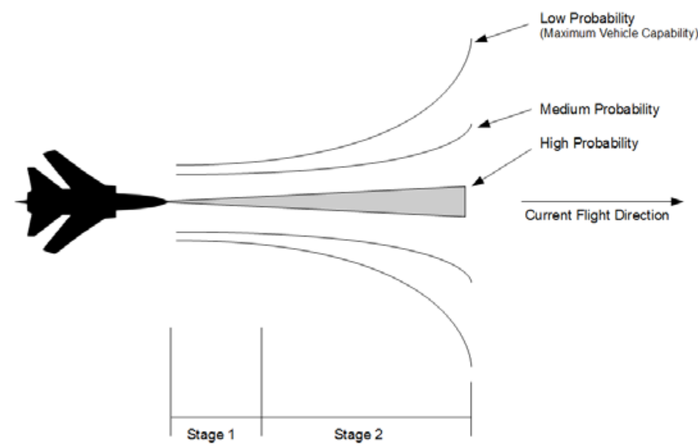
# Motivation - Rationale



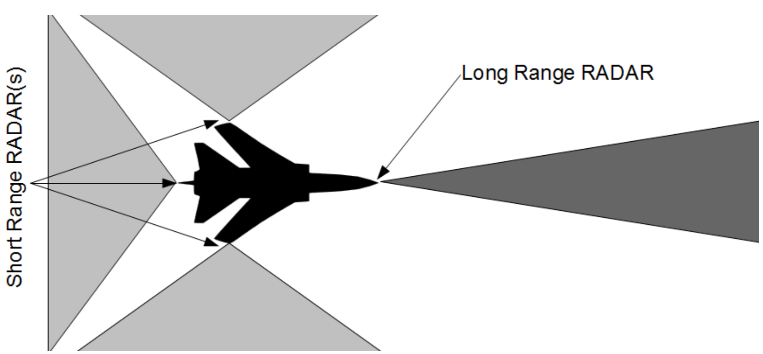

**Assumptions:**
- Non maneuvering target
- 12.5 sec decision delay (from AF -MACA)

**Example collision scenario:**
- 500 knot closing speed (250 kts each)
- 500 ft miss distance
- Moderate bank angle maneuver of 15 °
  (11 sec needed to complete maneuver)

**Total Time :** 23.5 sec
(1.1 + 11.4 + 11= 23.5)



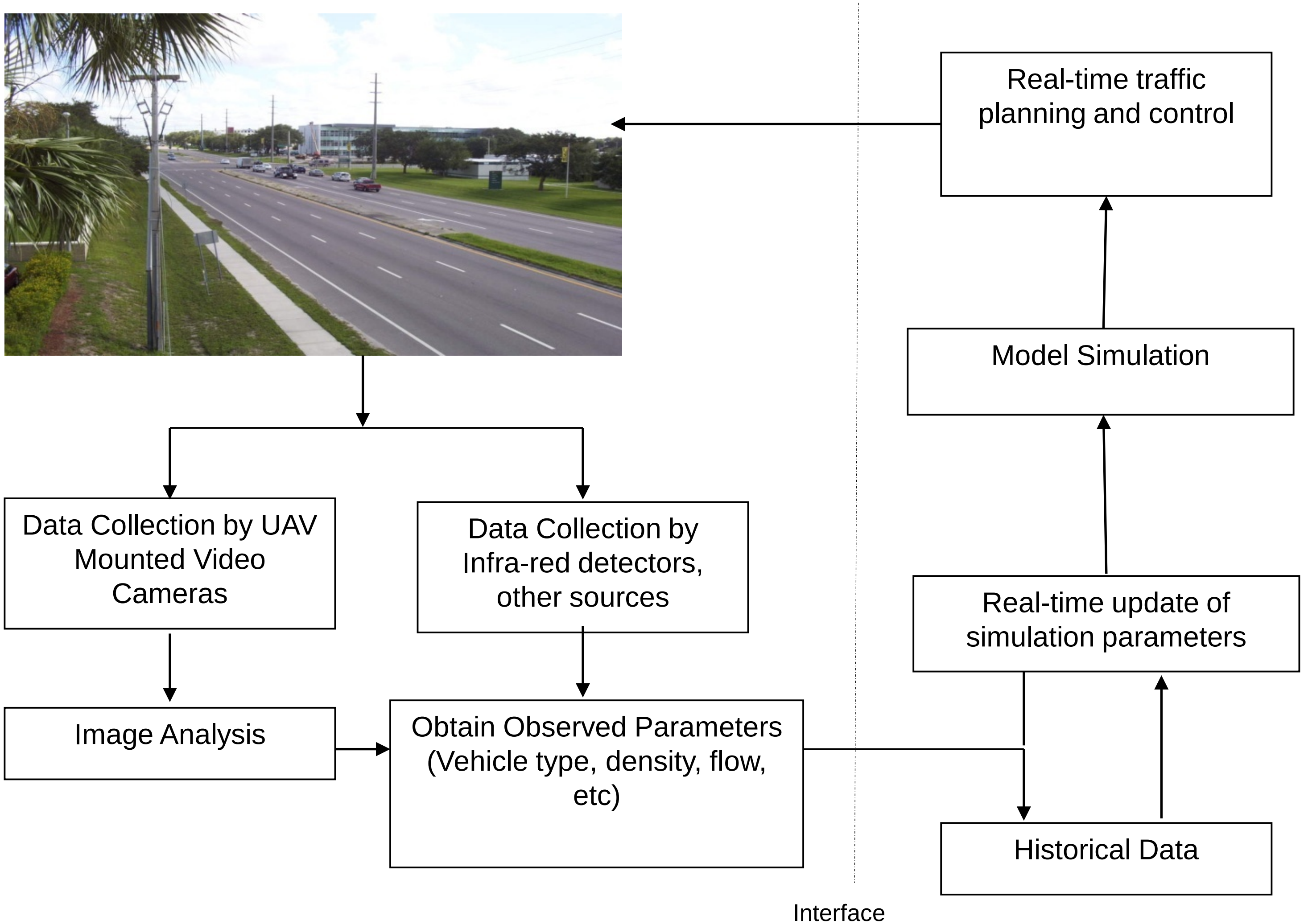

**•Evasion flight path depends on the flight characteristics of the threat aircraft(s)**




***In the U.S. the first to fly will be UAVs with MTOW < 25 pounds***
***Must demonstrate ELOS comparable to those of manned aviation (FAA)***
***Must operate "as if there were a pilot on-board"***

# Sample of Applications

- Power line inspection
- Pipeline inspection
- Fire detection
- Traffic monitoring
- Ship inspection
- Search and rescue
- Aerial photography
- SWAT support
- Imaging and mapping
- ISR
- Chemical spraying
- Hazard monitoring
- Mine inspection
- Dam inspection
- Watering restriction support
- Border patrol
- Police surveillance
- Harbor patrol
- Earth quake inspection
- Crop dusting
- Night vision
- Anomaly detection/prevention




**Traffic monitoring:** **Framework for incorporating real-time data in simulation models**

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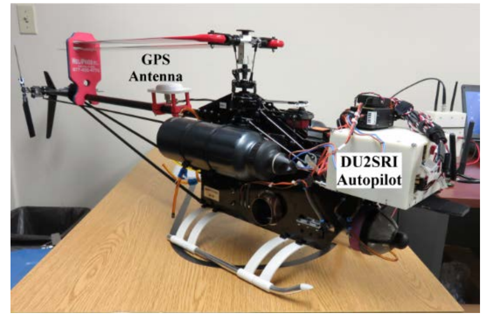
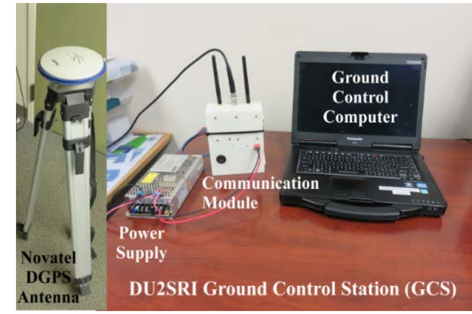
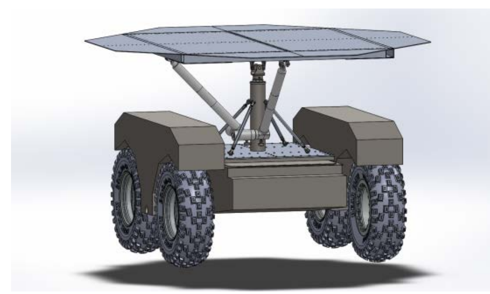
Traffic Monitoring -1
Traffic Monitoring – 2
Autotracking
Multiple Monitoring
Algorithm Works – Race1
Algorithm Works – Race2
Fire Detection – 2 (With fixed-wing UAV)
Formation - Ellipse
Formation: UGV – Helicopter
Landing Platform
Hovering to land
Circulation Control



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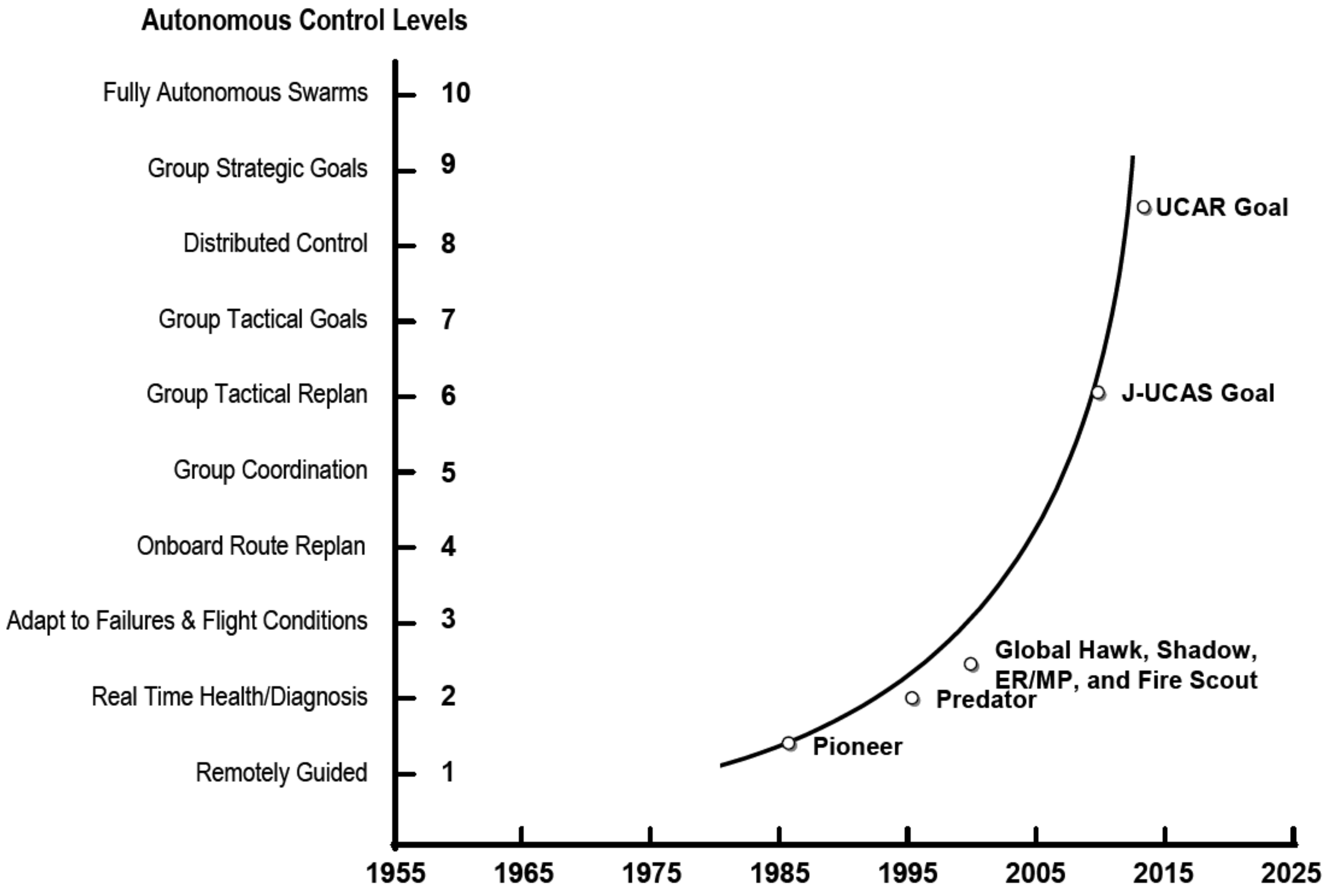
# DOD ROADMAP - AUTONOMY




TREND IN UA AUTONOMY.

# The Challenge of Autonomy (U.S. DoD)

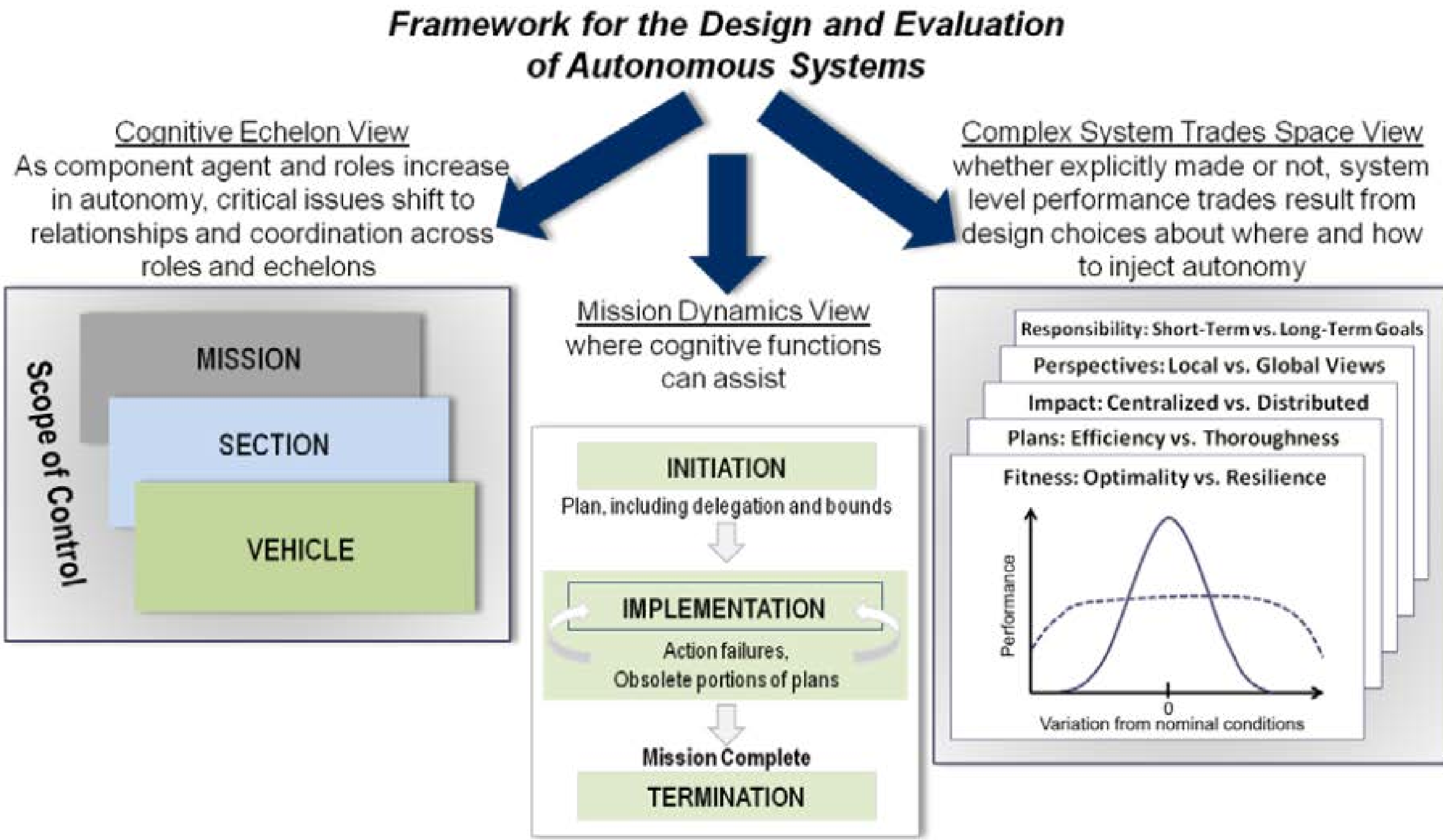



Figure 1-1 Framework for the Design and Evaluation of Autonomous Systems

# The Challenge of Autonomy (U.S. DoD)

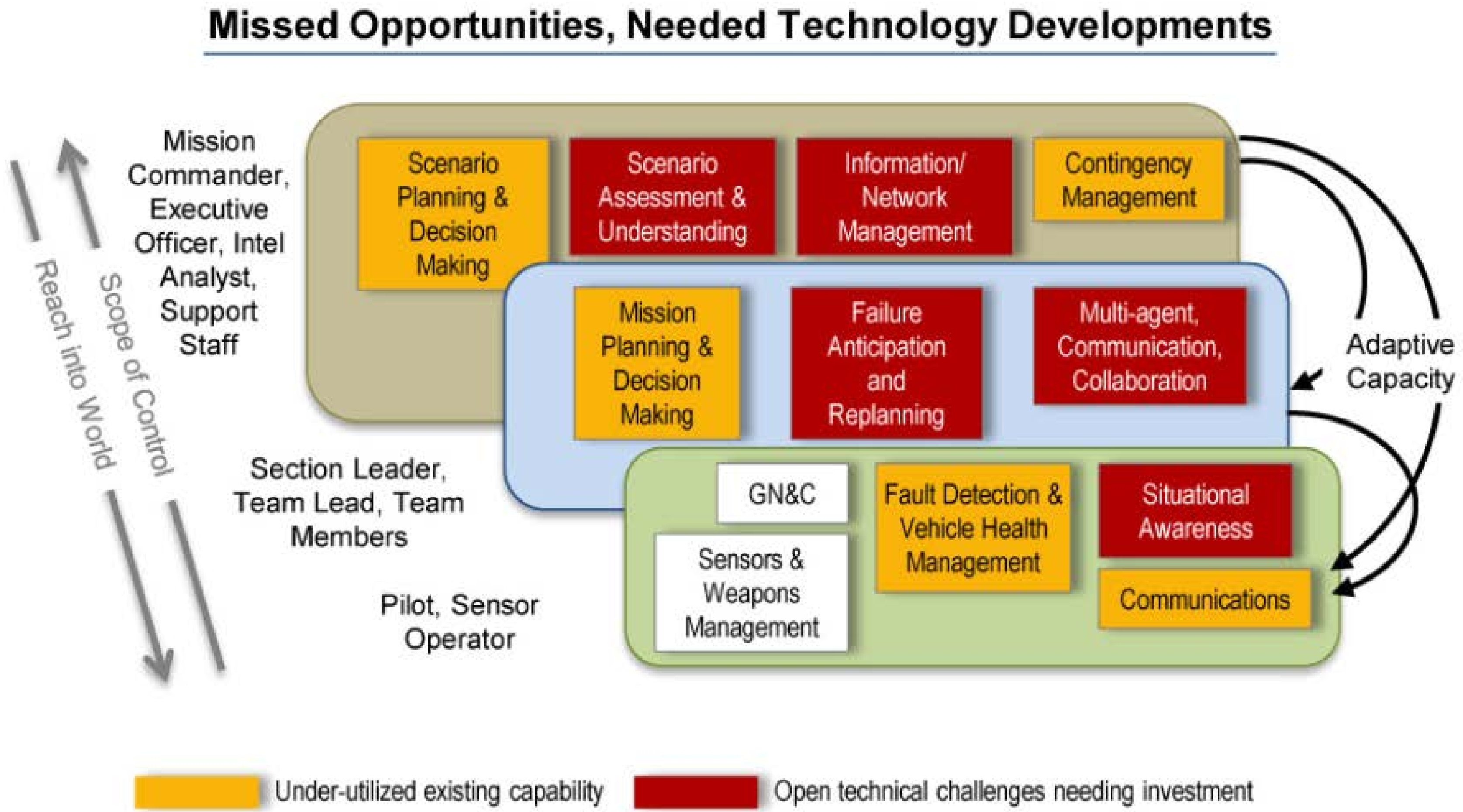
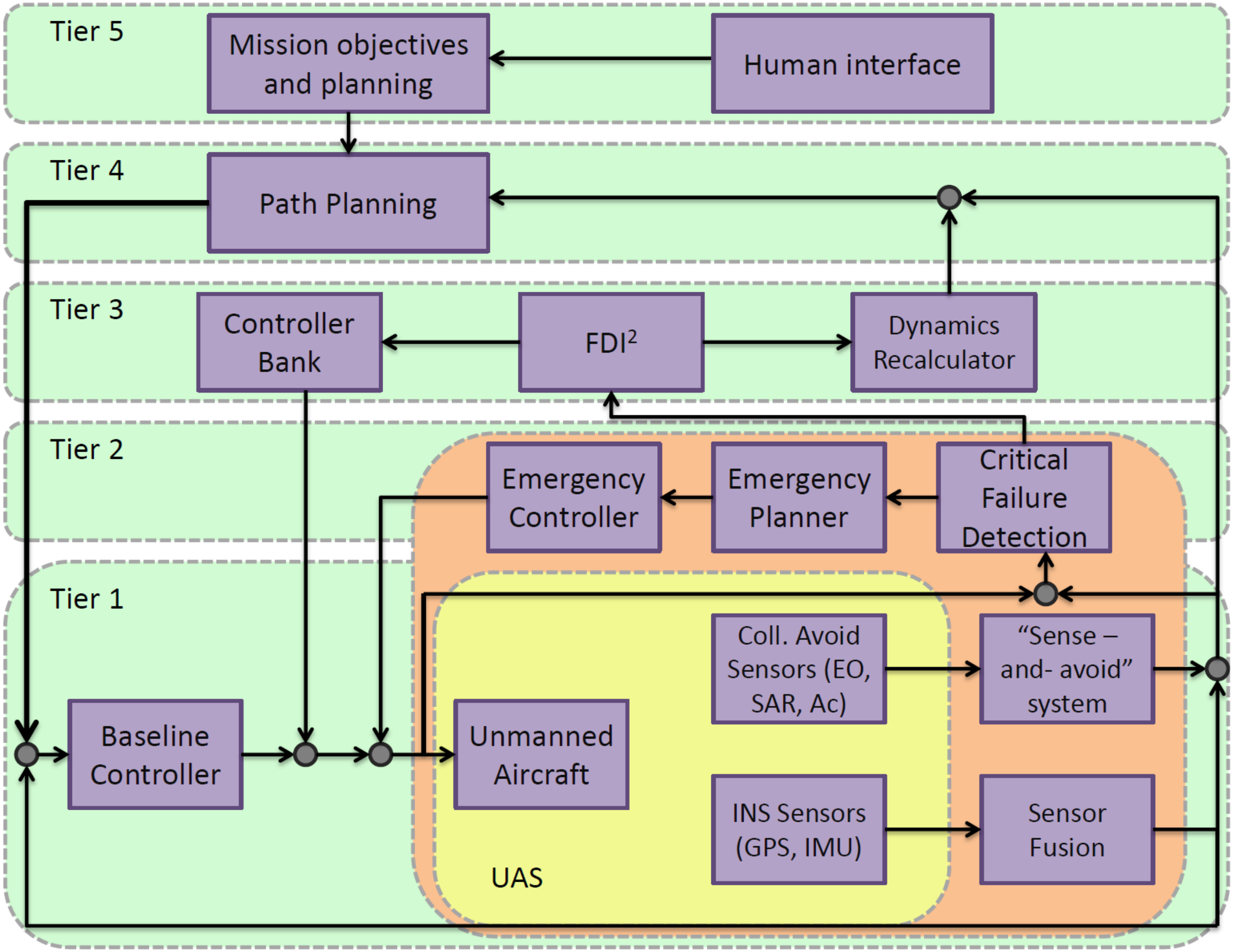
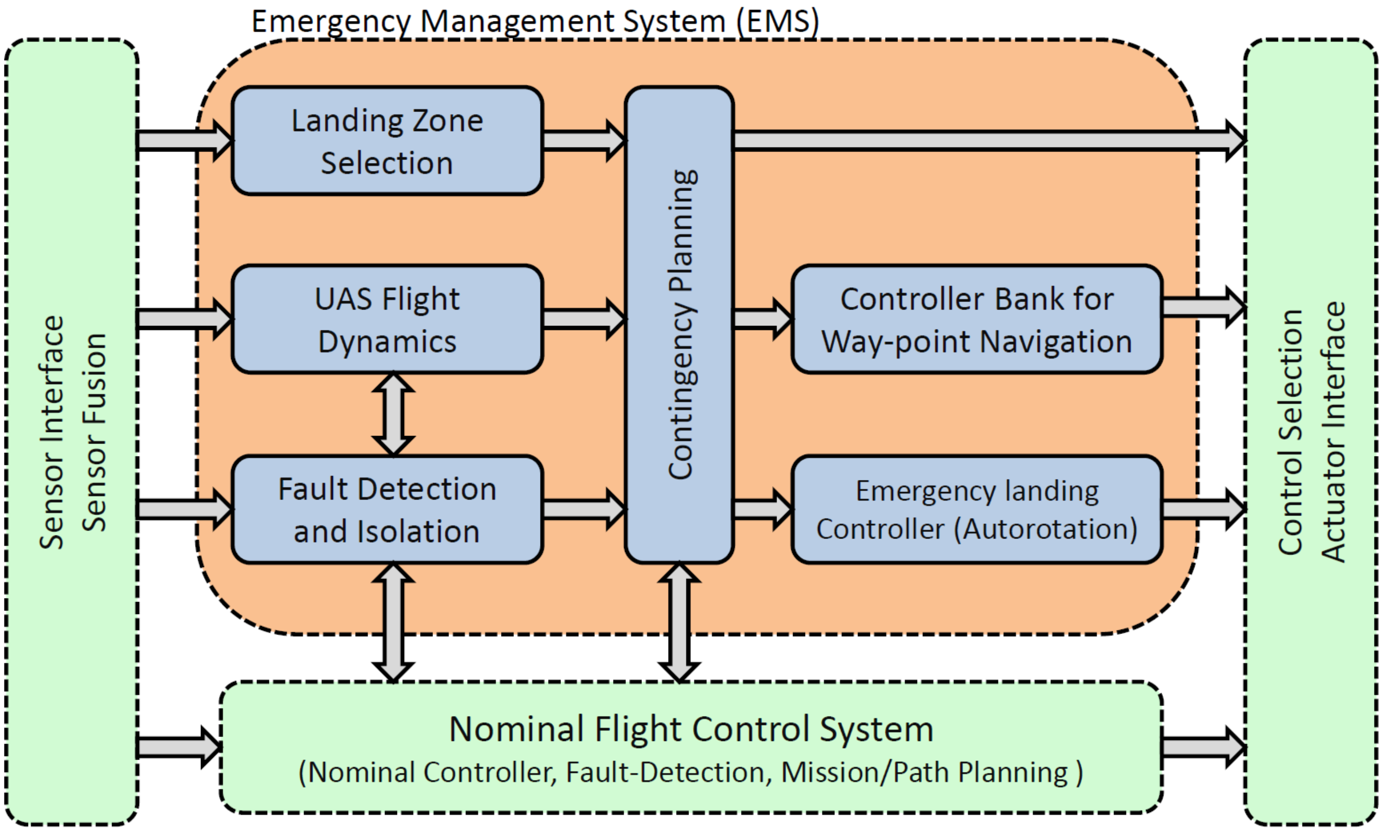



Figure 1-3 Status of Technology Deployment and Remaining Challenges

# (Our) Proposed Architecture



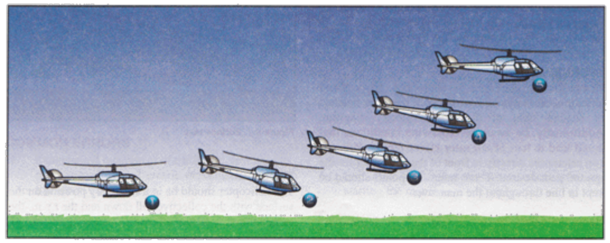
# (Our) Proposed Architecture



# (Example) Helicopter Maneuvers

## Basic Maneuvers (Basic navigation)

- Take-off/Landing
- Forward Flight
- Hovering
- Turns and side slips
- Taxiing
- Departure flight (reverse)
- Waypoint navigation



http://www.dynamicflight.com/flight_maneuvers/takeoffs/

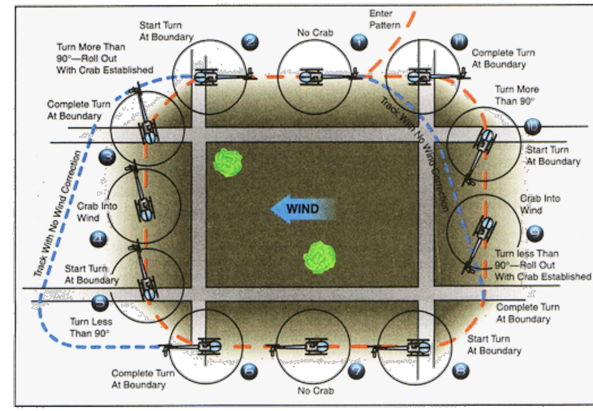
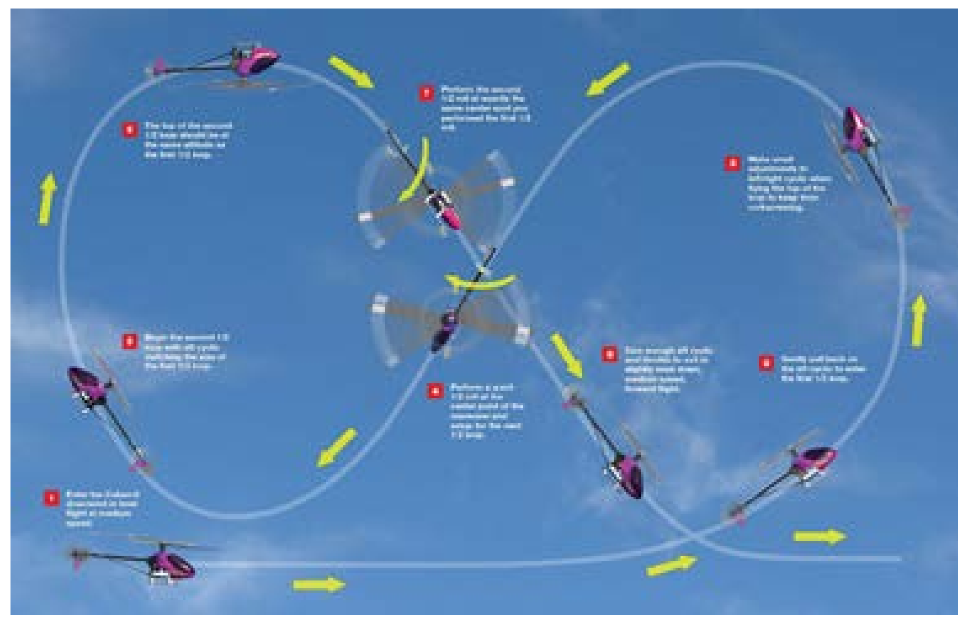



Figure 9-15. Rectangular course. The numbered positions in the text refer to the numbers in this illustration.

## Aggressive Maneuvers (acrobatics)

- Flips
- Loops
- Autorotation landing
- Avoidance

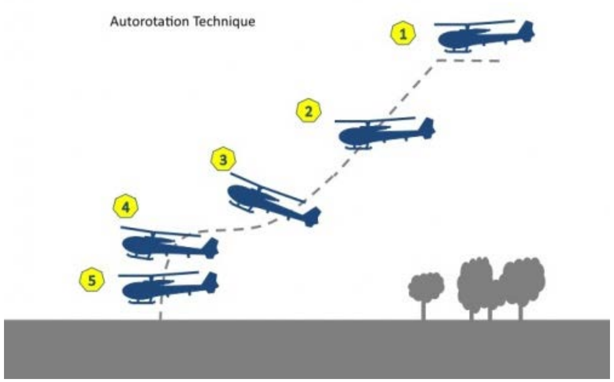


http://www.modelairplanenews.com/blog/2012/10/02/master-the-cuban-8/

*Thus, controller design **IS** a challenge*

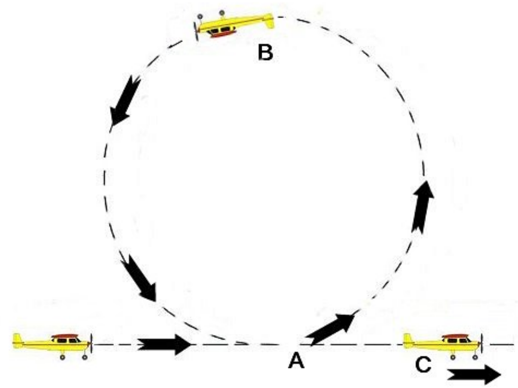
# Helicopter Failure Scenarios

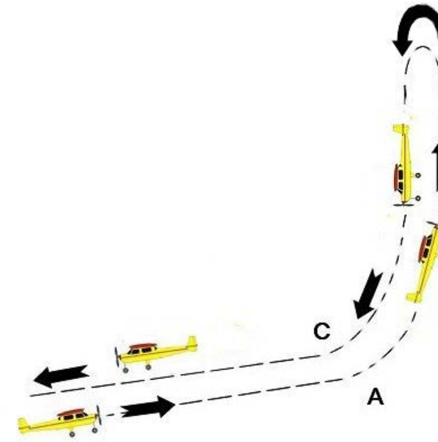
- **Possible failure scenarios:**
  - Total engine failure
  - Sensor failures
  - Controller failure
  - Structural failure




- **To make system fail-safe:**
  - Separate navigational and stabilization sensors
  - Install a servo multiplexer that can be taken over by an RC system and controlled by a remote human pilot
  - Include stabilization control modes in case of navigation sensor failures, such as attitude, altitude hold control
  - Include an autorotation landing controller in case of total engine failure to land aircraft
- **Running Landing**
- **Tail Failure**
- **Autorotation**

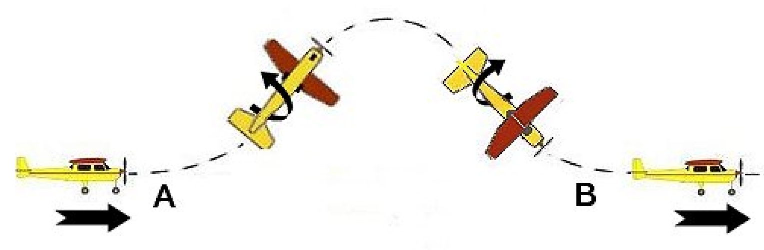
# (Example) Fixed-Wing Flight Maneuvers



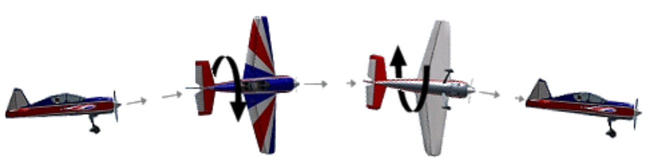

Basic Maneuvers (Basic navigation)

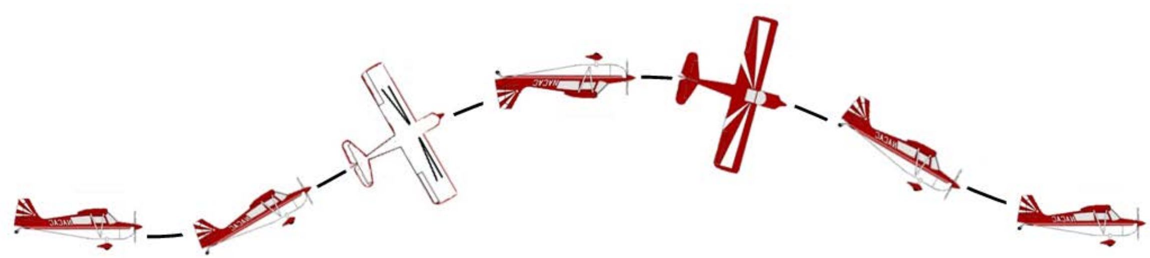
- Take-off/Landing
- Forward Flight
- Waypoint navigation




Aggressive Maneuvers (acrobatics)

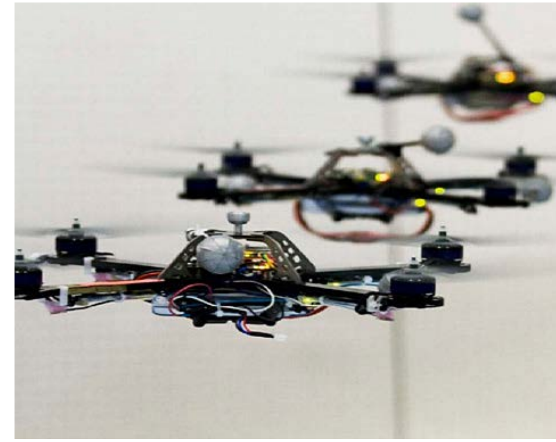
- Straight lines
- Turns
- Loops
- Rolls (line/barrel/snap)
- Knife's edge

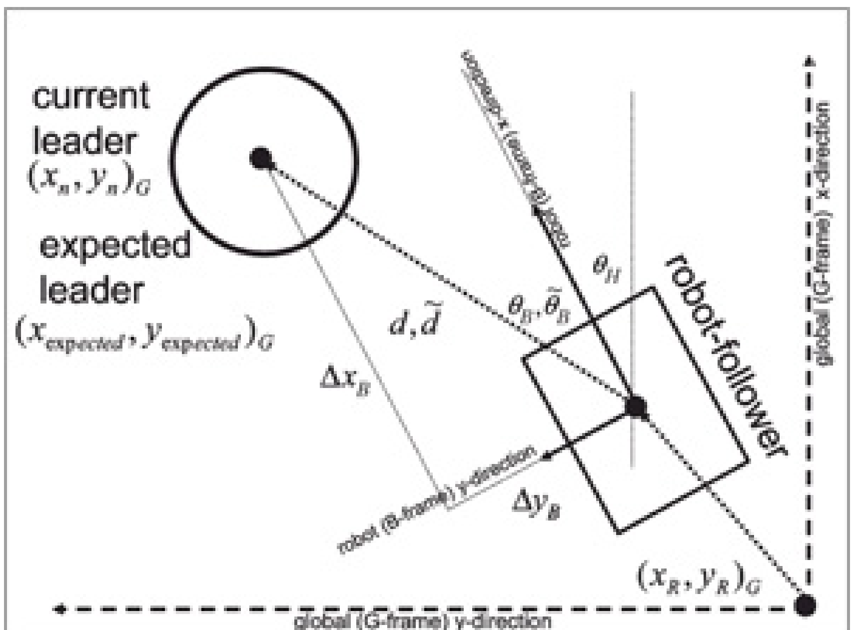




# Cooperative / Formation Flight

- Multiple UAVs coordinated either through a higher level supervisory / centralized controller or following a leader vehicle
- Other techniques include using potential fields or behavior-based approaches



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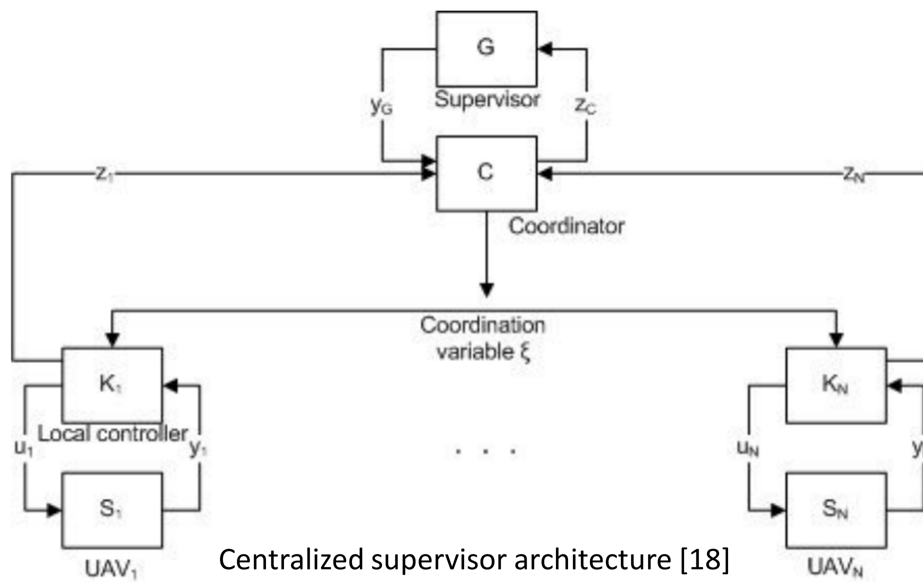
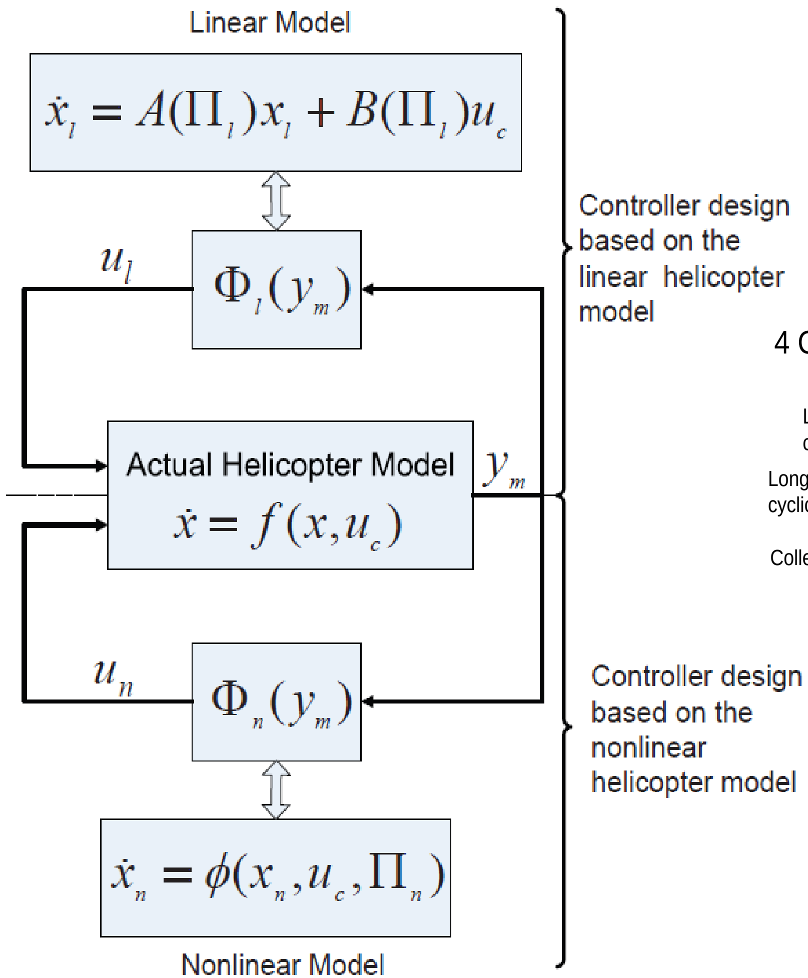
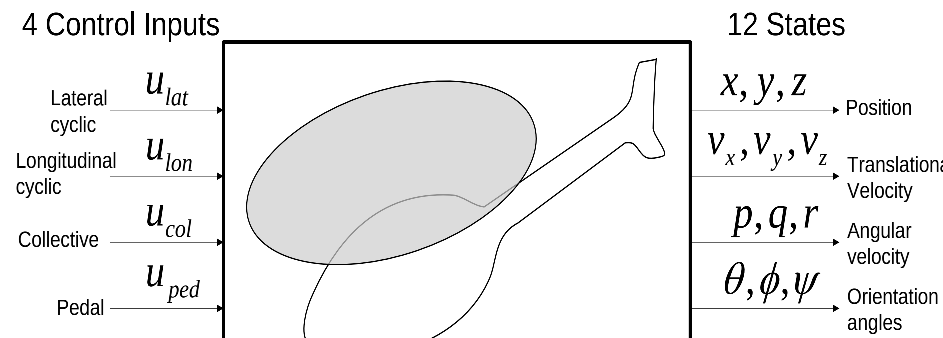


Centralized supervisor architecture [18]

# Framework for Controller Design




**Helicopter as an Input-Output System**

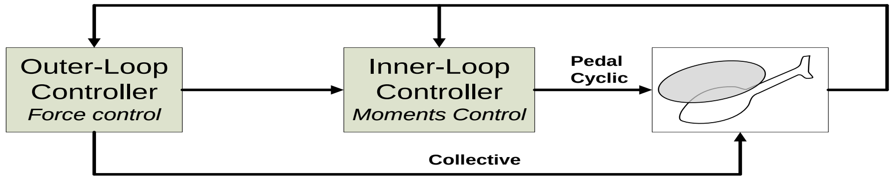
**Fig. 1** This block diagram illustrates the helicopter controller design problem. The helicopter dynamics can be represented by a linear or nonlinear system of differential equations. In either case, the feedback control law depends on the model choice.

# Helicopter Control/Dynamics Challenges

- **Open-loop unstable (Planes fly, helicopters crash!)**
  - E.g.: Hovering is open loop unstable
- **High degree of coupling**
  - Control channels have high interdependence
- **Nonlinear behavior**
  - Underactuated nonlinear system (fewer control inputs compared to system variables)
  - Linearization works in small regions
- **Dynamics spanning wide range of frequencies**
  - 6 DoF rigid body model; forces created by controlled/uncontrolled aerodynamics and gravity; *Significant* coupling between aerodynamic forces and moments
- **Fast dynamics**
  - High sampling freq. and processing speed required
- **Obtaining accurate models amenable for control design**
  - System identification procedures are lengthy and specialized personnel is required.
- **Diverse sources of noise and disturbances**
  - Lower grade sensors due to payload limitations; Wind; Rotor wake; Mechanical vibrations

**But**…..because of their advantages over fixed-wing UAVs, they are preferred for civilian/public domain applications, and also certain military applications.

# TYPICAL HELICOPTER CONTROLLER




- Inner-loop
  - Stabilizes unstable plant.
  - Partial decoupling of control channels.
  - Generates four low level commands; longitudinal and lateral cyclic, collective, and pedal.
  - High bandwidth
- Outer-loop
  - Generates set points for inner-loop.
  - External set points: inertial frame position ($x$, $y$, $z$) and heading ($\psi$).

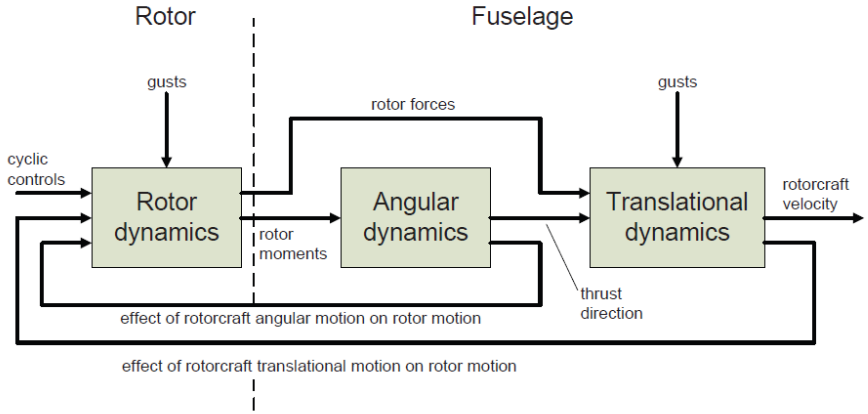
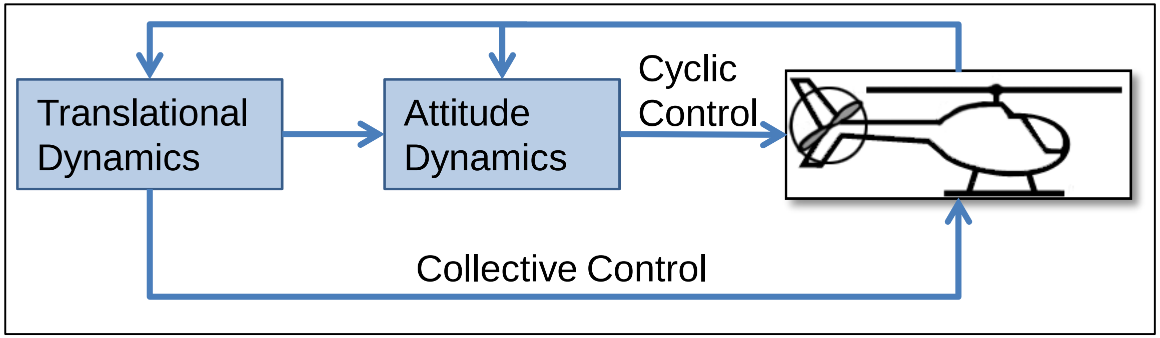



Figure: Block diagram of the longitudinal-lateral helicopter control problem. Illustration of the cross coupling effect in the torque and force generation.




- Most typical helicopter control architectures separate dynamics into inner attitude control and outer translational control. A third loop is added for navigational control.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# Rotorcraft state vector

- **The resulting equations are found to depend on a number of parameters, including**:
  - rigid body variables $(u, v, w, p, q, r, \phi, \theta, \psi)$
  - main rotor flapping dynamics $(a_0, a_1, b_1, \dot{a}_0, \dot{a}_1, \dot{b}_1)$
  - Pitt-Peters inflow dynamics $(\lambda_0, \lambda_s, \lambda_c)$, stabilizer bar dynamics $(a_s, b_s, \dot{a}_s, \dot{b}_s)$
  - actuator dynamics $(\theta_{lon}, \dot{\theta}_{lon}, \theta_{lat}, \dot{\theta}_{lat}, \theta_{col}, \dot{\theta}_{col}, \theta_{ped}, \dot{\theta}_{ped})$[13]

- **Full state vector**:

$$\boldsymbol{x} = [\, u\ v\ w\ p\ q\ r\ \phi\ \theta\ \psi\ a_0\ a_1\ b_1\ \dot{a}_0\ \dot{a}_1\ \dot{b}_1\ \lambda_0\ \lambda_{\mathrm{s}}\ \lambda_{\mathrm{c}}\ \ a_{1_{\mathrm{s}}}\ b_{1_{\mathrm{s}}}\ \dot{a}_{1_{\mathrm{s}}}\ \dot{b}_{1_{\mathrm{s}}}\ \theta_{\mathrm{lon}}\ \dot{\theta}_{\mathrm{lon}}\ \theta_{\mathrm{lat}}\ \dot{\theta}_{\mathrm{lat}}\ \theta_{\mathrm{col}}\ \dot{\theta}_{\mathrm{col}}\ \theta_{\mathrm{tr}}\ \dot{\theta}_{\mathrm{tr}}\, ]^{\mathrm{T}}$$

- *For most applications, and consideration of simplifications, derivatives and inflow dynamics are ignored*.

# Flight Dynamics Modeling

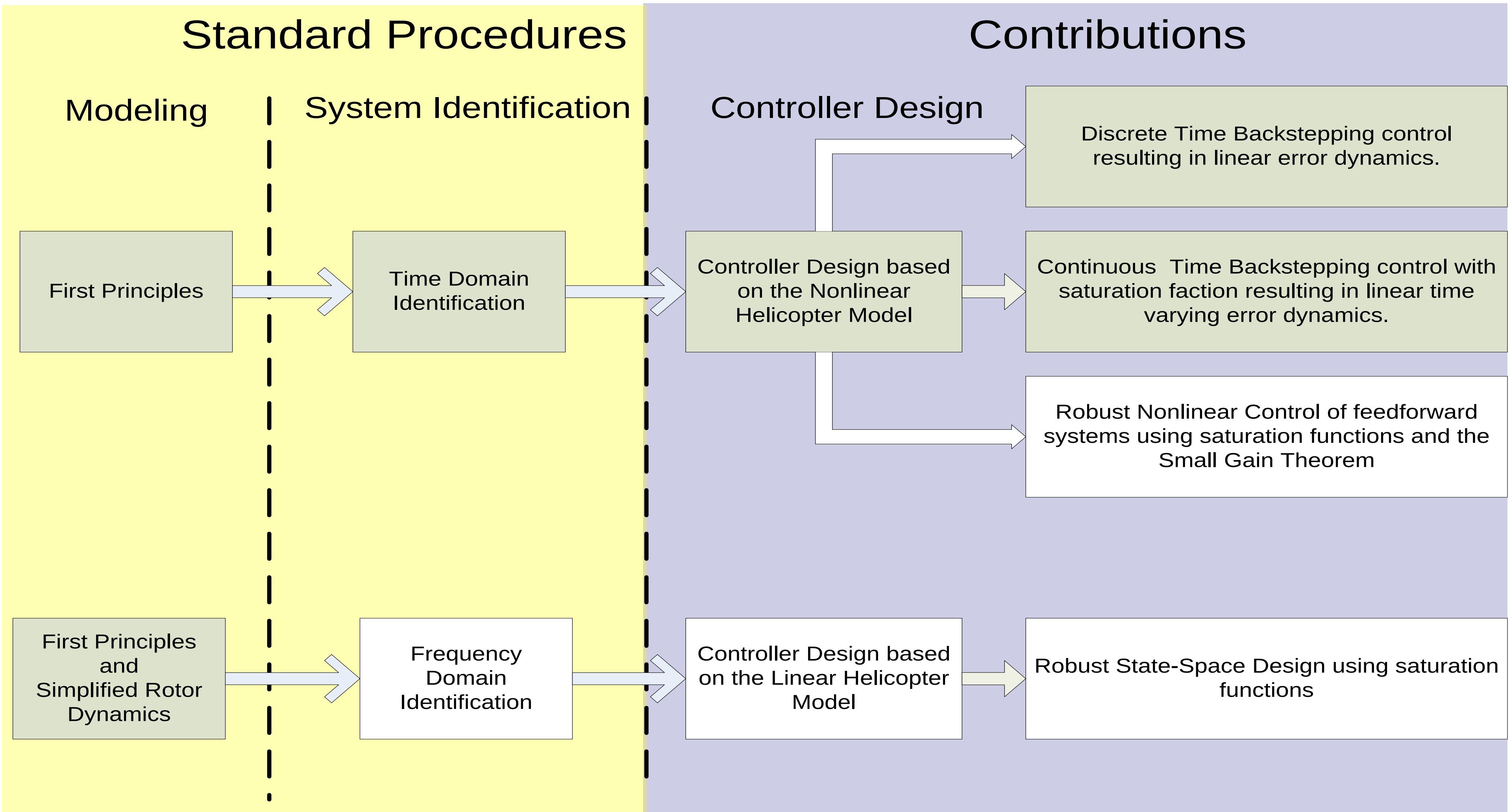
- **Linear Models**
  - Require a number of assumptions in order to linearize dynamics
  - Usually valid for a particular set of operating conditions
  - Works for simple maneuvers and non-aggressive flight (hover, forward flight, etc.)
  - Allow for simplified control approaches

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

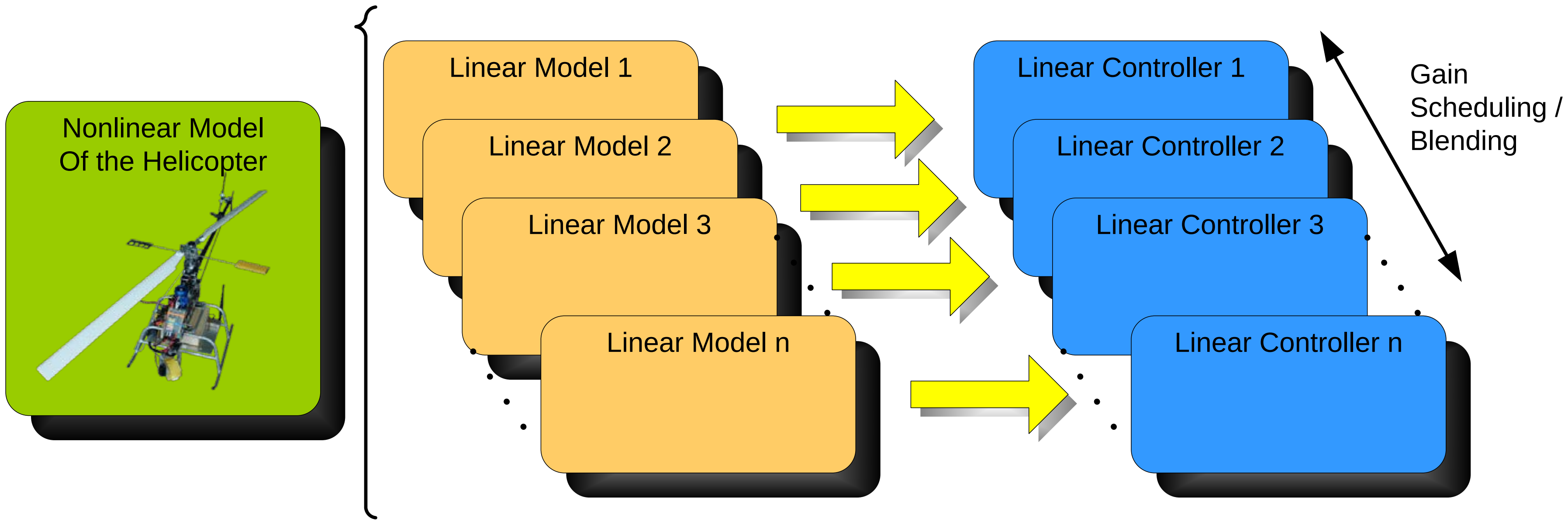
- **Nonlinear Models**
  - More difficult to implement
  - Valid for larger range of operating conditions
  - Allow for more complex maneuvers and aggressive flight (Loops, etc.)
  - Control efforts are more robust

$$f(x, u, y, \dot{x}, \dot{u}, \dot{y}, \dots) = 0$$

- **Model Free**
  - Requires numerous flight tests
  - Employs learning algorithms to teach control system to perform various maneuvers through analysis of piloted flight data
  - Control restricted to particular aircraft and flight conditions

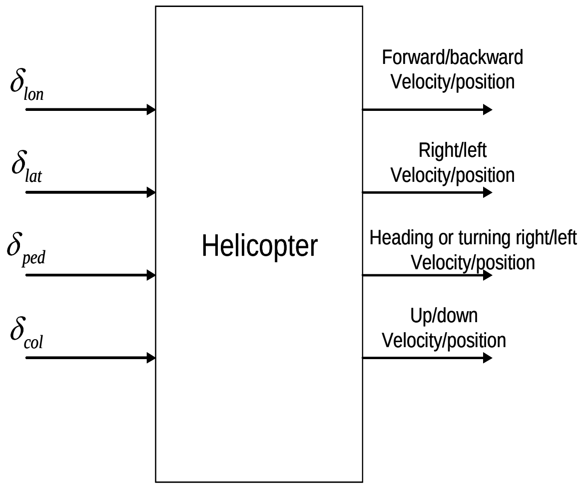

Standard Procedures
Contributions
Modeling
System Identification
Controller Design
First Principles
Time Domain Identification
Controller Design based on the Nonlinear Helicopter Model
Discrete Time Backstepping control resulting in linear error dynamics.
Continuous Time Backstepping control with saturation faction resulting in linear time varying error dynamics.
Robust Nonlinear Control of feedforward systems using saturation functions and the Small Gain Theorem
First Principles and Simplified Rotor Dynamics
Frequency Domain Identification
Controller Design based on the Linear Helicopter Model
Robust State-Space Design using saturation functions

# Handling Nonlinearity through Linearization and Gain Scheduling



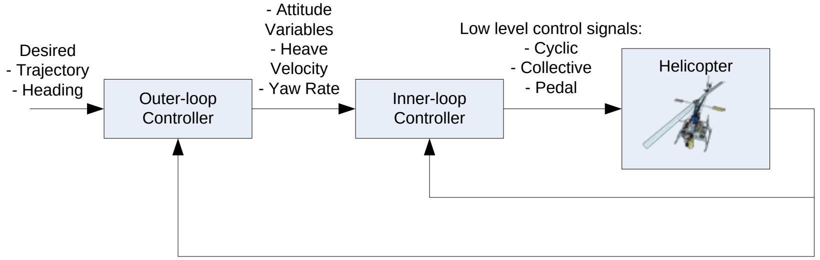
# Considerations

- Non-aggressive flight
  - Configuration space: change position in 3D and heading ($R^3 x S^1$).
  - Two regimes considered:
    - Hovering (includes slow motion).
    - Forward Flight.
  - Decomposition:
    - Outer loop: guidance
      - Velocity, position commands
    - Inner loop: control
      - Decoupling
      - Stabilization



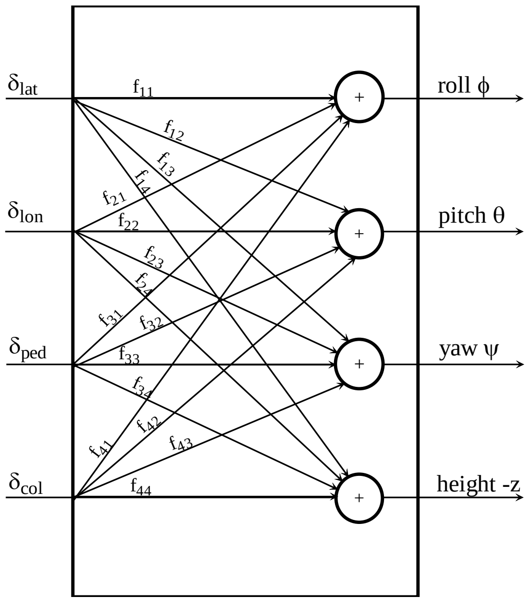

| Input | Output |
|---|---|
| Lateral Cyclic<br>Longitudinal Cyclic | Position in horizontal plane |
| Collective | Altitude |
| Pedal | Yaw |

## Inner/Outer Loop Decomposition

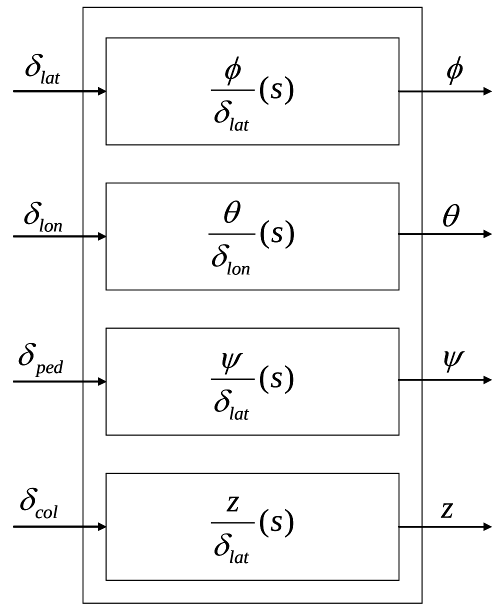


# Decentralized Control

Simplifying assumption: coupling is treated as a disturbance with linear MIMO system treated as multiple SISO systems




Fully coupled MIMO system




Helicopter control with SISO subsystems

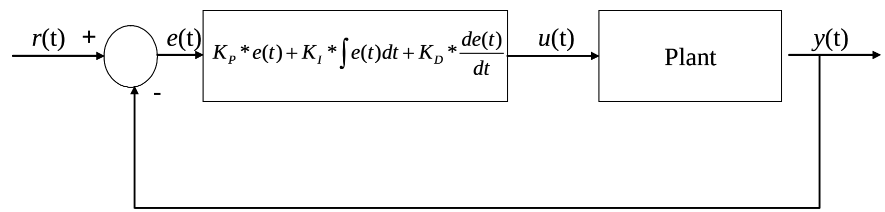
# PID Controllers

- Time-domain equation for the PID controller with $K_P$ the proportional gain, $K_I$ the integral gain, and $K_D$ the derivative gain

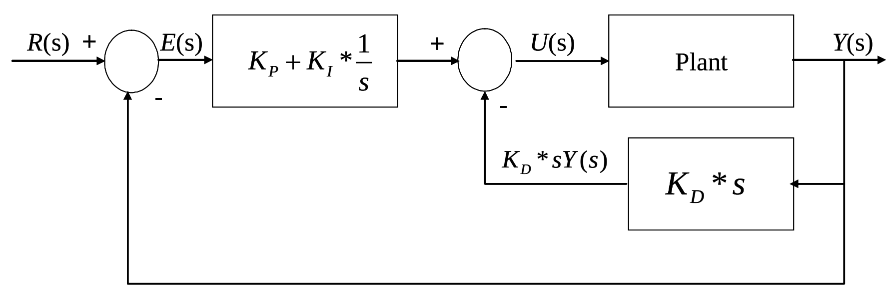
$$e(t) = r(t) - y(t)$$

$$u(t) = K_P * e(t) + K_I * \int e(t)dt + K_D * \frac{de(t)}{dt}$$

- The derivative term of a PID controller produces to suddenly changing signals
- to avoid an undesirable sharp response the derivative term is moved from the closed loop forward path.
- If derivative term is measurable, this output is used directly rather than implementing differentiator.



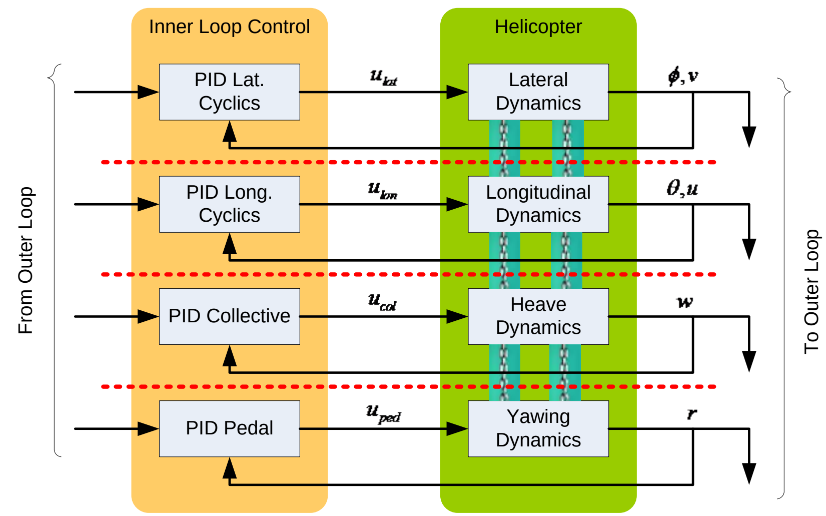

SISO PID closed loop control

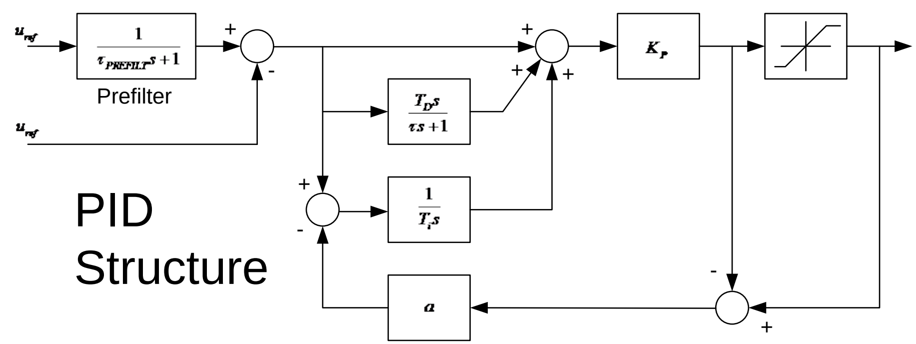



Rate feedback PID control

# PID Control Revisited

- Two degree of freedom controllers with anti-windup
- Tuning
  - Basic stabilization with complete plant: four proportional controllers.
  - Reduce input/output channel dynamics including cross couplings.
  - Iterate procedure on other channels.

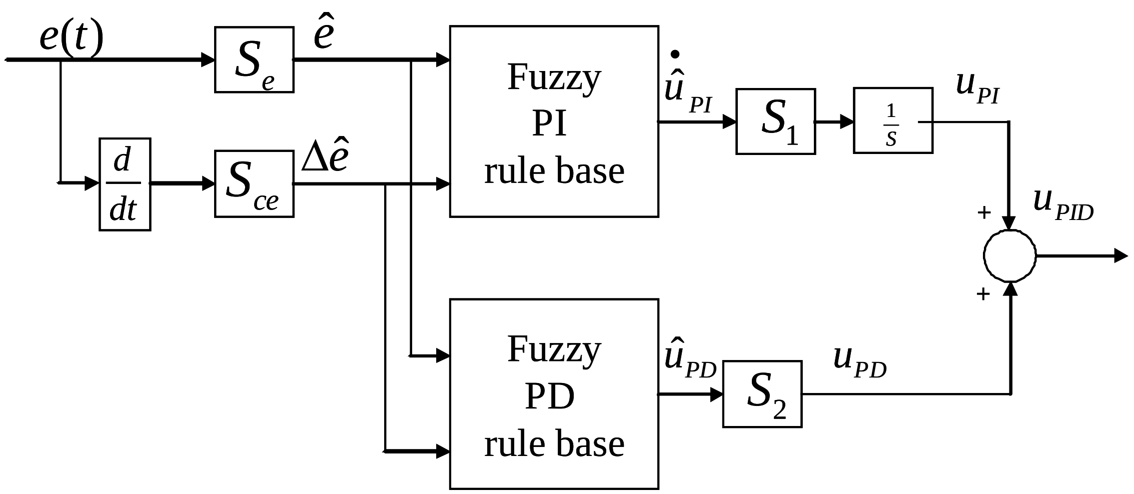



PID Structure

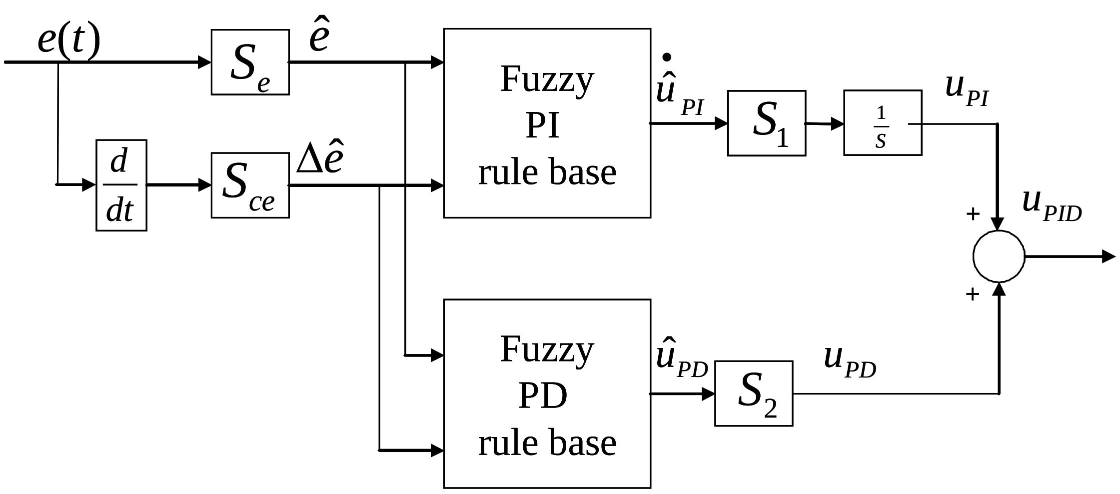
# PD-like Fuzzy Logic Controller

- The error $e$(t) is defined as the difference between the desired signal value (set point) and the real value of the controlled variable
- $\Delta e$(t) is the error change.
- $S_e$ is the scaling factor for the error, $e$(t).
- $S_{ce}$ is the scaling factor for the change of the error, Δe(t).
- $S_u$ is the scaling factor of the PD-like controller's output..



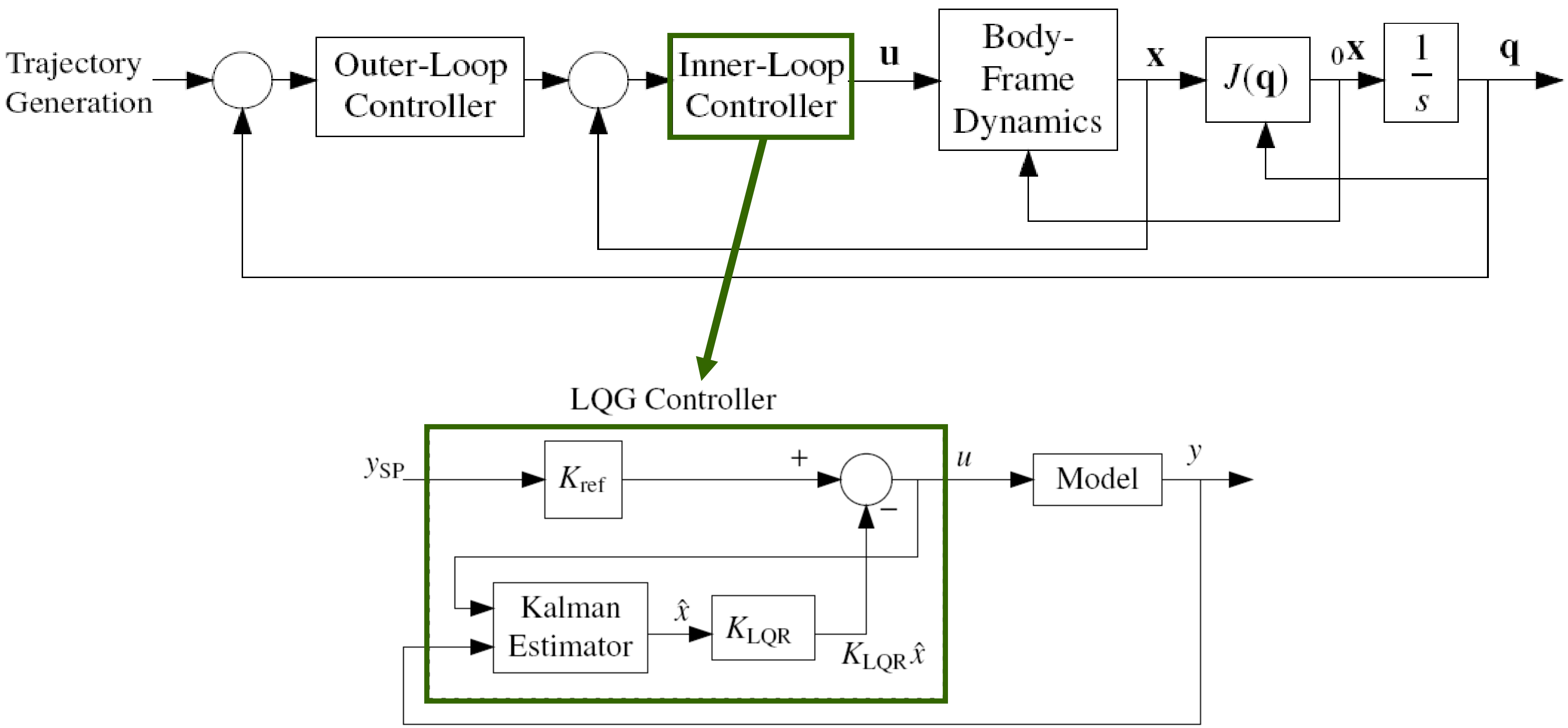
# PID-like Fuzzy Logic Controller

- The error $e$(t) is defined as the difference between the desired signal value (set point) and the real value of the controlled variable.
- $\Delta e$(t) is the error change.
- $S_e$ is the scaling factor for the error, $e$(t).
- $S_{ce}$ is the scaling factor for the change of the error, Δe(t).
- $S_1$ and $S_2$ are the output scaling factors of the PI-like and PD-like controller that constitute the fuzzy PID-like controller.



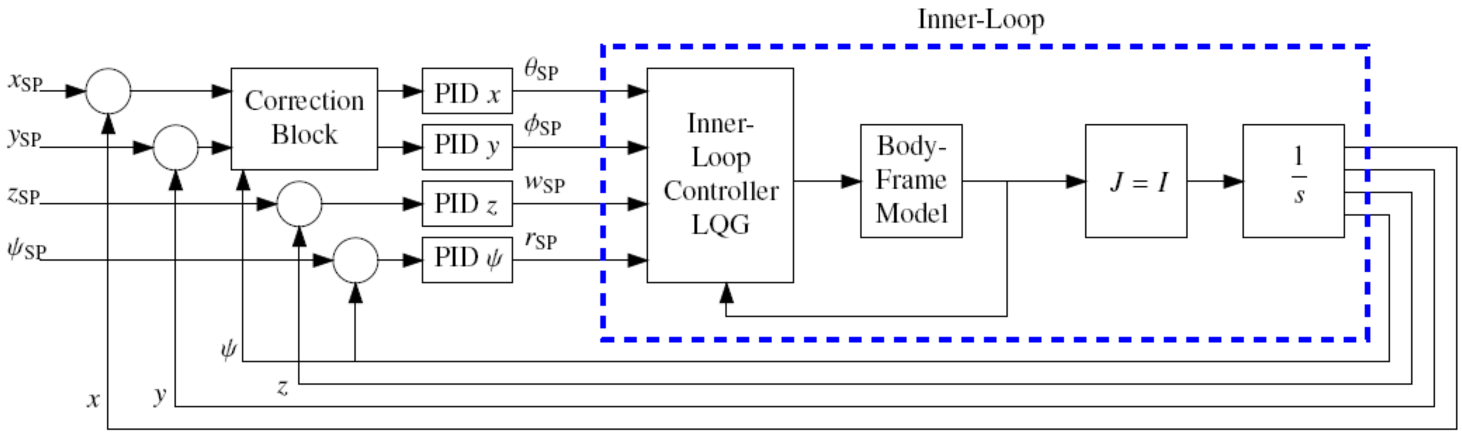
# LQG Control Strategy

## Cascaded Control Structure



# Outer-Loop Control Design

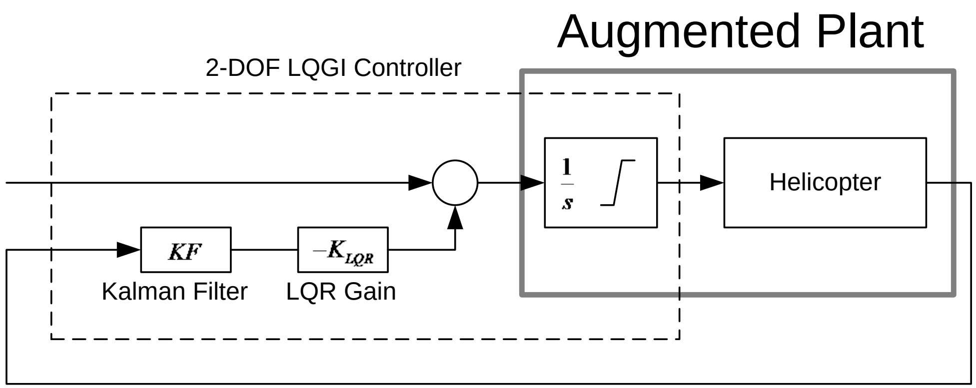
- Inner-loop reduction
- Outer loop handled by 4 PID controllers and a correction block for trajectory input.



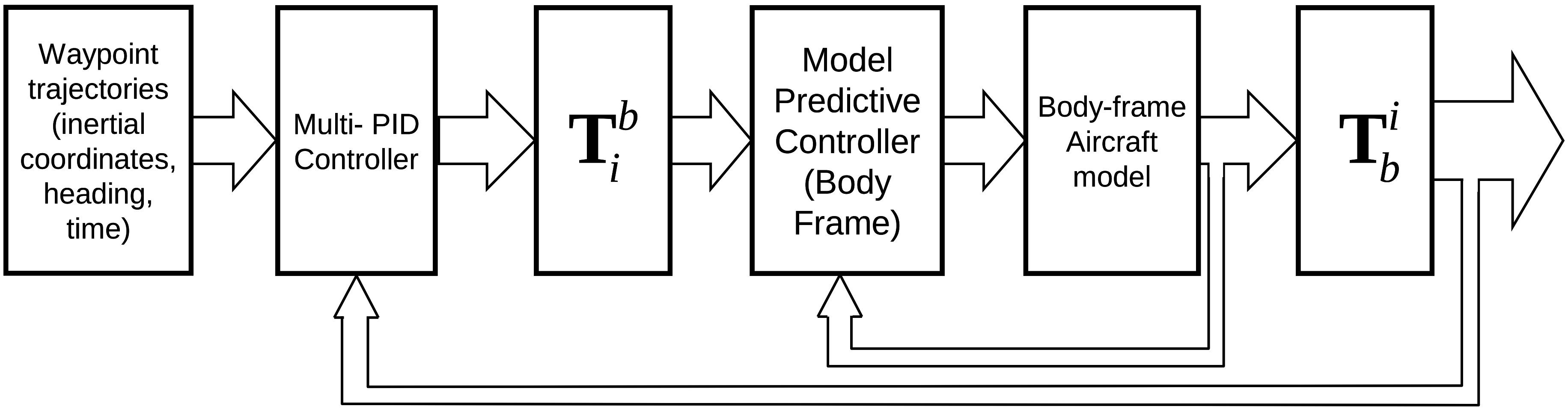

- PID controllers can be designed by SISO approximation using classical control techniques.

# LQGI Control

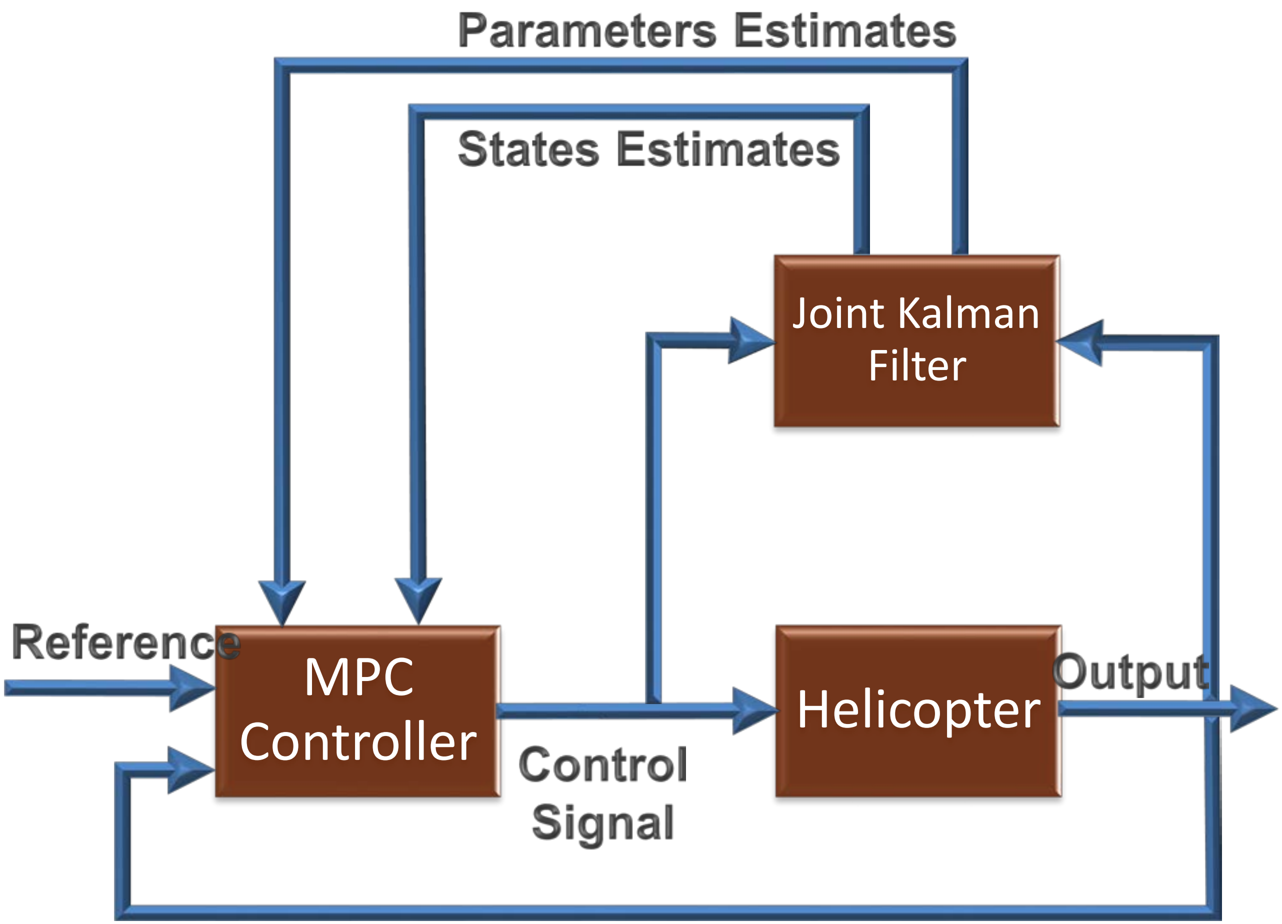
- LQG control with integrator for tracking
  - Plant augmented with integrators
- Separation principle
  - Kalman filter design
  - LQR gain design
- Full support of Computer Aided Control System Design (CACSD) tools: MATLAB



# MPC Control Position Tracking System




**where:** $$\mathbf{T}_i^b = \begin{bmatrix} c\theta c\psi & c\theta s\psi & -s\theta \\ s\phi s\theta c\psi - c\phi s\psi & s\phi s\theta s\psi + c\phi c\psi & s\phi c\theta \\ c\phi s\theta c\psi + s\phi s\psi & c\phi s\theta s\psi - s\phi c\psi & c\phi c\theta \end{bmatrix}$$ **and** $$\mathbf{T}_b^i = (\mathbf{T}_i^b)^T$$


Parameters Estimates
States Estimates
Joint Kalman Filter
Reference
MPC Controller
Helicopter
Output
Control Signal

# NONLINEAR CONTROLLER METHODOLOGY

- Backstepping Approach
- Derive Helicopter Model
    - Rigid body dynamics, External Wrench model, complete rigid body dynamics
- Translational Error Dynamics
- Attitude Error Dynamics
    - Yaw, Orientation error dynamics
- Angular Velocity Error Dynamics
- Stability of the Attitude error dynamics
- Stability of the Translational error dynamics

# Concepts of backstepping controller - I

## Pure feedback form

The controller requires that the equation describing the system dynamics could assume the following form:

$$\begin{cases} \dot{x} = f(x) + g(x)\xi_1 \\ \dot{\xi}_1 = f_1(x, \xi_1, \xi_2) \\ \dot{\xi}_2 = f_2(x, \xi_1, \xi_2, \xi_3) \\ \vdots \\ \dot{\xi}_{k-1} = f_{k-1}(x, \xi_1, ..., \xi_k) \\ \dot{\xi}_k = f_k(x, \xi_1, ..., \xi_k, u). \end{cases}$$

- $x \in R^n$ and $\xi_k$ states
- $f_i$ $(i=1,\ldots,k)$ nonlinear function
- $f_i$ depends only on $\xi_j$ $(j=1,\ldots,i+1)$

# Concepts of backstepping controller - II

## Nonlinear recursive control

Each differential equation is considered as a subsystem to be controlled, its control is the state of the upper order equation. The external input *u* controls in cascade the all system.

$$
\begin{cases}
\dot{x} = f(x) + g(x)\xi_1 \\
\dot{\xi}_1 = f_1(x, \xi_1, \xi_2) \\
\dot{\xi}_2 = f_2(x, \xi_1, \xi_2, \xi_3) \\
\vdots \\
\dot{\xi}_{k-1} = f_{k-1}(x, \xi_1, \ldots, \xi_k) \\
\dot{\xi}_k = f_k(x, \xi_1, \ldots, \xi_k, u).
\end{cases}
$$

$\xi_1$ controls the state $x$

.
.
.

$\xi_k$ controls the state $\xi_{k-1}$

u controls the state $\xi_k$

# Why a backstepping controller

## Problems with traditional (linear) UAV control techniques:

• Highly nonlinear behavior.

↳ a proper control law uses natural nonlinearities to stabilize the system

• Unmodeled system dynamics.

↳ inclusion of dynamics contained in the nonlinear terms

• Robustness to parametric uncertainties and external disturbances.

↳ inclusion in the control of nonlinear damping terms to improve robustness

• Coupling between longitudinal and latero-directional planes.

↳ inclusion of nonlinear coupling terms

**The main strength of backstepping is the ability to deal with nonlinearities.**

# Equations of Motion

**Set of 12 nonlinear equations describing the dynamics of any aircraft (rotary or fixed wing) [1].**

States:

Position dynamics

$$\dot{p}^I = v^I$$

$$\dot{v}^I = \frac{1}{m} R f^B$$

Orientation dynamics

$$\dot{R} = R\hat{\omega}^B$$

$$\mathcal{I}\dot{\omega}^B = -\omega^B \times (\mathcal{I}\omega^B) + \tau^B$$

- Position
- Velocity
- Orientation matrix
- Angular velocity

[1] *I.A. Raptis and K.P. Valavanis, 'Linear and Nonlinear Control of Small-Scale Unmanned Helicopters', Springer, 2010*

# Helicopter

**Helicopter: equations of motion are already in cascade form**

$$\dot{p}^I = v^I$$

$$\dot{v}^I = \frac{1}{m} R f^B$$

$$\dot{R} = R\hat{\omega}^B$$

$$\mathcal{I}\dot{\omega}^B = -\omega^B \times (\mathcal{I}\omega^B) + \tau^B$$

Control inputs, forces and moments generated by the rotors, they do not depend on the states.

**The rotorcraft controller design problem has been tackled!**

**Integrated control + diagnostics has been studied**

**NMPC+ANN design for vertical autorotation (post-failure)**

**Sense-and-avoid/see-and-avoid systems to be integrated with the FCS.**

**Next step: Complete implementation and testing.**

# Summary of Control Approaches

| FCS Type | Algorithm | Pros | Cons | Maneuvers |
|---|---|---|---|---|
| Linear | PID (SISO) | • Easily Implemented<br>• Assumes simplified decoupled dynamics<br>• Gains can be tuned in flight | • Lacks robustness<br>• Ignores coupling of dynamics | Mostly hovered flight<br>Attitude/Altitude control<br>Lateral/Longitudinal control |
| | LQR/LQG | • Can be used to stabilize outer/inner loop dynamics | • Limited to certain flight conditions<br>• Gain calculation is an iterative process | Hovering, trajectory tracking |
| | H-∞ | • Can cope with parametric uncertainty and un-modeled dynamics<br>• Loop shaping | • Higher level of mathematical understanding and computation<br>• Need a reasonably good system model | Hover, trajectory tracking |
| | Gain scheduling | • Switching between a family of linear controllers to be used to cover a larger range of operating conditions | • Higher computation requirements and storage of controller gains<br>• Need to determine parameters used in decision making | Hover, trajectory tracking, backflip (quadrotor) |
| Non-linear | Back stepping | • Well known technique for under actuated systems | • Need exact knowledge of nonlinear functions | Trajectory tracking, autorotation landing |
| | Feedback Linearization | • Nonlinear transformations techniques transforms variable to a new coordinate system where dynamics are linear | • Higher computational complexity<br>• Transformed variables and actual output may differ greatly | Auto take-off, landing, hovering, aggressive maneuvers |
| | Adaptive | • Robust technique that can handle un-modeled dynamics and parametric uncertainty | • Complex analysis<br>• Various approaches<br>• Need decent knowledge of system | Formation flight, vision based navigation |
| | Model Predictive Control | • Can handle multivariable control<br>• Tracking errors can be minimized | • Prediction model must be formulated correctly | Target tracking, |
| Learning Based | Neural Networks | • Models can be identified offline or online<br>• Can be combined with standard techniques | • Need to train the network<br>• Can increase the order of the controller | Hovering, autorotation,etc. |
| | Fuzzy Logic | • Able to execute basic flight behaviors | • Need to train the system and develop accurate rules | Hovering, forward flight, climbing turns |
| | Human Based Learning | • Learns from human pilot execution of maneuvers | • Requires both modeling and flight data | Aggressive maneuvers |

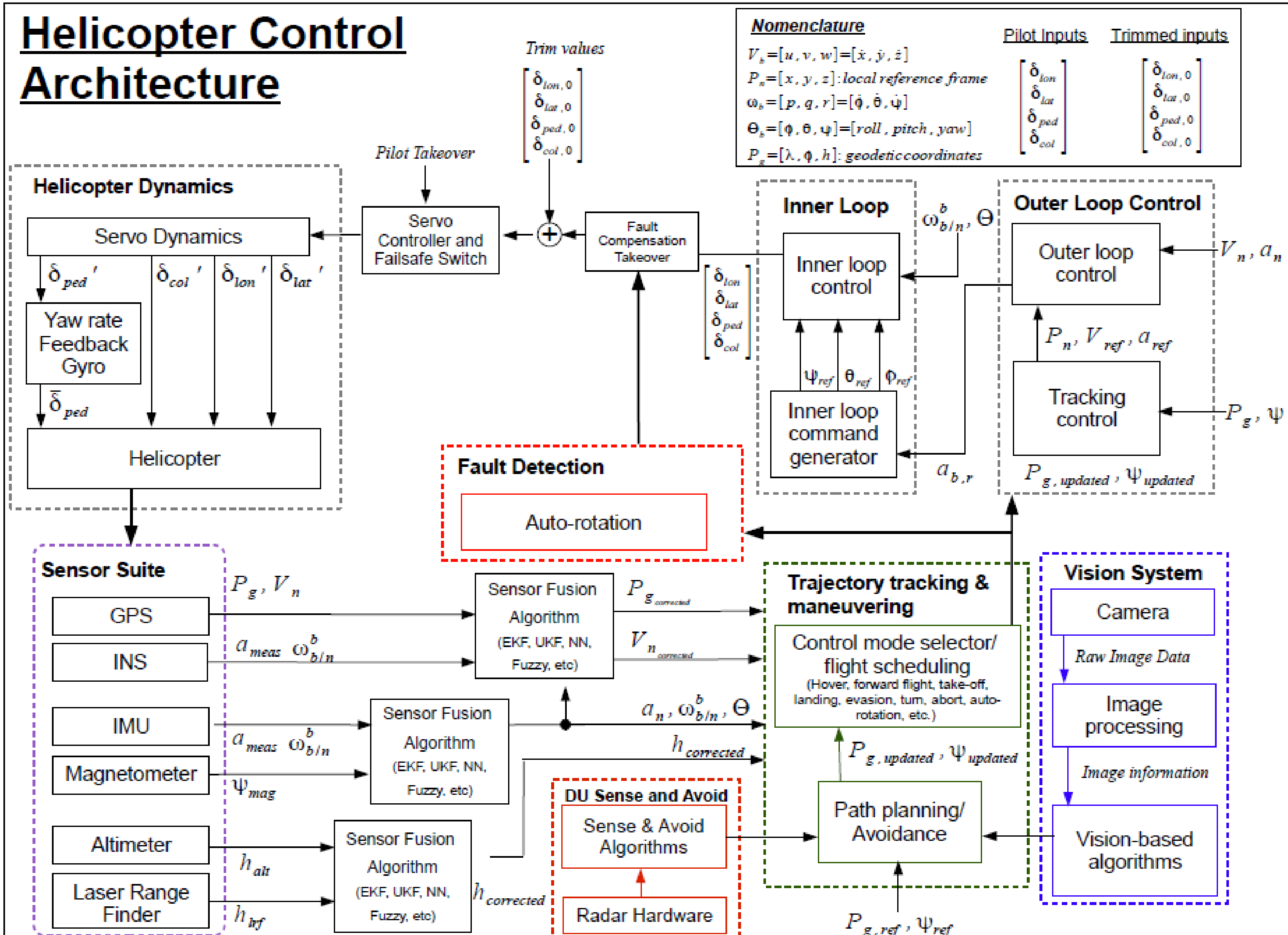
# Controller Performance

- **Hover and cruise**:
  - Has been shown to be achievable with all controller types

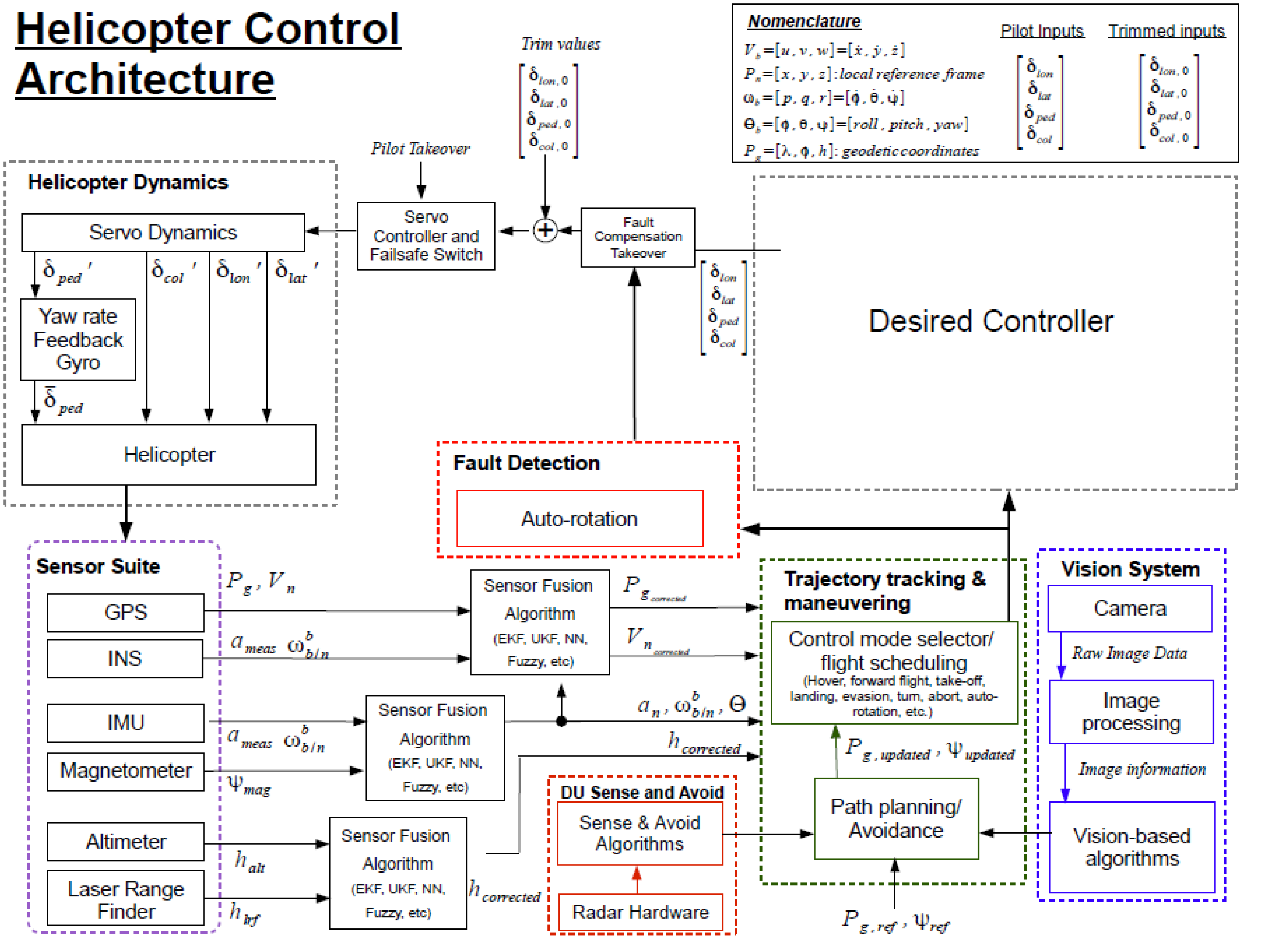
- **Tracking**
  - Necessary and sufficient to define desired position trajectory and heading for control purposes

- **Improved flight envelope**
  - Combine various control schemes (PID, LQR, MPC, NN, …) in order to improve robustness and flight envelope.
  - Use of Fuzzy networks, NN, or learning algorithms to switch between control strategies in order to create smooth control action transitions.
  - Account for actuator saturation to ensure stability and performance.

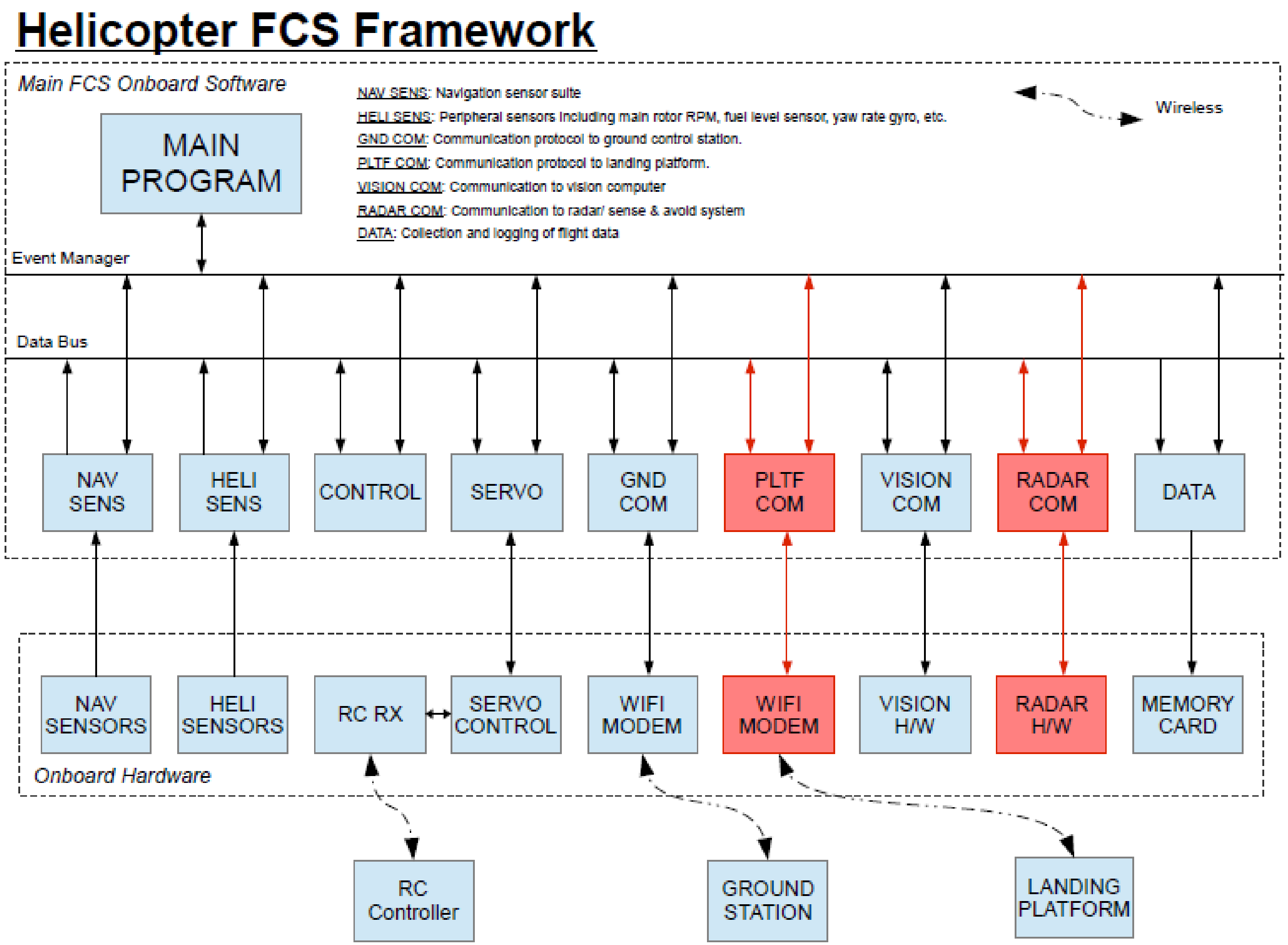
# Proposed Overall Control Architecture



# Helicopter Control Architecture



# Challenge: Timing and synchronization



# Requirements

- “The system must be equal to or better than the theoretical see and avoid capability of a human pilot”

| Field of Regard | | |
|---|---|---|
| Source | Azimuth | Elevation |
| Int’l Standards, Rules of the Air, Section 3.2.2.4 (ICAO) | +/- 110° | No guidance |
| ACC/DR-UAV SMO Sense and Avoid Requirement for Remotely Operated Aircraft (ROA) 25 June 2004 | +/- 110° | +/- 15° |
| American Standards for Testing and Materials (ASTM) 2411.04 | +/- 110° | +/- 15° |
| U.S. DoD Standardization Program Office | +/- 110° | +/- 15° |

- Detection range dependent on vehicle cruising speed.

# Why Radar?

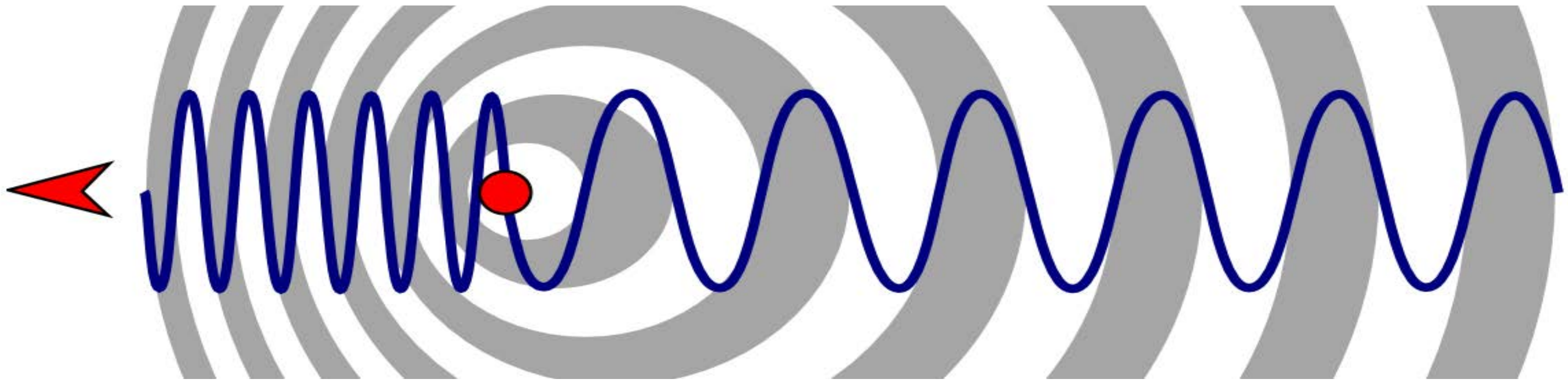
- In addition to optical systems our radar system offers:
  - Lower computational requirements for detection and identification
  - Immunity to sunlight  and other common light sources
  - Less affected by "optical clutter" (Clouds, Dust, glass, etc…)
  - Multimode operation:
    - Range detection, Doppler  sensing, SAR mapping, Data Communication, etc…
  - Does not require inter-vehicle cooperation as is the case with other systems (TCAS, PCAS, FLARM)

# Signal Origins

$$\Delta F = F\left(\frac{2v}{c - v}\right)$$

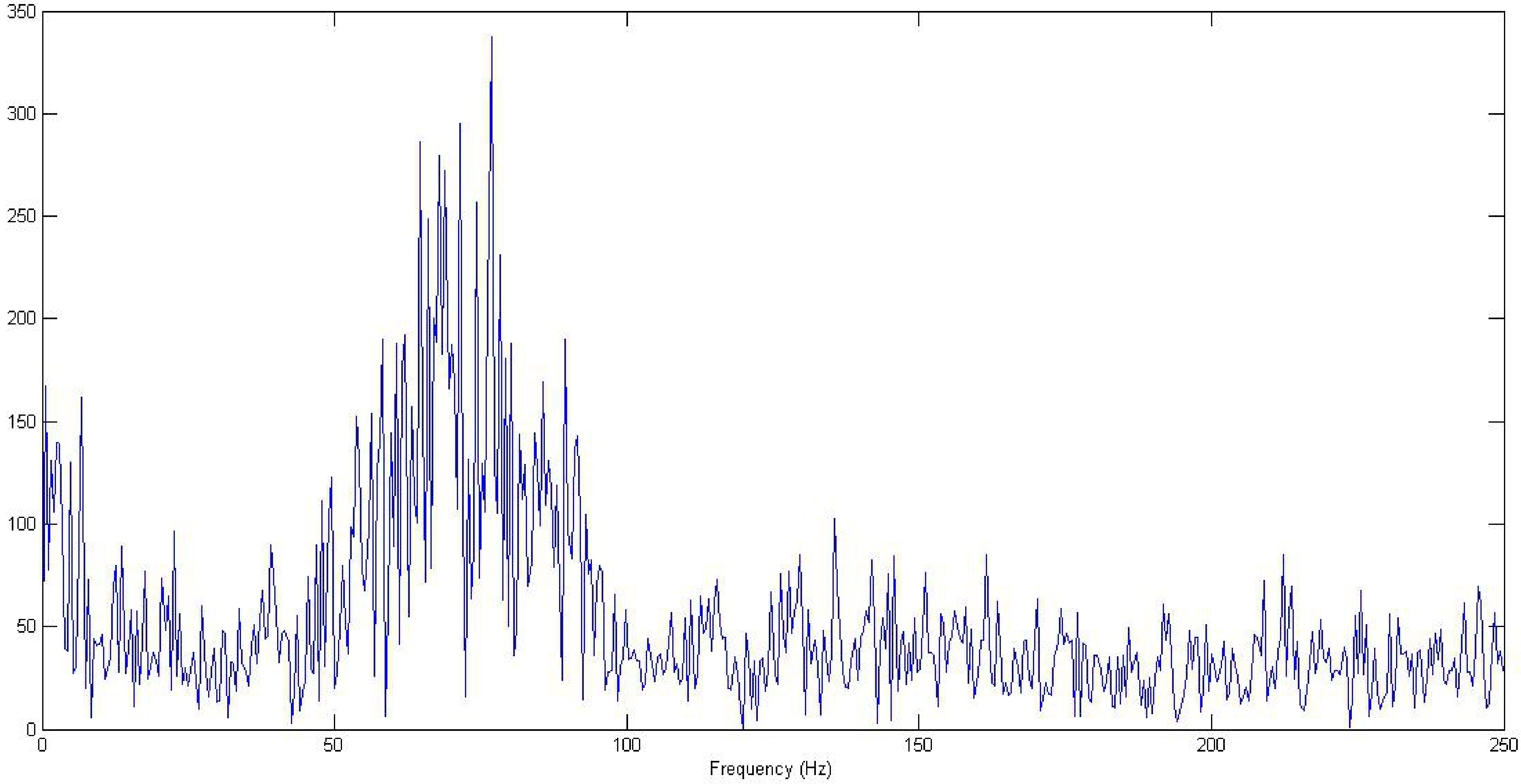
$$\Delta F = 70.048v$$

*F* = Transmit frequency (10.5GHz)
*c* = Speed of light
*v* = Object velocity
*ΔF* = Doppler shifted frequency

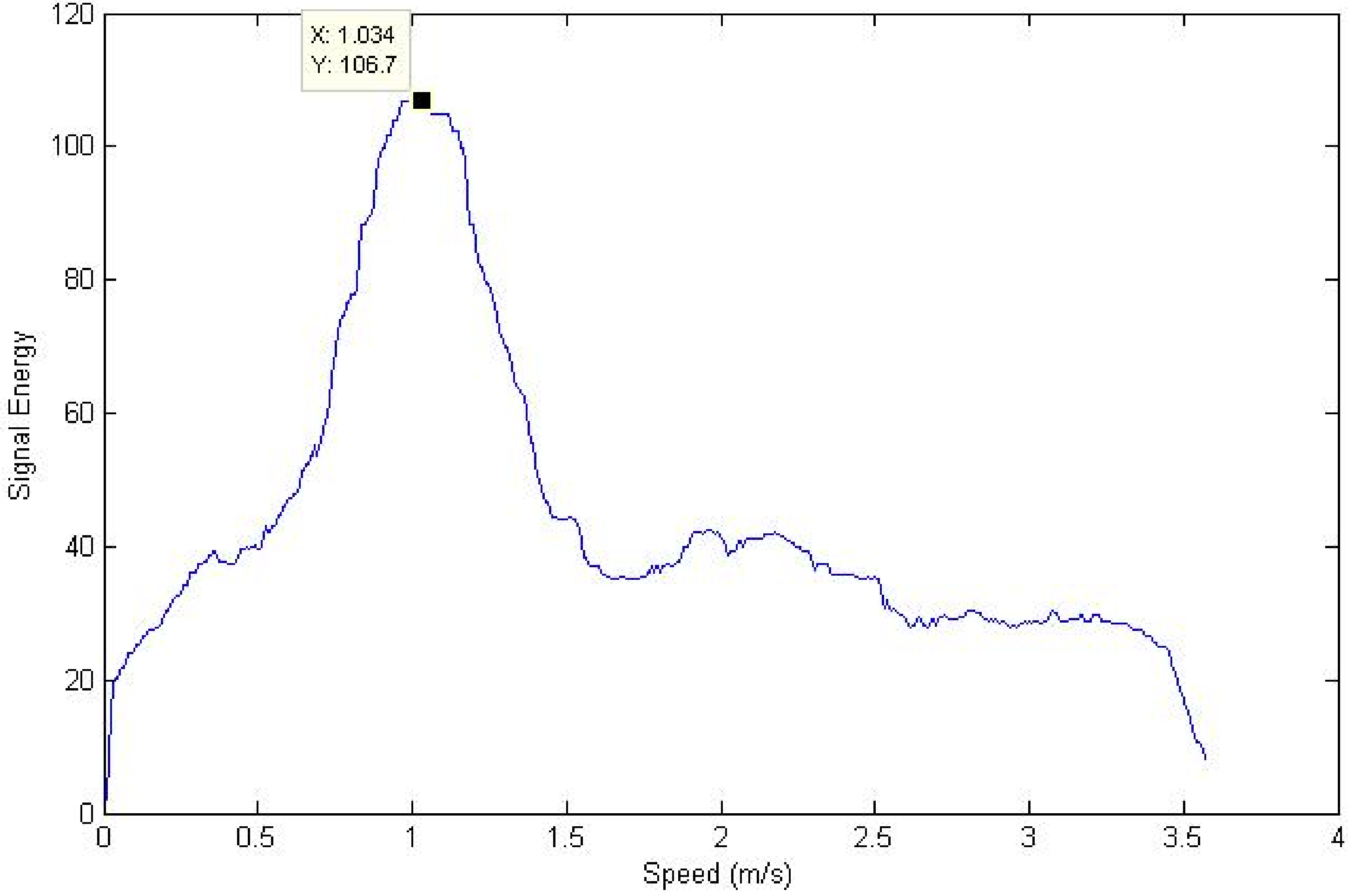


http://withfriendship.com/images/b/9240/Doppler-effect-pic.jpg

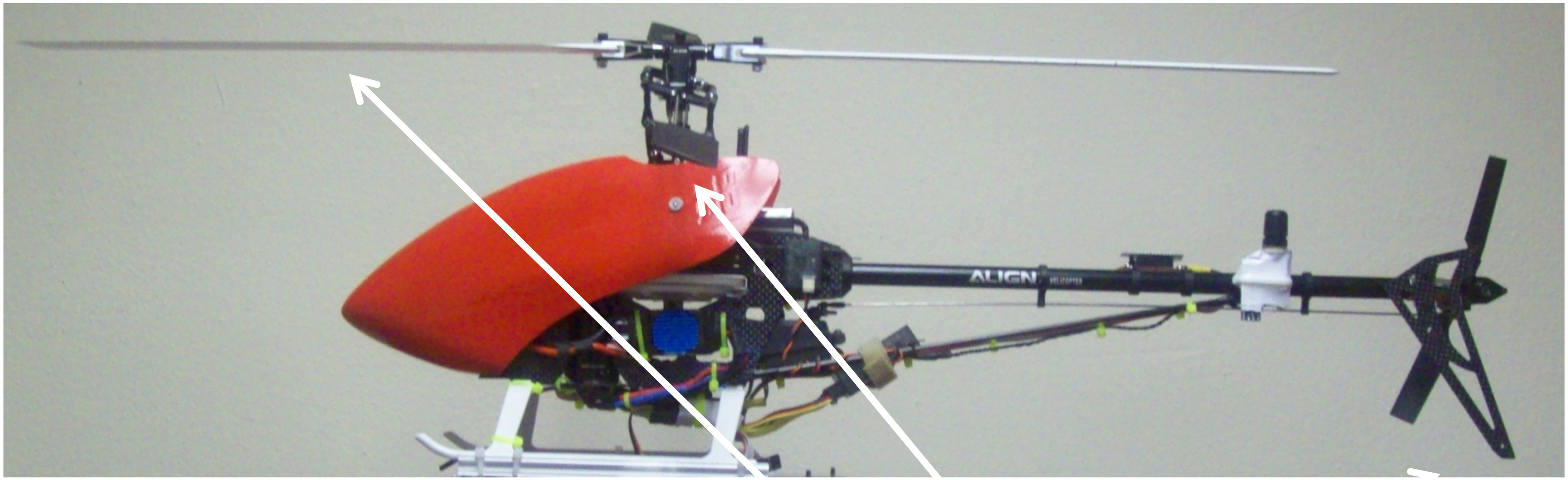
# Target Detection (Walking Human)



# Target Detection (Walking Human)



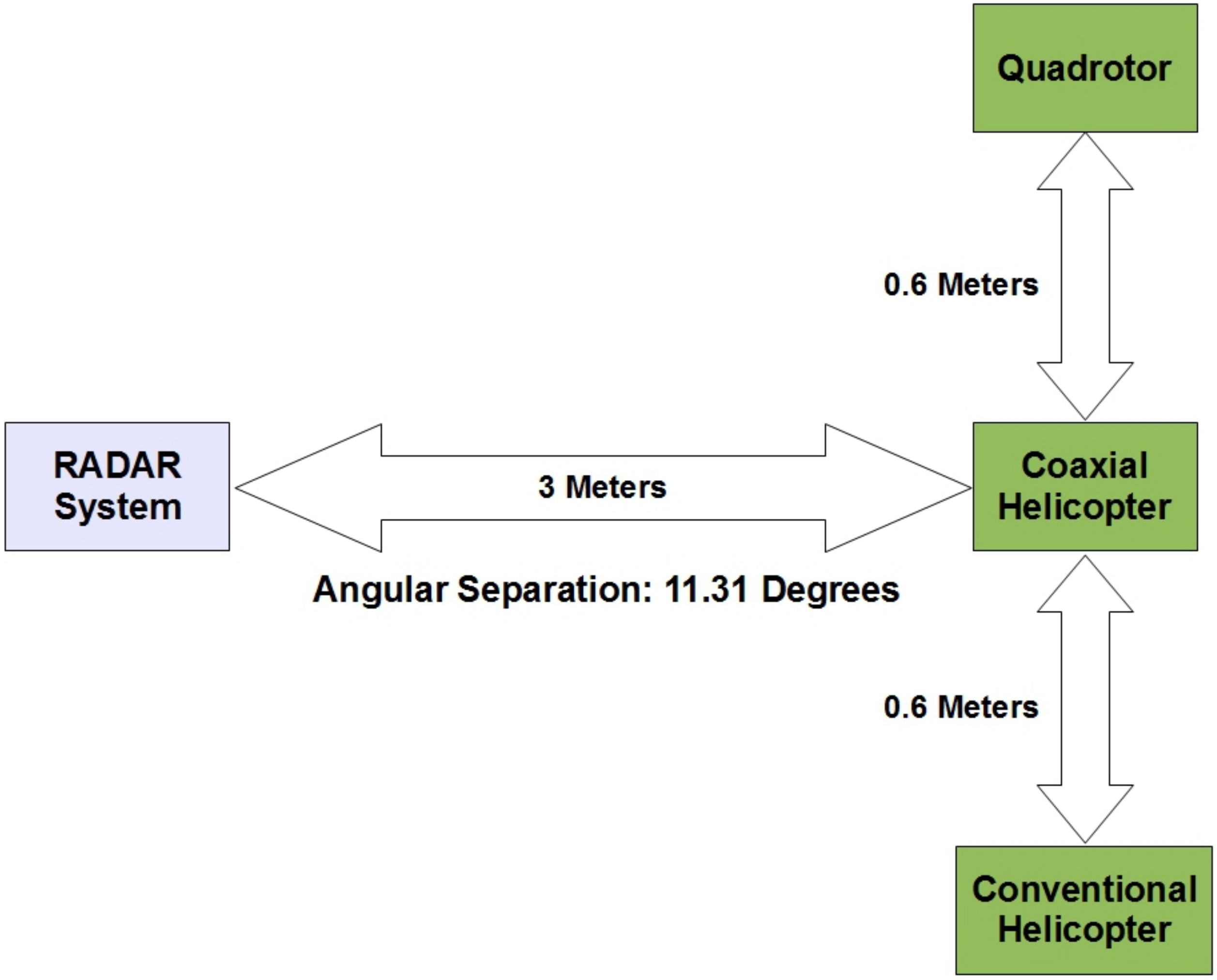
# Origin of Complex Signatures: Helicopter



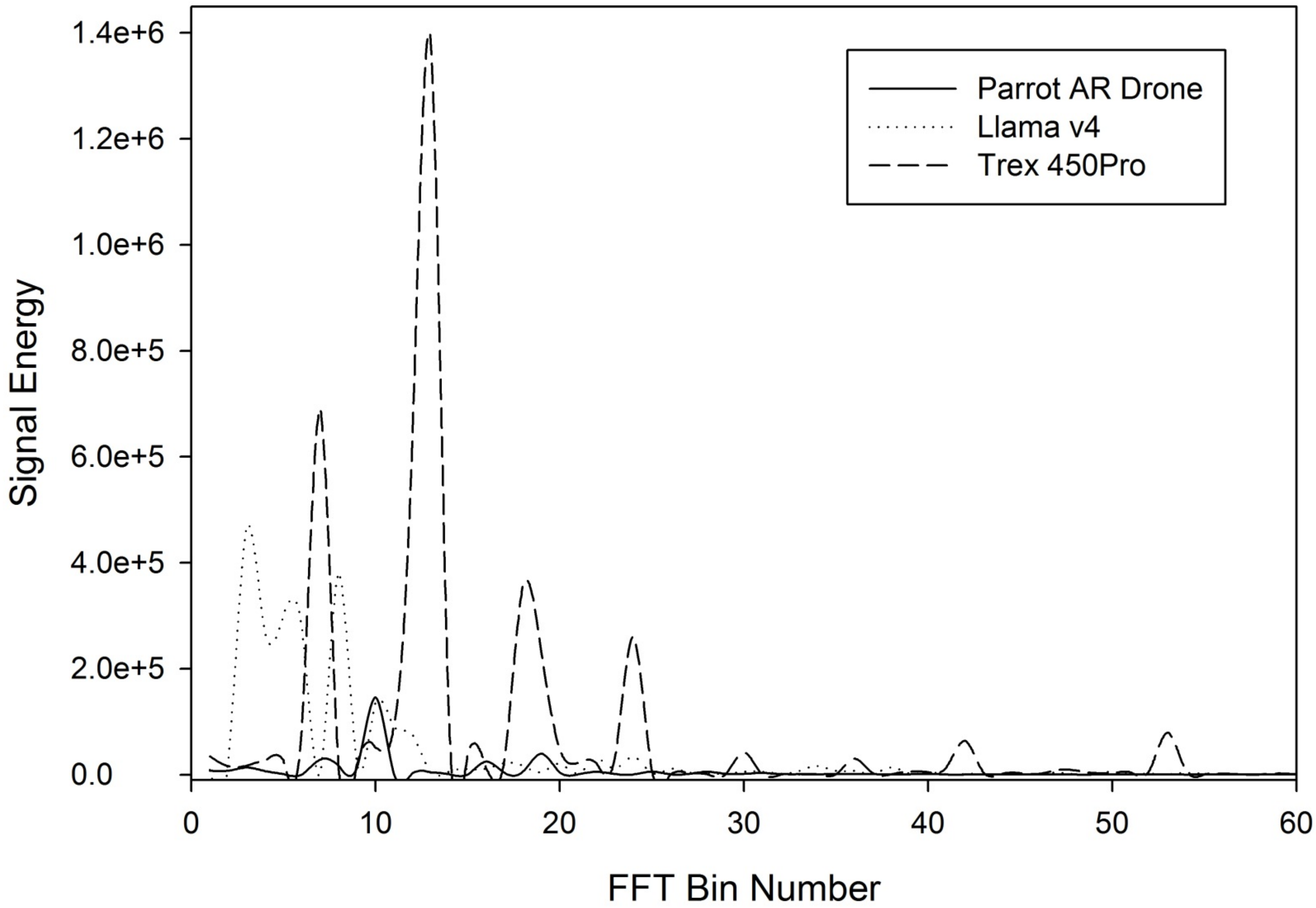

$$Helicopter\_Spectrum(T) = \left(\frac{2F}{c}\right)\left[\frac{\pi d_{mr}}{T} + \frac{\pi d_p}{T} + \frac{\pi d_{tr}}{T/_{4.24}} + Aux(T)\right]$$

*d* = Component diameter
*T* = Rotational period of main rotor
*F* = RADAR transmit frequency (10.5GHz)
*c* = Speed of light

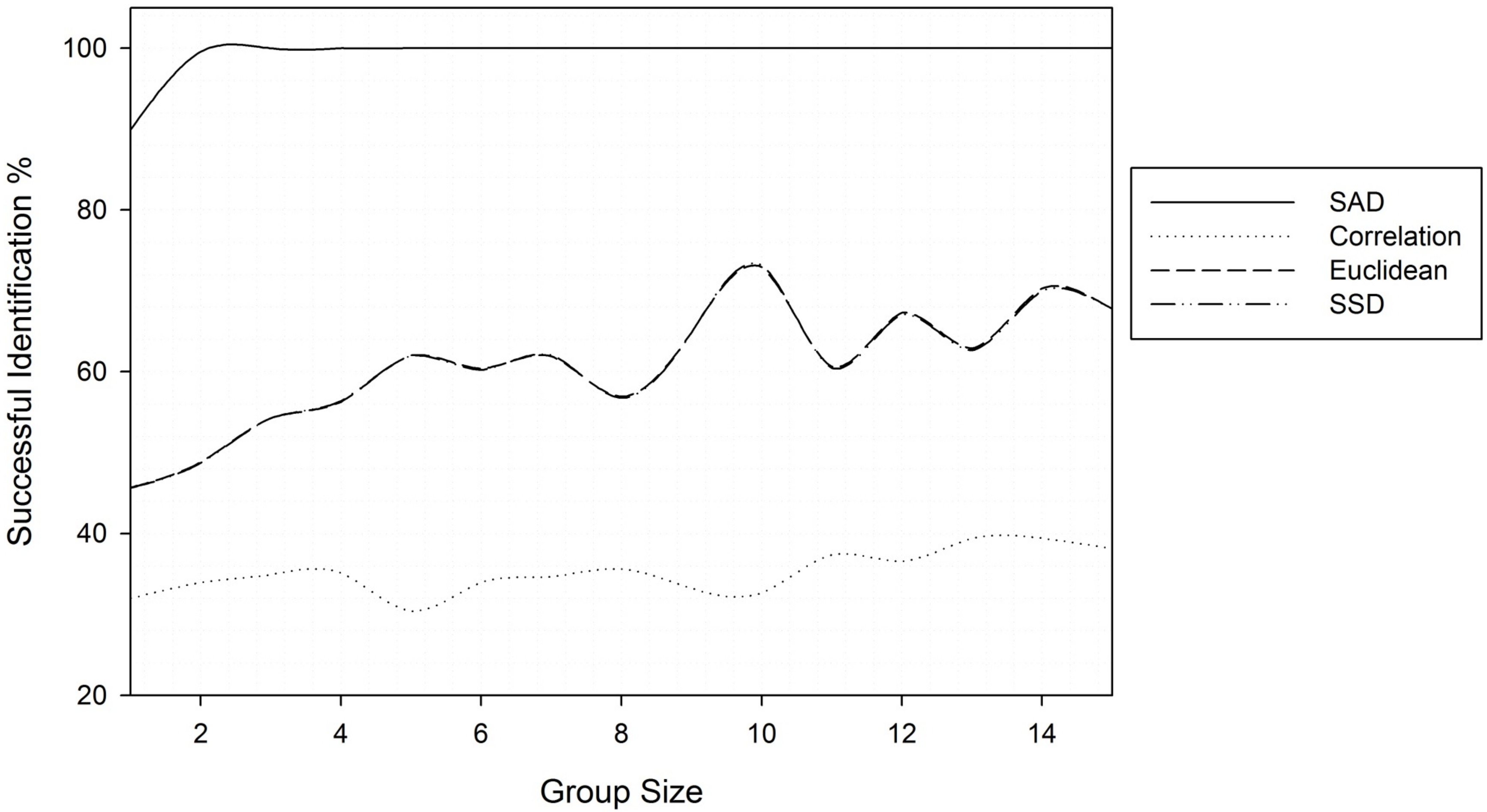
# Experimental Setup



# Technical Details: Rotorcraft Signatures



# Processing Algorithms



# Applications: Manned Aircraft Evasion

| UAV | Evasion Region | Detection Region | Safety Region | Other Air Traffic |
|---|---|---|---|---|

- **Evasion scenario divided into range "shells"**

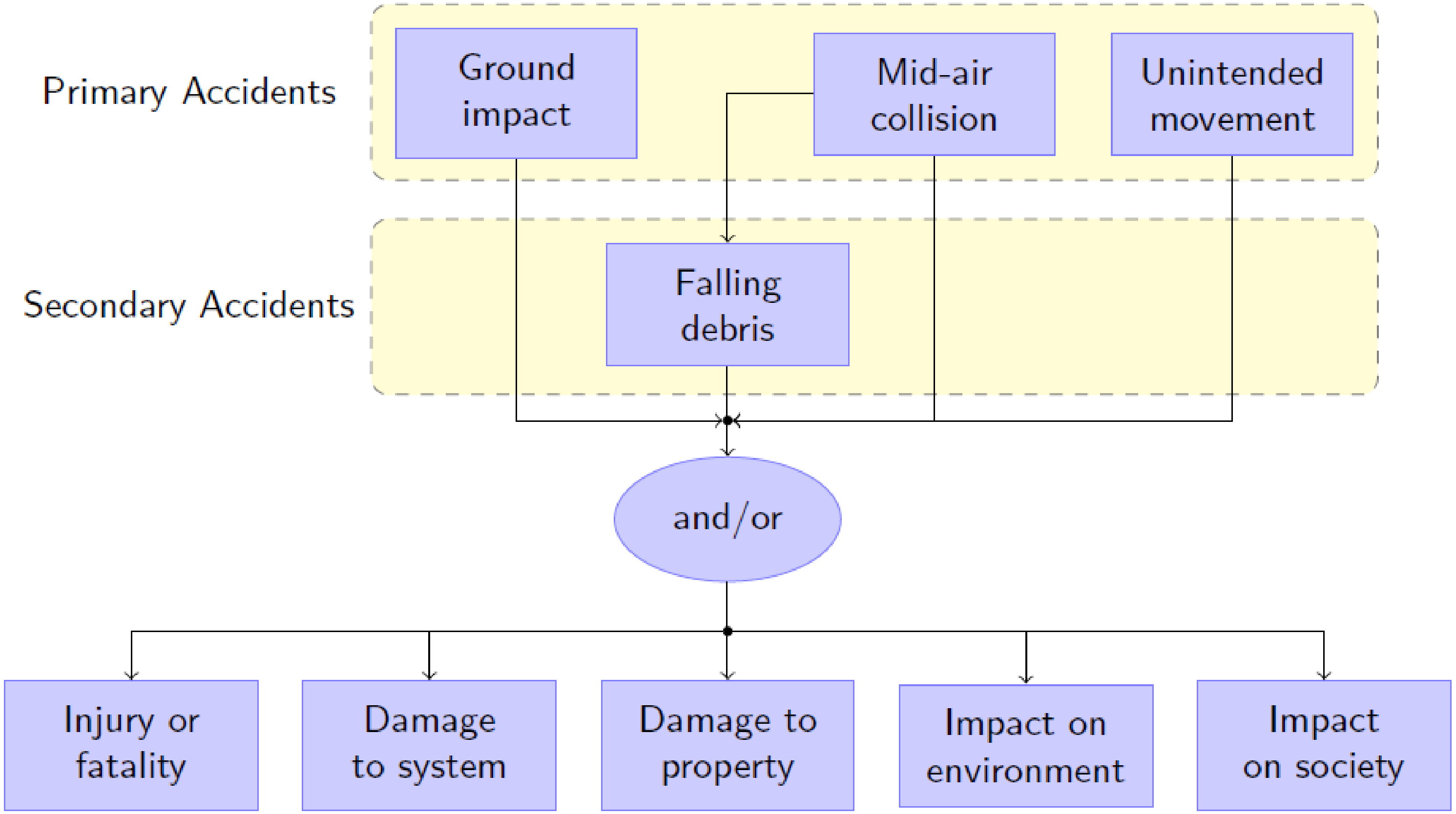
  - **Evasion –** Determined by opposing aircraft dimensions and UAV's acceleration
  - **Detection Region –** Determined by threat Radar Cross Section
  - **Safety region –** "N" multiple of the combined evasion and detection regions

- **All regions affected by the combined vehicle velocities.**

# Uniqueness

- Other devices address larger vehicles, and the associated high acquisition costs hinder widespread implementation
- Furthermore, commercially available, miniature airborne radar systems do NOT address the air to air collision scenario. There are, however, systems for the following:
  - SAR Mapping
  - Radar Altimetry / range finding
- Our system is capable of addressing  the above scenarios IN ADDITION to air-air collision mitigation

## Accidents and damages



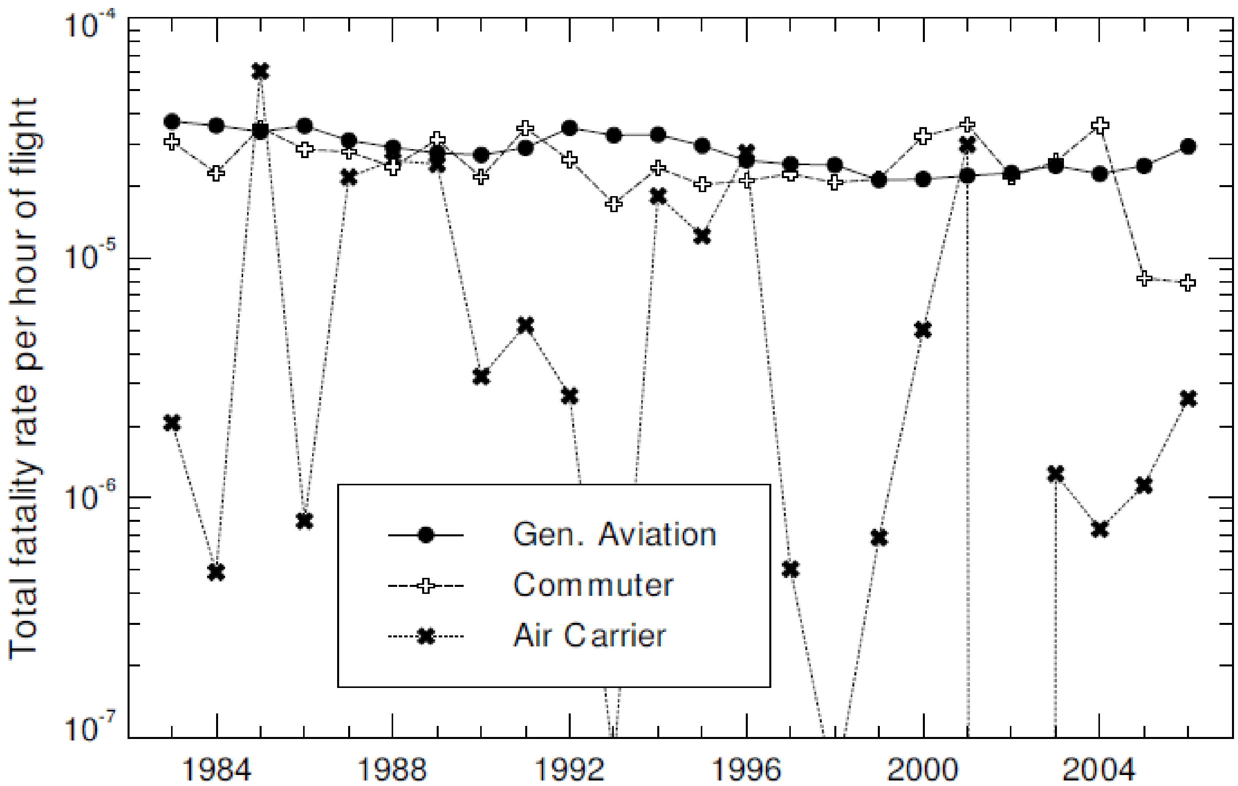



Fig. 5.2: Fatality rates from general aviation, commuter and air carrier accidents as a function of time. Based on analysis of NTSB accident data [15] between 1983 and 2006.

# Equivalent levels of safety - study

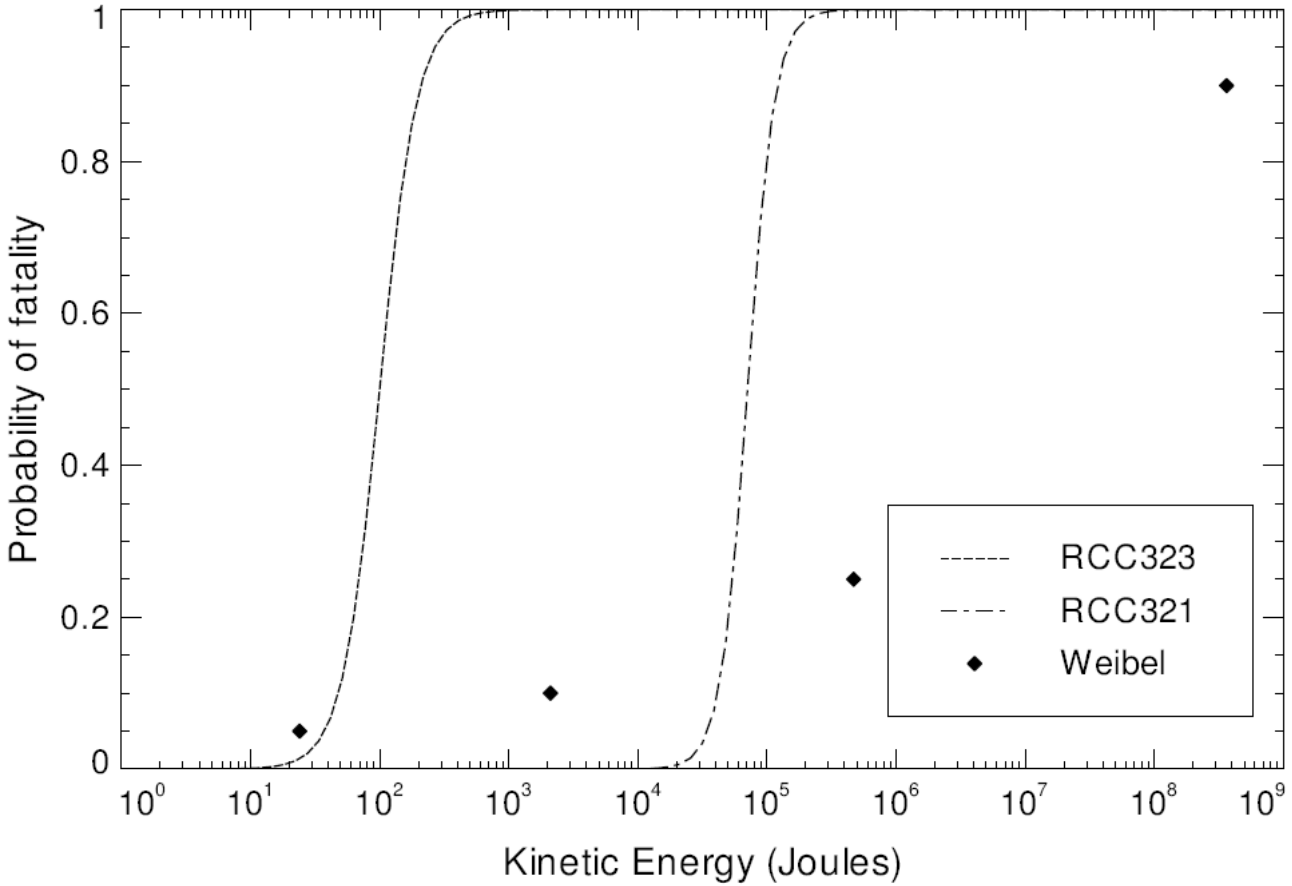



Fig. 5.4: The probability of fatality as a function of kinetic energy impact as estimated by Weibel [20] and models derived in RCC321 [18] and RCC323 [17].

# Equivalent levels of safety - study

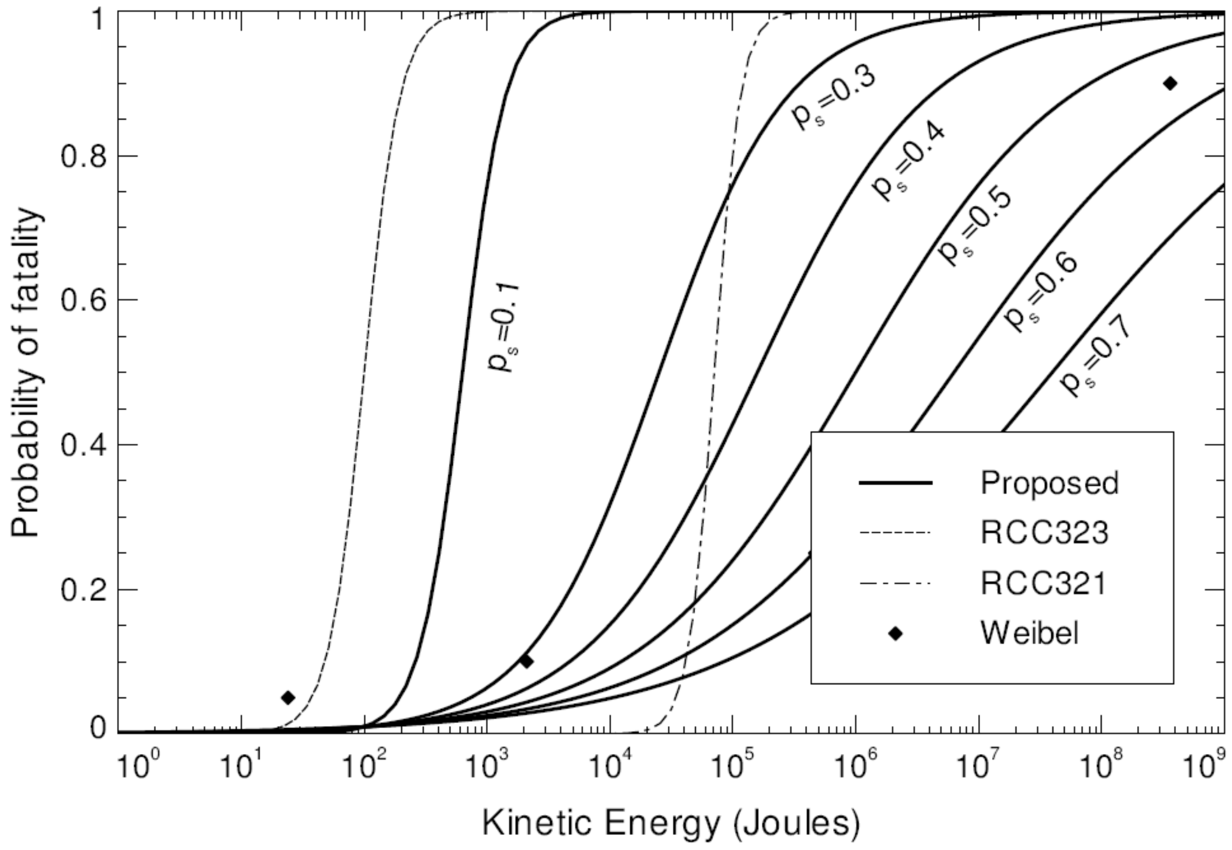


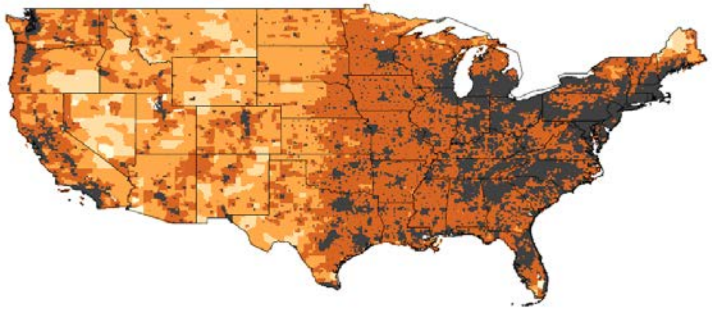

Fig. 5.5: The probability of fatality as a function of kinetic energy impact for the proposed model with $\alpha = 10^6$J, $\beta = 100$J and for several values of $p_s$. For comparison purposes the estimates of Weibel [20] as well as the models of RCC321 [18] and RCC323 [17] are given.

# Case Study Results – Over the US

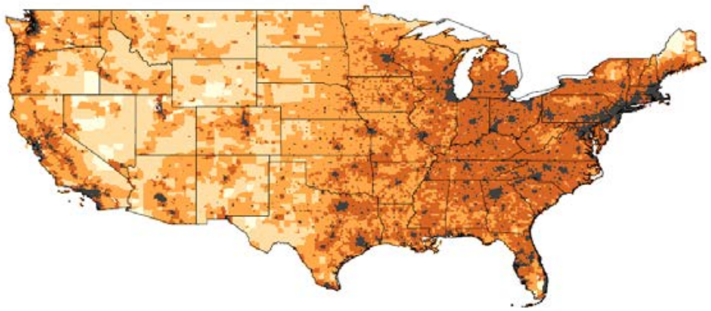
Table 5.12: The percentage of the US area over which each UAS can loiter without violating set TLS requirement, based on exhibited reliability. The bold column represents the reliability of manned general aviation. Population density data: [1].

| | $T_{GI}$ in hr | | | | |
|---|---|---|---|---|---|
| | $10^2$ | $10^3$ | $10^4$ | $10^5$ | $10^6$ |
| RQ-4A Global Hawk | 0.4% | 7.1% | 38.8% | **79.5%** | 96.6% |
| MQ1 Predator | 2.5% | 25.6% | 64.2% | **93.8%** | 99.0% |
| RQ-2 Pioneer | 14.7% | 52.9% | 90.3% | **98.3%** | 100.0% |
| Neptune | 43.8% | 83.9% | 97.2% | **99.9%** | 100.0% |
| Aerosonde | 53.2% | 90.4% | 98.3% | **100.0%** | 100.0% |
| RQ-6 Fire Scout | 7.7% | 40.8% | 81.4% | **96.8%** | 99.8% |
| Guardian | 32.7% | 72.4% | 95.5% | **99.5%** | 100.0% |
| Rmax type IIG | 55.9% | 91.5% | 98.5% | **100.0%** | 100.0% |
| Vario XLV | 79.1% | 96.5% | 99.7% | **100.0%** | 100.0% |
| Maxi Joker | 89.4% | 98.1% | 100.0% | **100.0%** | 100.0% |

# Case Study % of US – Flying over



(a) RQ-4A Global Hawk



(b) MQ-1 Predator

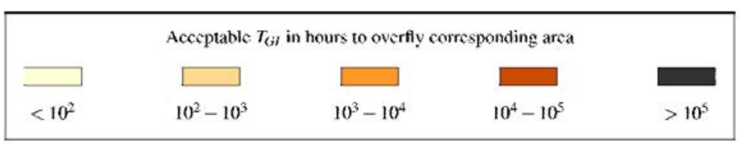
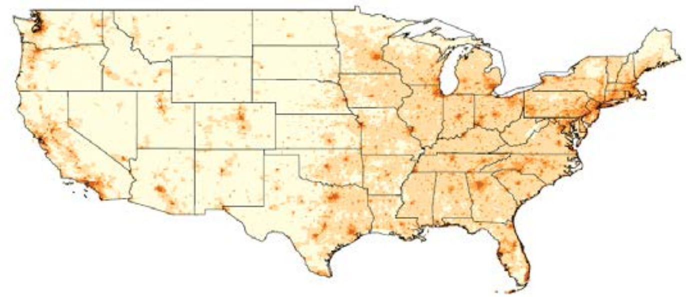
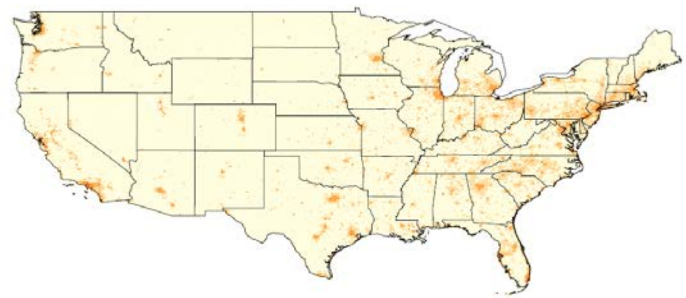



Fig. 5.6: The areas of the US, the RQ-4A Global Hawk and the MQ-1 Predator UAS are allowed to loiter over based on their reliability with respect to ground impact occurrence frequency.



(a) Yamaha Rmax IIG



(b) Maxi Joker 2

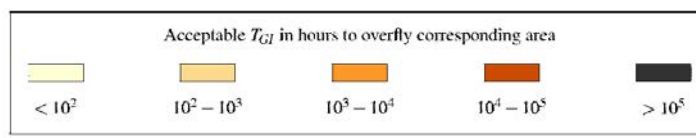
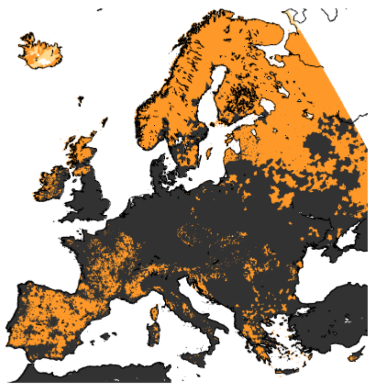
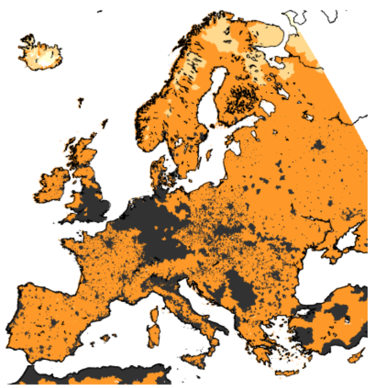



Fig. 5.8: The areas of the US, the Yamaha Rmax IIG and Maxi Joker 2 helicopters are allowed to loiter over based on their reliability with respect to ground impact occurrence frequency.

# Case Study % of Europe– Flying over



(a) RQ-4A Global Hawk



(b) MQ-1 Predator

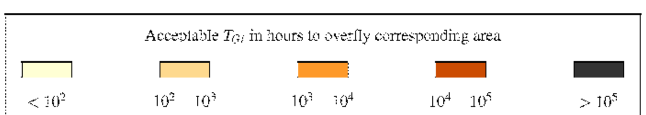
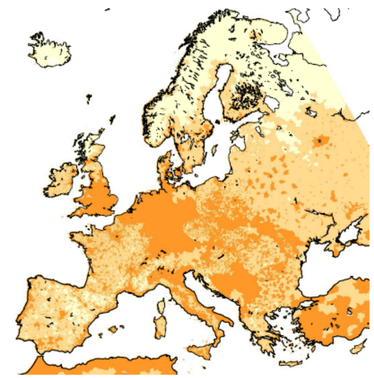
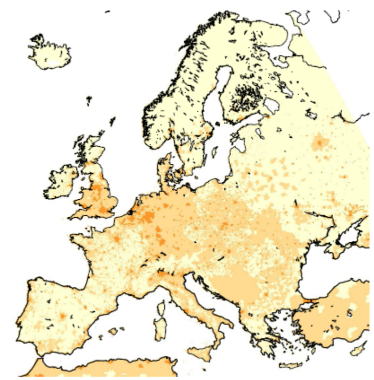



Fig. 5.9: The areas of Europe, the RQ-4A Global Hawk and the MQ-1 Predator UAS are allowed to loiter over based on their reliability with respect to ground impact occurrence frequency.



(a) Yamaha Rmax IIG



(b) Maxi Joker 2

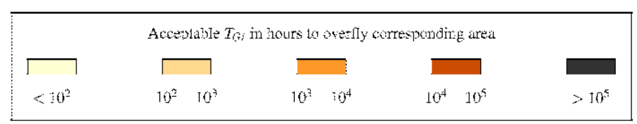
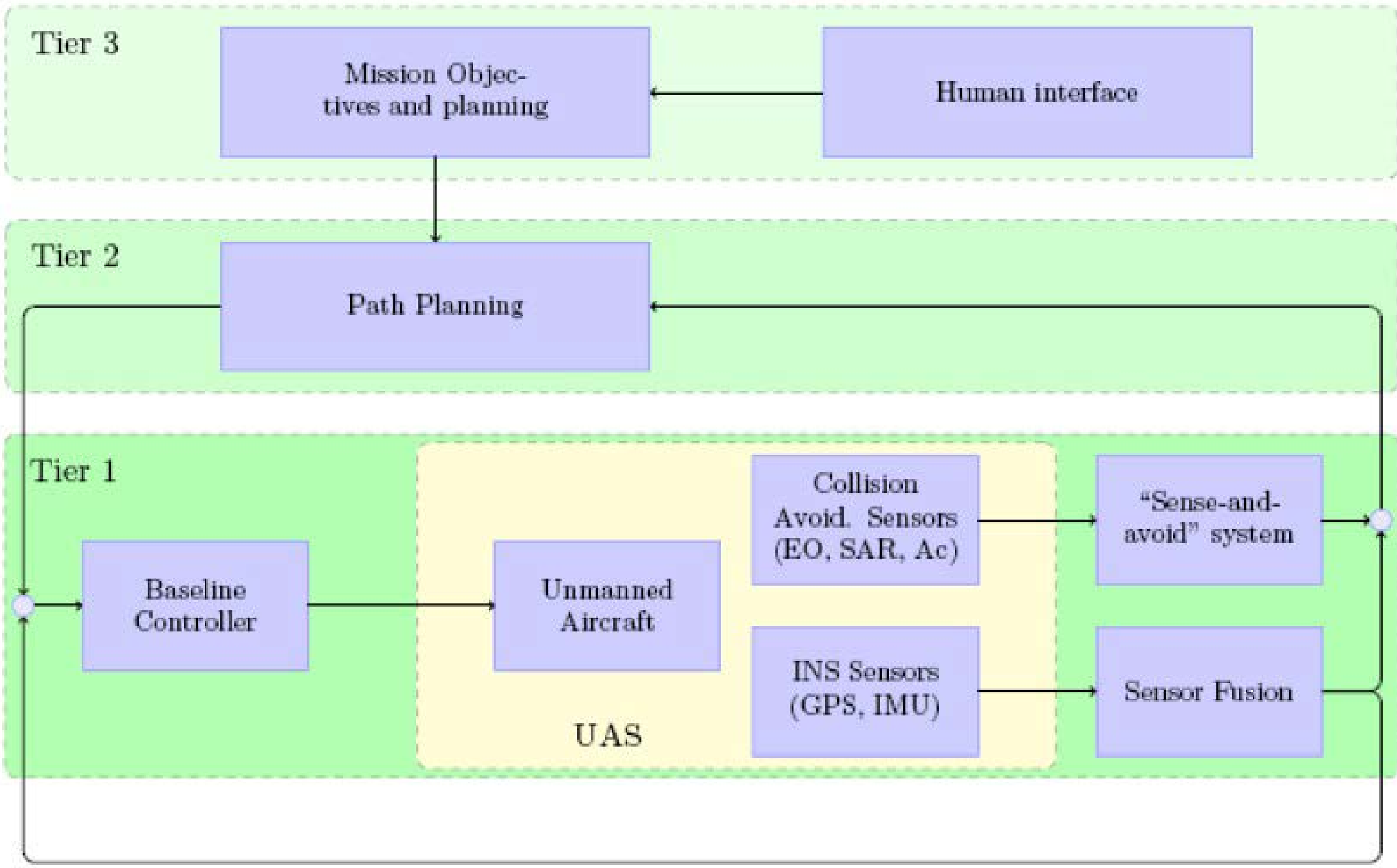
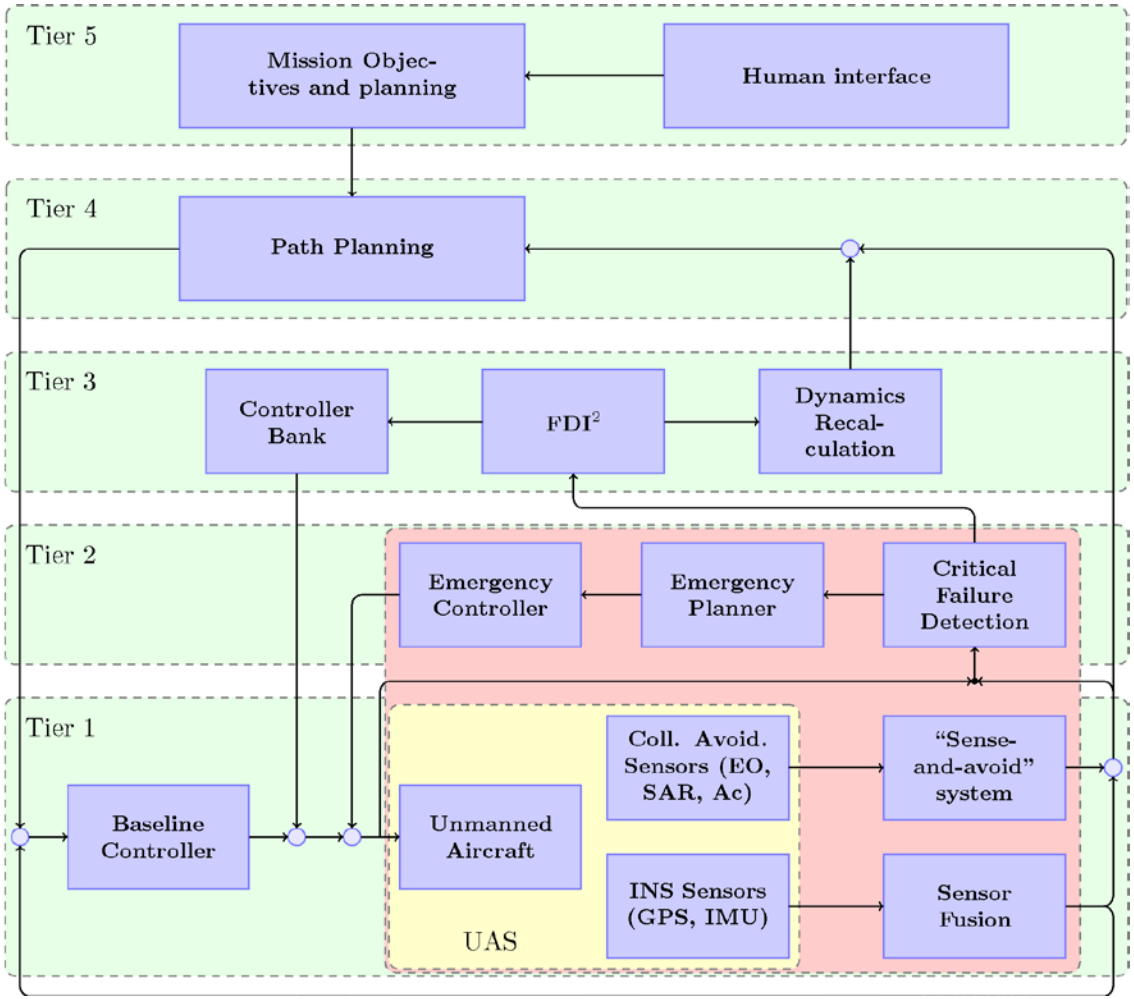



Fig. 5.11: The areas of Europe, the Yamaha Rmax IIG and Maxi Joker 2 helicopters are allowed to loiter over based on their reliability with respect to ground impact occurrence frequency.

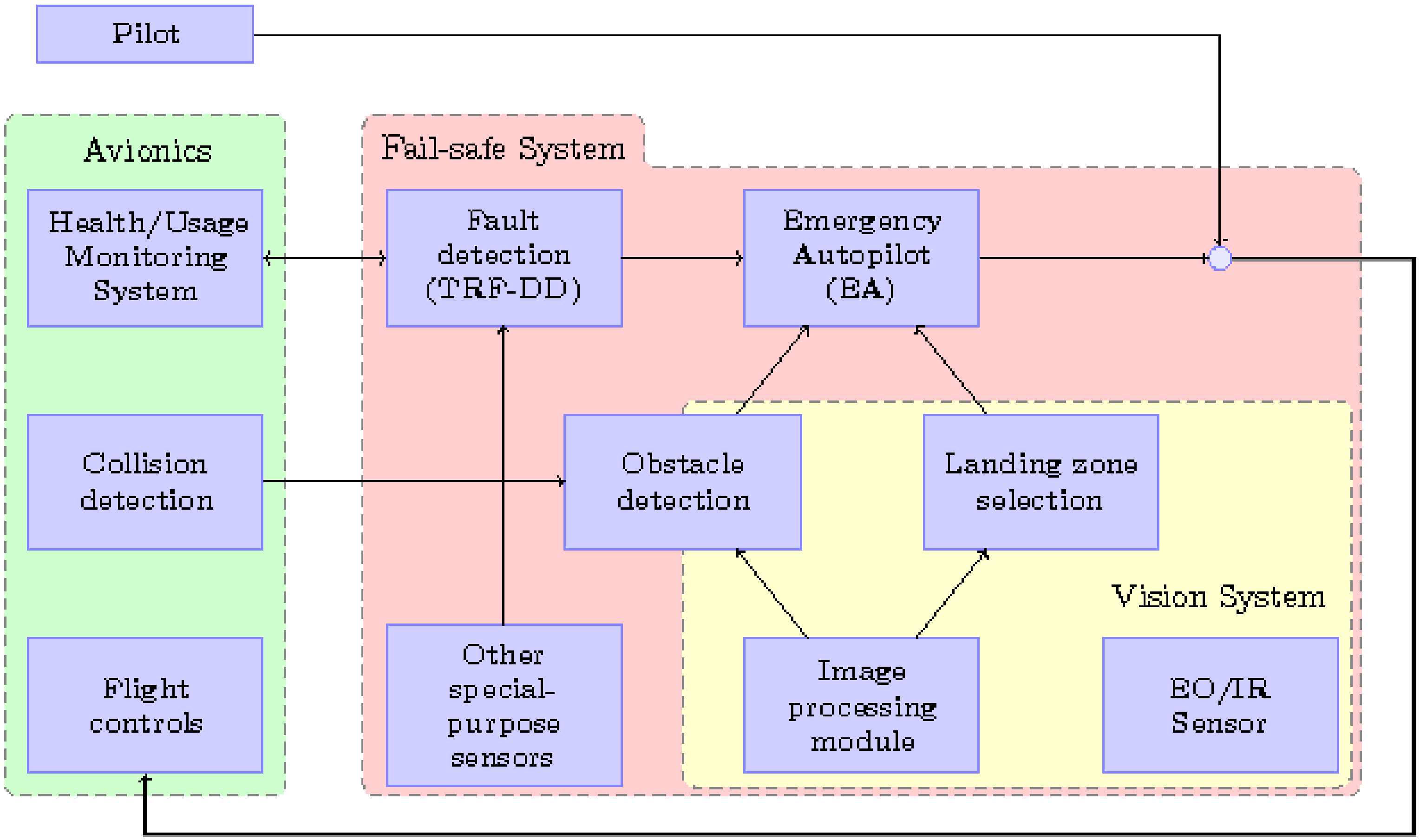
# ADDED SAFETY: THE CURRENT STATE



# THE PROPOSED SYSTEM



# THE 'AUGMENTED' SYSTEM FOR MANNED HELICOPTERS



# IDEA Presentation, 2016

## *$UC^2AV$: Unmanned Circulation Control Aerial Vehicle for Short Takeoff and Enhanced Payload*


**Konstantinos Kanistras, Pranith C. Saka, Kimon P. Valavanis and Matthew J. Rutherford**

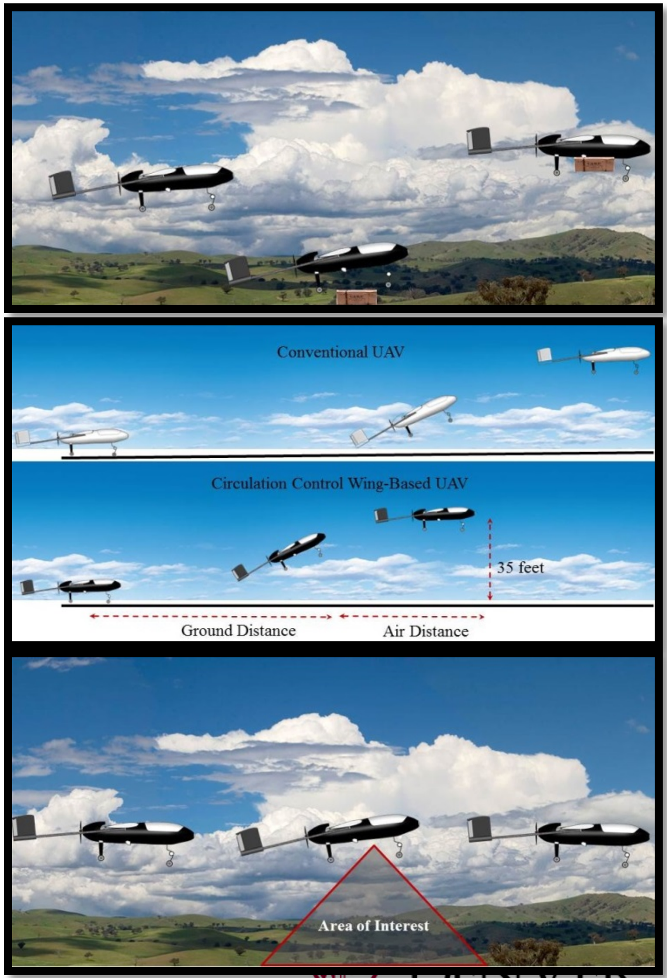
# Research Goals

Focus on *designing*, *modeling*, *developing* and *experimentally validating and verifying* through wind tunnel and flight testing Circulation Control Wings (CCWs) for unmanned aircraft, which will allow for ***lift enhancement***, resulting in:

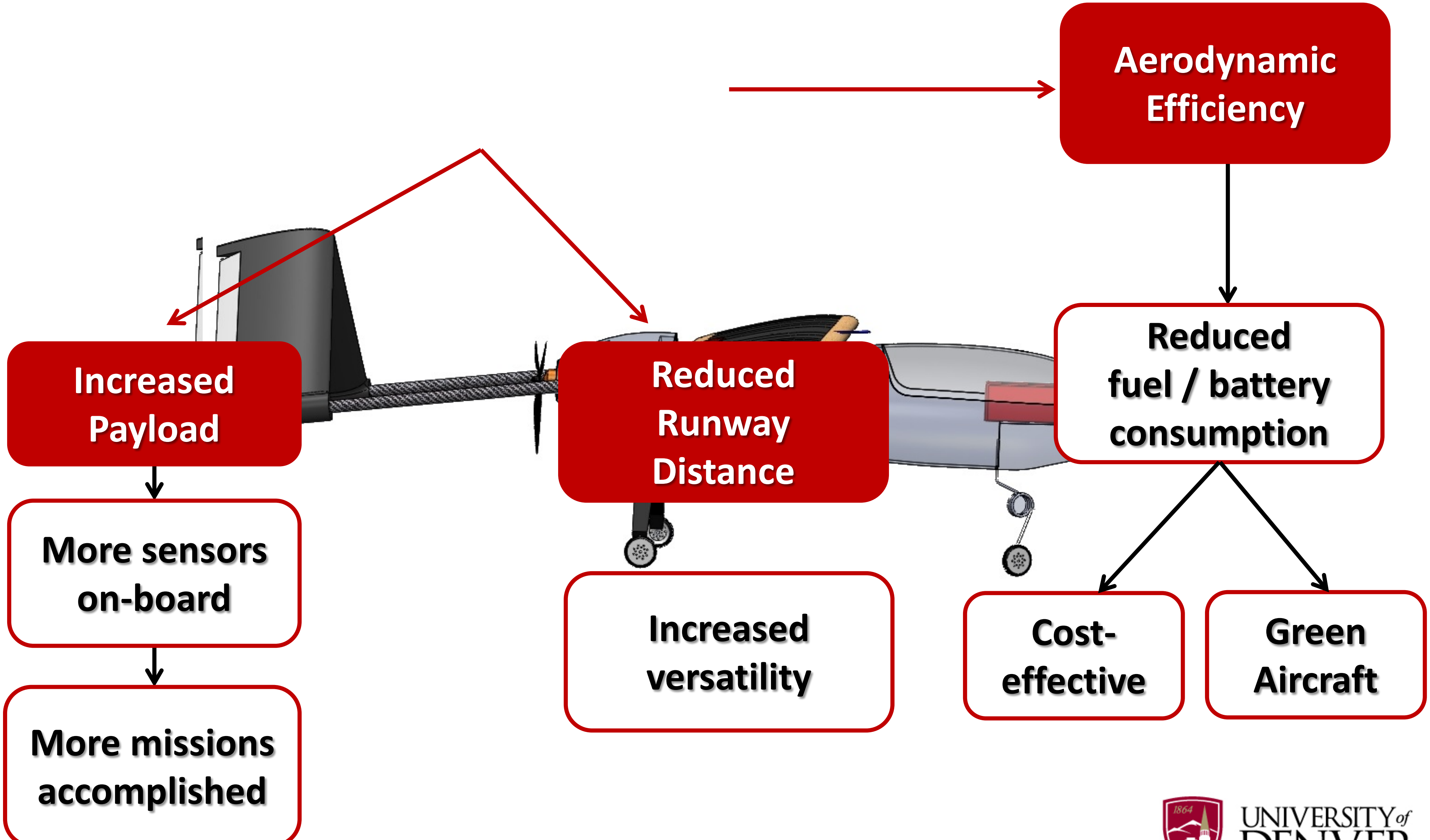
- **Increased payload capability**
  - ✓ More sensors on-board
  - ✓ Additional payload (more cargo, fuel, etc.) that allows for mission flexibility

- **Reduced takeoff / landing runway distance**
  - ✓ Less infrastructure required
  - ✓ Smoother landings

- **Increased stall angle and reduced $V_{stall}$**
  - ✓ Allow for lower velocity over areas of interest
  - ✓ Increase maneuverability



# What is important in the UAV industry?




UNIVERSITY of DENVER

# UC$^2$AV Tasks

**Weight Specifications:**

- Wing : 1780 g / 3.90 Lbs
- Tail & Booms: 340 g / 0.75 Lbs
- Fuselage: 1840 g / 4.05 Lbs
- Batteries: 940 g / 2.10 Lbs

**Specifications:**

- MTOW : 4.7 kg / 10.8 Lbs
- Ground Speed: 19.5 m/s
- Max Speed: 20-23 m/s

# Research Achievements

**The UC²AV is integrated with a Circulation Control system that:**

- All parts are 3D printed

**Flight tests are conducted to identify:**

- o The maximum payload enhancement
- o Improvement in Aerodynamic efficiency

**Using Circulation Control the UC²AV achieved:**

The UC²AV achieved a *takeoff runway distance reduction* up to **53.8%** using upper surface trailing edge blowing **(Circulation Control).**

- Double lift generation during takeoff
- Runway distance reduction during takeoff by 53.8%
- o Smoother landings
- o It can be integrated to any size UAV

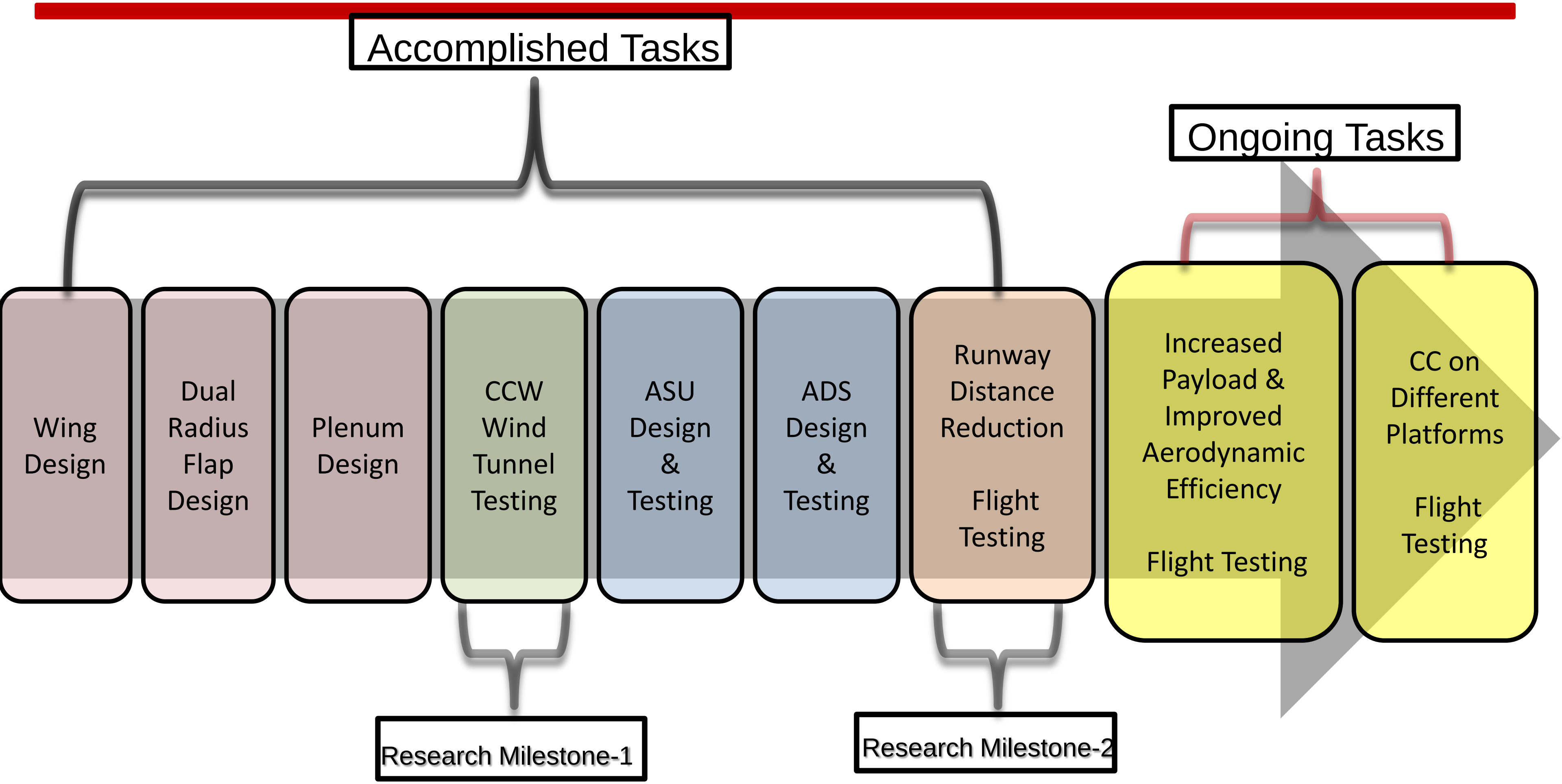
Circulation Control off

Circulation Control on

Circulation Control : Off
Flaps Deflection : 30 degrees
Take off Distance : 117m/ 383ft

Circulation Control : On
Flaps Deflection : 30 degrees
Take off Distance : 54m / 117ft

# Research Timeline



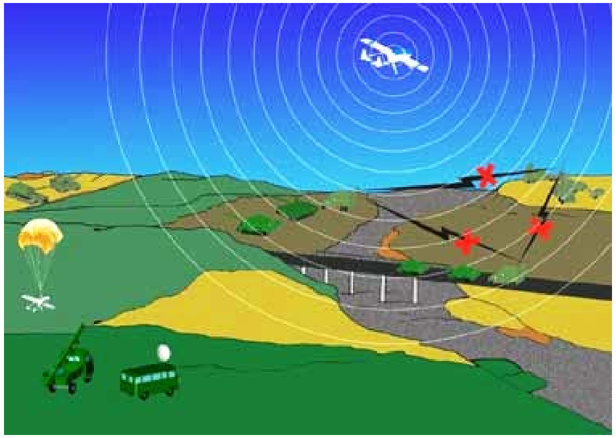

Research Milestone-1 → https://www.youtube.com/watch?v=S4ELDVsnvYE

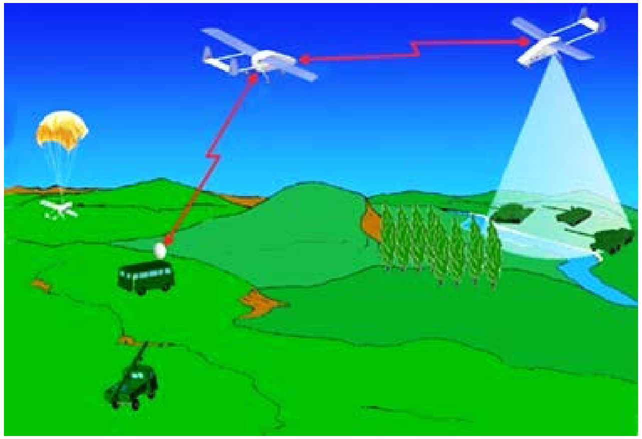
Research Milestone-2 → https://www.youtube.com/watch?v=pOMFNH5R3zU

# The Road Ahead

**Prepare for the new era of NAS operations**

- ❑ Develop experimentally proven and reliable technology
- ❑ Address safety issues through technology
    - ❑ Design and build stable controllers with fault tolerance
    - ❑ Enhance onboard intelligence to overcome issues with lost comm links
    - ❑ Design emergency systems to protect the public in the event of catastrophic failures.
    - ❑ Enhance vision systems and alternative sensors to provide true see-and-avoid capability
- ❑ Obtain FAA experimental (and later on full) certification

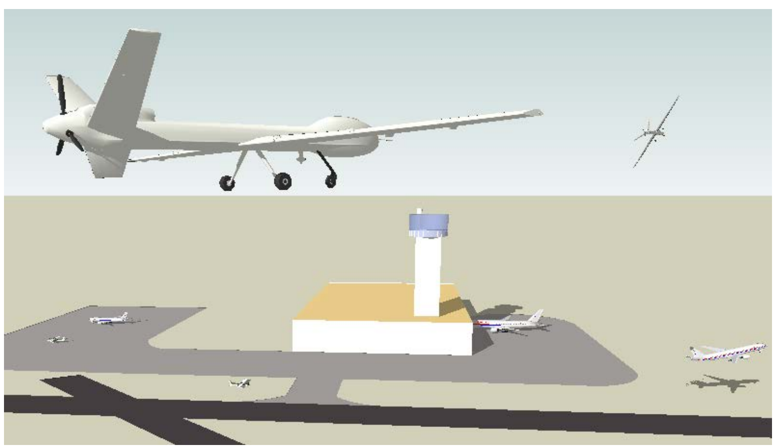


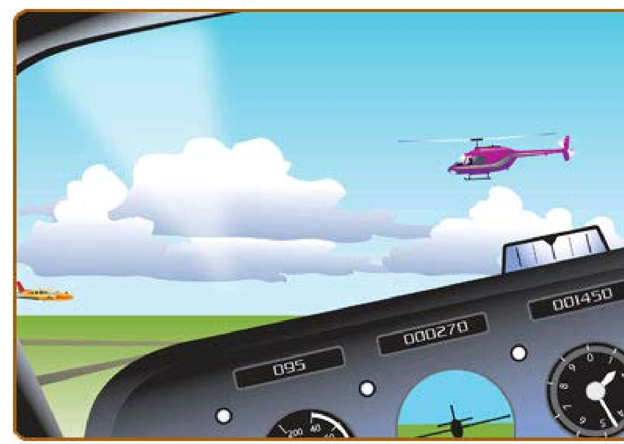


# The Road Ahead

## See and Avoid Technology

- ❑ Use of latest estimation tools to provide adequate information even under very strict size, weight and power limits.
- ❑ Focus on full trajectory estimation of detected targets (v.s. position only)
- ❑ Definition of appropriate metrics to determine performance
- ❑ Full proof-of-concept demonstration in accurate simulation environment
- ❑ Integration with guidance, navigation and control algorithms to provide efficient “avoid” capability





# The Road Ahead

**Safety Technology**

- ❑ Full control architectures that incorporate:
  - ❑ Robustness (all weather design)
  - ❑ Intelligent path planning with provisions for lost comm links
  - ❑ Redundancy
  - ❑ Health monitoring
  - ❑ Reconfigurable control algorithms
- ❑ Emergency systems for safe flight termination
  - ❑ Same robust design to allow recovery under any conditions
  - ❑ Minimal requirements to provide adequate performance under the strictest size, weight and power limitations.
  - ❑ Focus on public safety v.s. aircraft integrity

    It is better to lose a UAS than risk an injury