Challenges in Unmanned Aircraft Systems (UAS)

From Controller Design to Integration into the National Airspace

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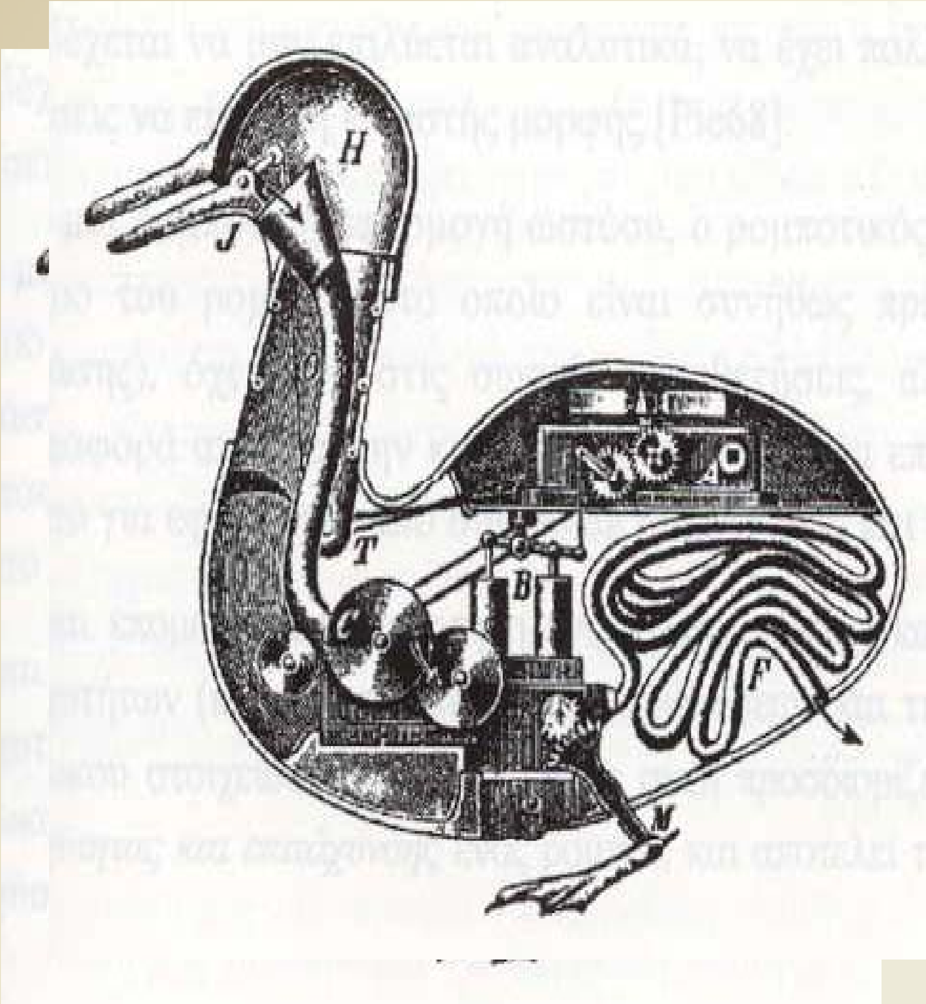
Outline

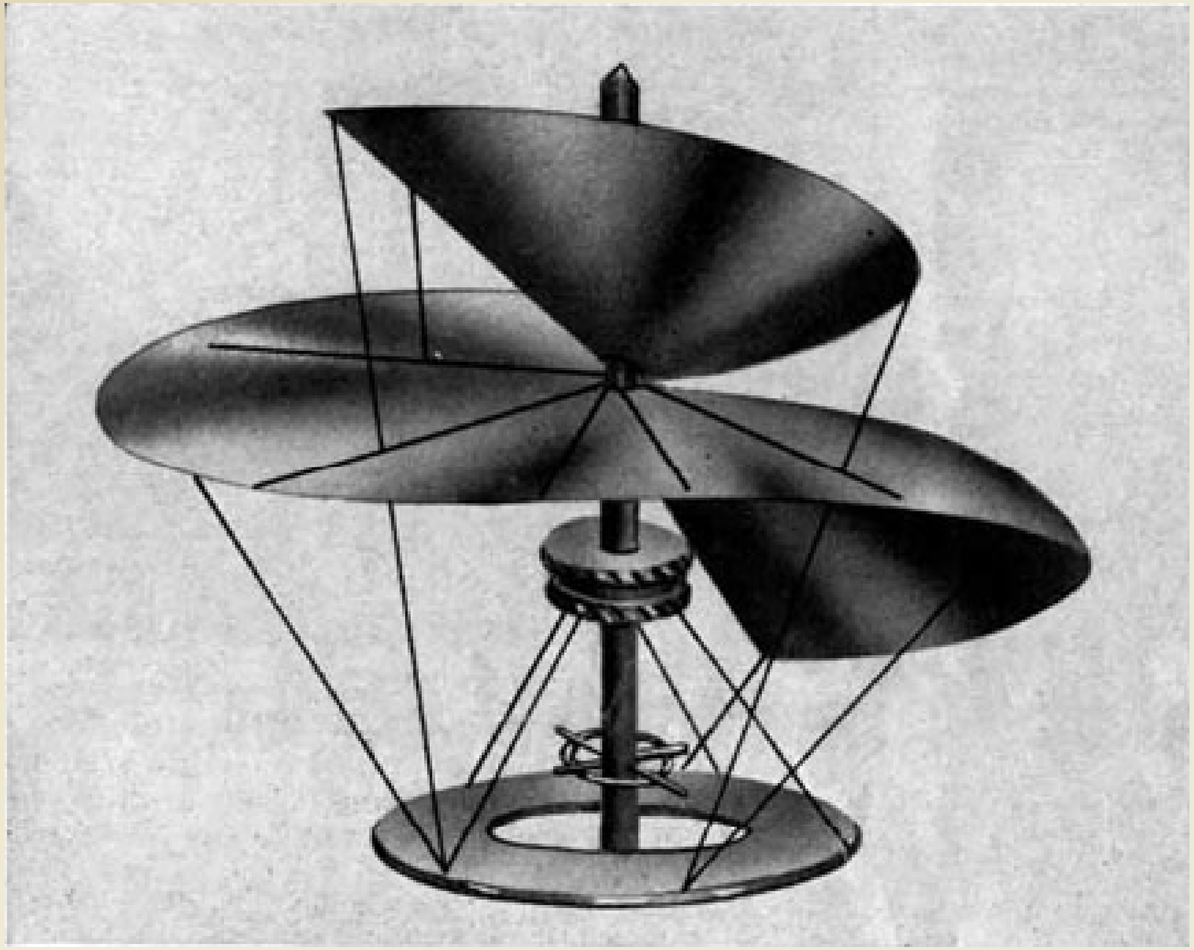
- Very brief historical perspective
  - Pictorial 'tour' of UAVs / UAS
- UAS Roadmap: DOD, FAA
  - Challenges and Conflicts
  - A Possible UAS Classification?
- The Wide Spectrum of Applications
  - (Our) Available Testbeds
  - Sample Videos (Our applications)
- Formally: What are we doing? Why? How? Final Objective? Why Unmanned Rotorcraft (< 150 Kgr)?
- Control and Controller Design Challenges
- Linear and Nonlinear Controller Design
- Emergency Landing System
  - Nonlinear MPC + Recurrent NN
  - Autonomous vertical autorotation
- On integrating UAS into the NAS

Historical Perspective

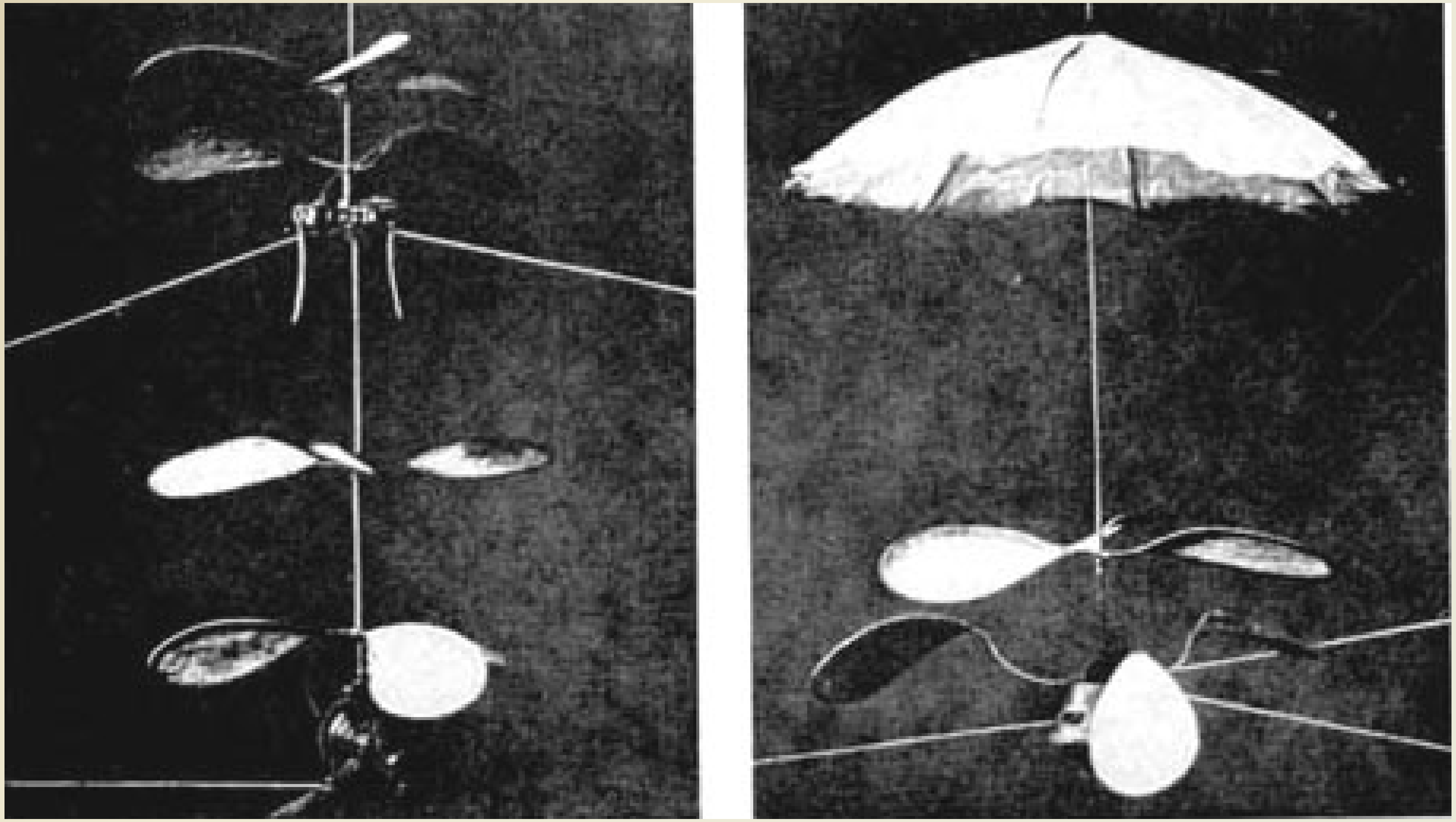
Figure 4. Artist's drawing of Archytas' flying mechanical pigeon created in 425 B.C. The bird could fly by flapping its wings and deriving energy from a mechanism in its stomach. It is alleged that it flew about 200 meters before falling to the ground.



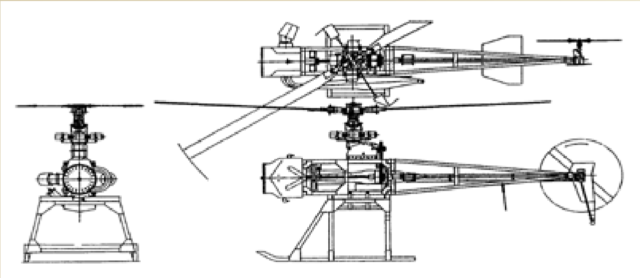
Autonomous mechanism designed by somebody during the 1400s.



Leonardo Da Vinci's Air Screw



Ponton d' Amecourt's helicopters (Credit, Hiller Aviation Museum [2]).



Dragonfly DP-4
AeroCopter, Inc.

MAYA
Alcore Technologies, SA

iStar
Allied Aerospace

Air Scooter
Air Scooter Corporation

Eagle Eye UAV
Bell Helicopter

Hummingbird UAV
Boeing

Dragonfly
Boeing

Unmanned Little Bird
Boeing

TYPES OF UAVs

Scorpio
EADS

ORKA-1200
EADS

GT Max
Georgia Tech

RoboCopter
Kawada Industries

X-cell
Nancent Technology

AutoCopter Explorer
Neural Robotics

AutoCopter Express
Neural Robotics

TYPES OF UAVs

SR 20
Rotomotion

SR 100
Rotomotion

SR 200
Rotomotion

RMAX
Yamaha

T-series
UAV Vision

G-series
UAV Vision

i-Copter Seeker
V-TOL Airspace

APID 55
CybAero

Fixed-wing

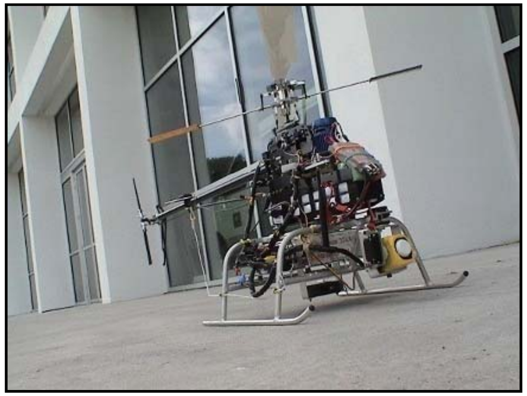
Rotorcraft

RQ-8B FIRE SCOUT (NORTHROP GRUMMAN)

Tilt-rotor

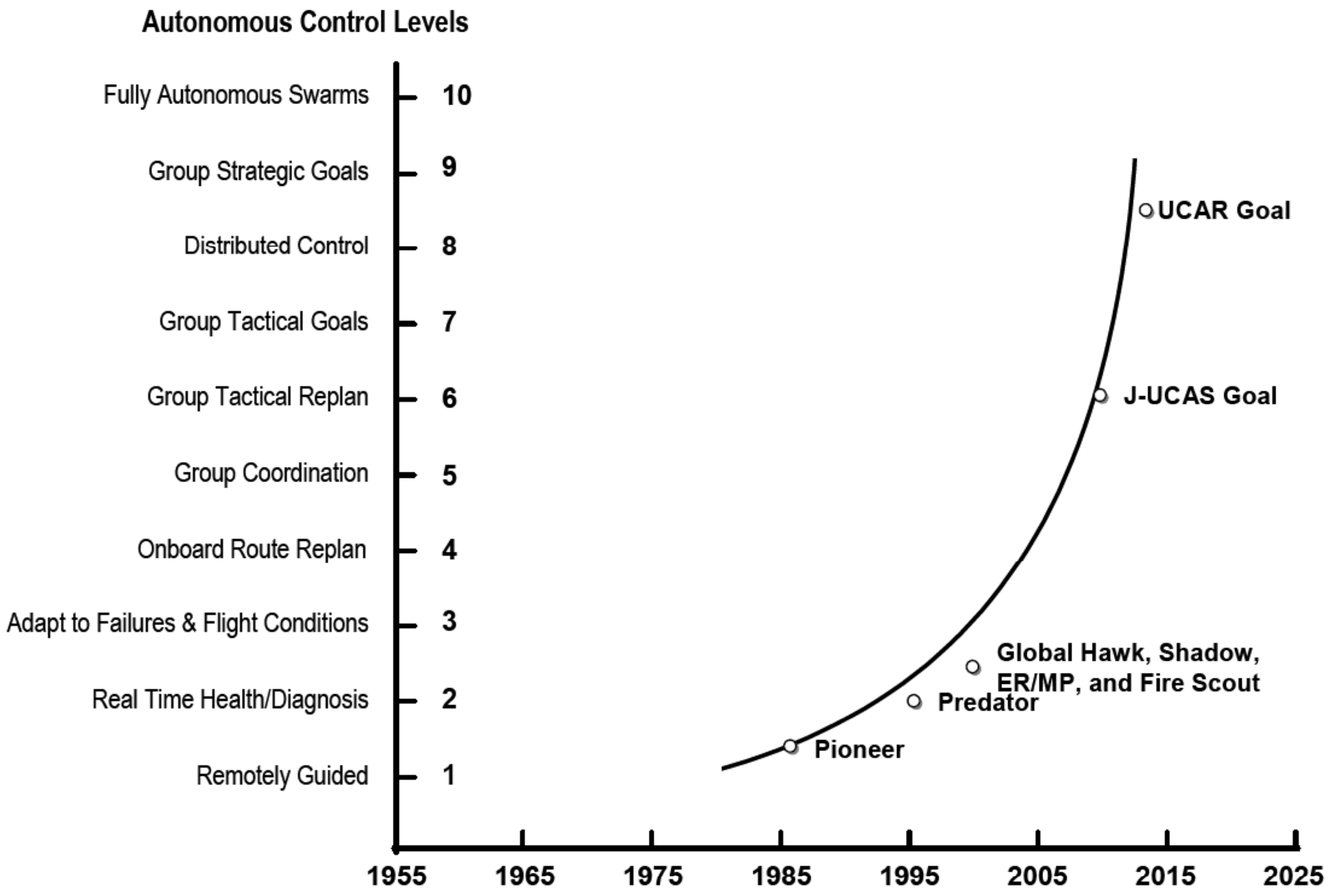
EAGLE EYE IN USCG COLORS (BELL)

Experimental Prototypes
Maxi Joker II



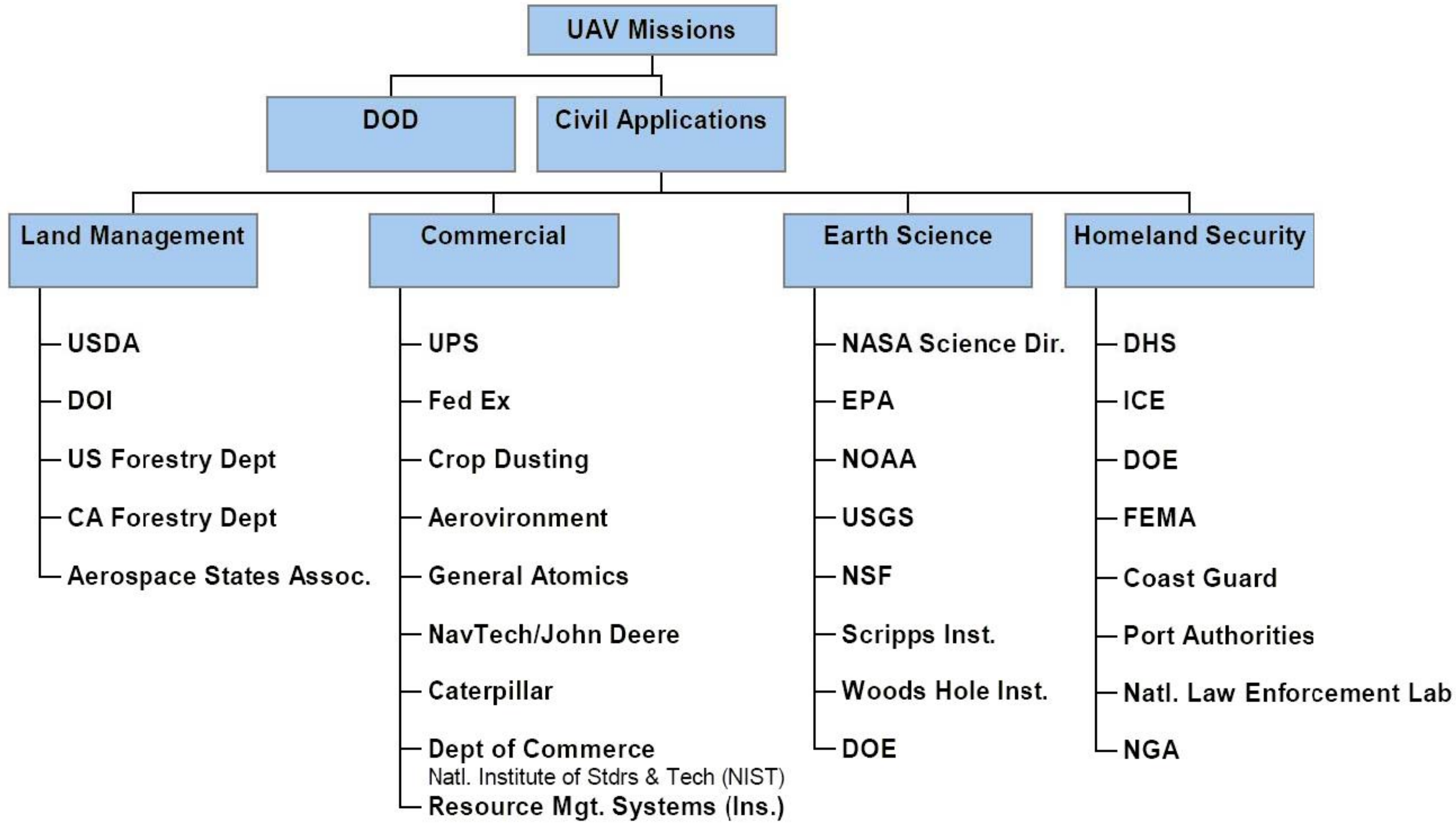
TYPES OF UAVs

DOD ROADMAP



TREND IN UA AUTONOMY.

USERS SPECTRUM



Classification of UAV Users

FAA 'Ultimatum'

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

CLASSIFICATION

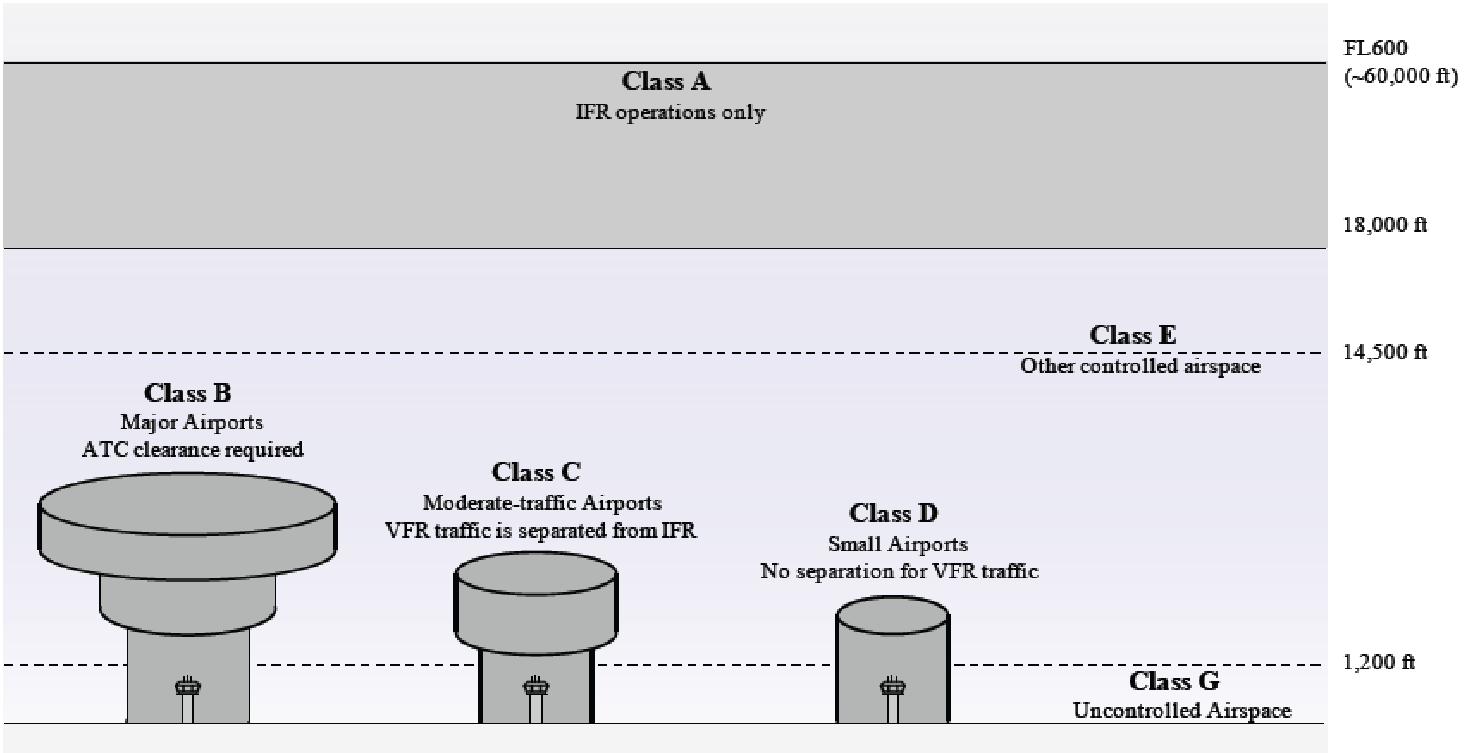
Table 6.3: UAS categorization for differentiation of existing systems. Source: [3]

	Mass (kg)	Range (km)	Flight Alt. (m)	Endurance (h)
Micro	<5	<10	250	1
Mini	<20/25/30/150[a]	<10	150/250/300	<2
Tactical				
Close Range (CR)	25-150	10-30	3.000	2-4
Short Range (SR)	50-250	30-70	3.000	3-6
Medium Range (MR)	150-500	70-200	5.000	6-10
MR Endurance (MRE)	500-1500	>500	8.000	10-18
Low Altitude Deep Penetration (LADP)	250-2500	>250	50-9.000	0.5-1
Low Altitude Long Endurance (LALE)	15-25	>500	3.000	>24
Medium Altitude Long Endurance (MALE)	1000-1500	>500	3.000	24-48
Strategic				
High Altitude Long Endurance (HALE)	2500-5000	>2.000	20.000	24-48
Stratospheric (Strato)	>2.500	>2.000	>20.000	>48
Exo-Stratospheric (EXO)	TBD	TBD	>30.500	TBD
Special Task				
Unmanned combat AV (UCAV)	>1.000	1.500	12.000	2
Lethal (LET)	TBD	300	4.000	3-4
Decoys (DEC)	150-250	0-500	50-5.000	<4

[a] Varies with national legal restrictions

UAS & THEIR INTEGRATION INTO THE NAS

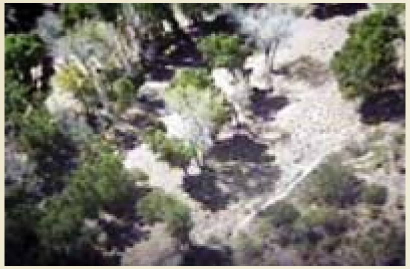
Airspace Classes



Possible 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

- Surveillance, e.g. border patrol
- Search and rescue, e.g. locate people/items on land and sea
- Sniper detection (civilian as well as military)
- Hazardous area inspection (radiation, chemicals, pandemic, etc)
- Mine detection
- Forestry, e.g. timber inventory
- FEMA – damage assessment



Border patrol

Convoy protection

Mapping for security

Real-time traffic planning and control

Model Simulation

Data Collection by UAV Mounted Video Cameras

Data Collection by Infra-red detectors, other sources

Real-time update of simulation parameters

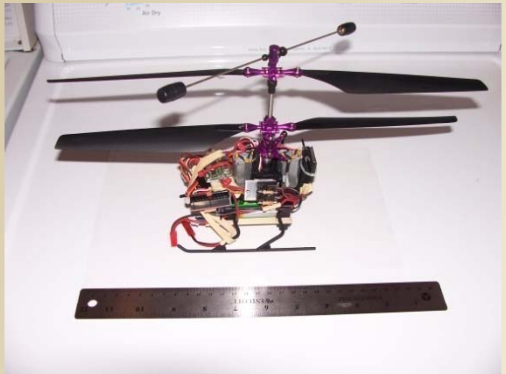
Image Analysis

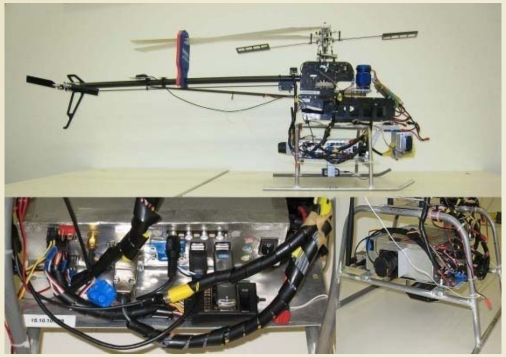
Obtain Observed Parameters (Vehicle type, density, flow, etc)

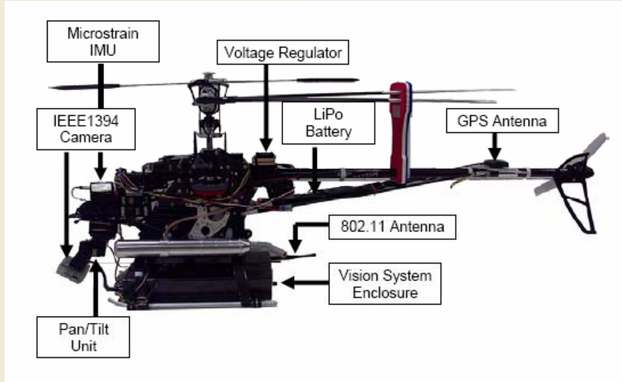
Historical Data

Interface

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



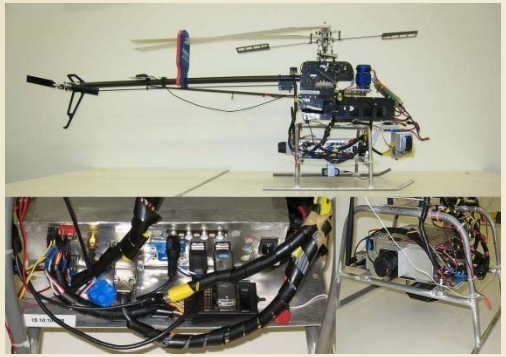




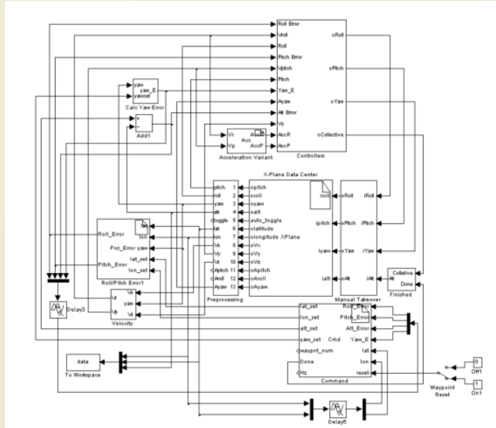
Small chopper,
autonomous
(Maxi Joker frame)

FOCUS ON SMALL ROTORCRAFT – HELICOPTERS

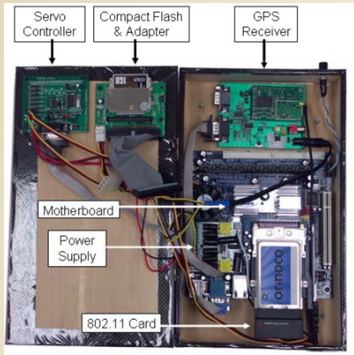
Fleet of ground vehicles
(custom made for ARL)



Small chopper,
autonomous
(Maxi Joker frame)

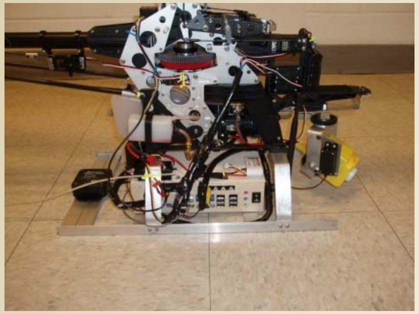


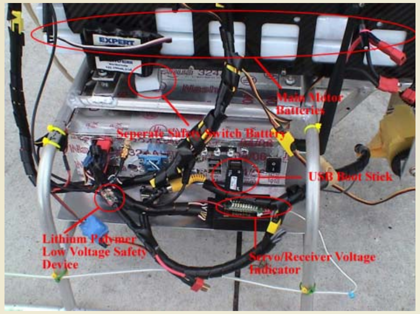
Testing by simulation



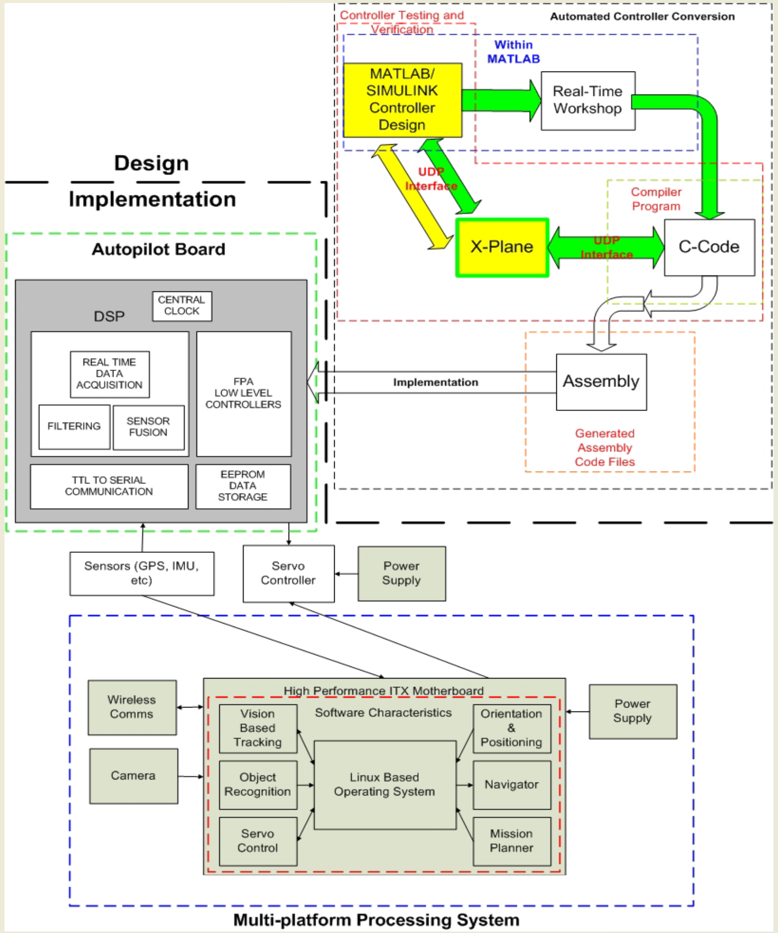
Navigation Controllers: first, second, third generation

Comparison, 2nd / 3rd generation navigation controllers

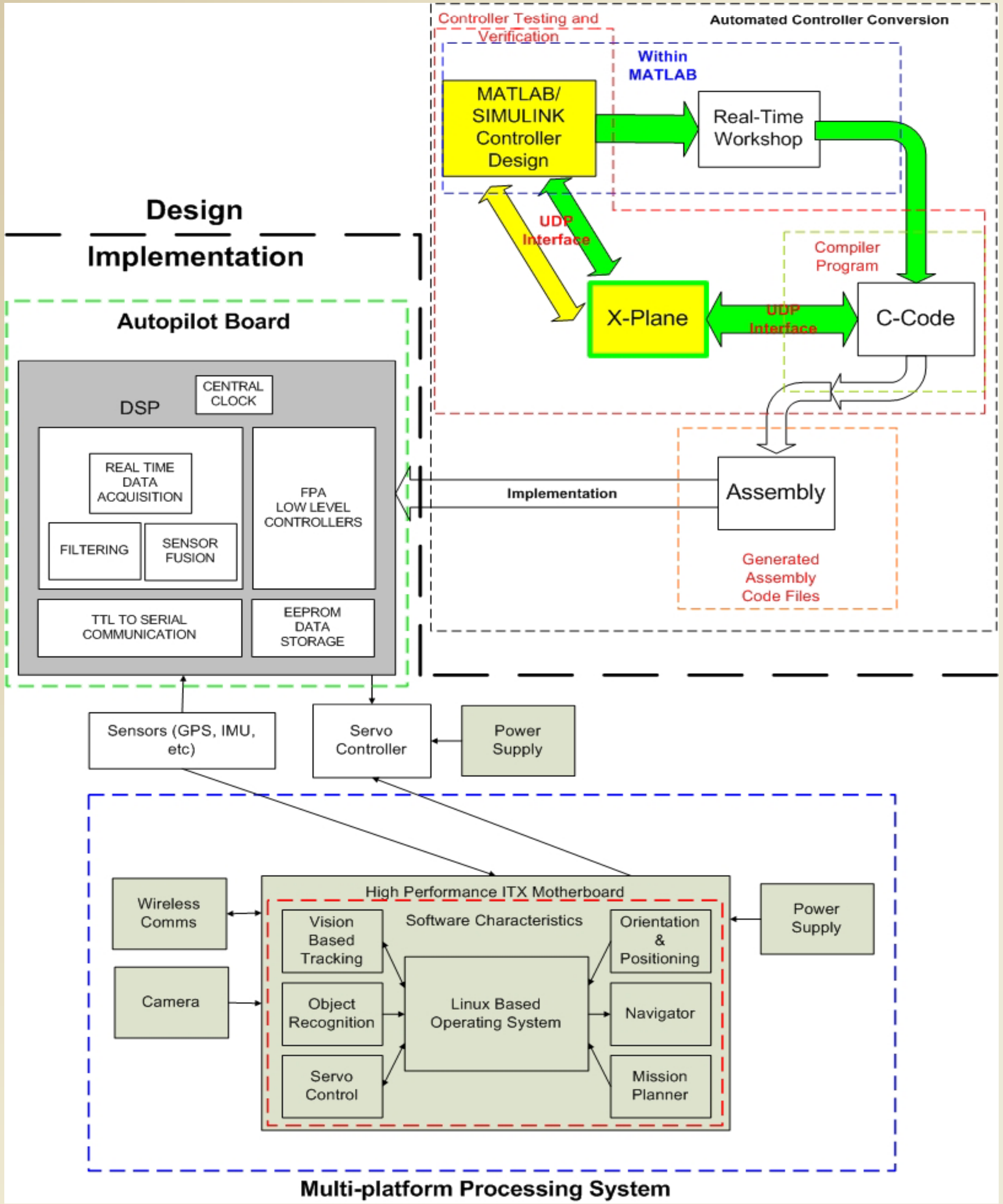




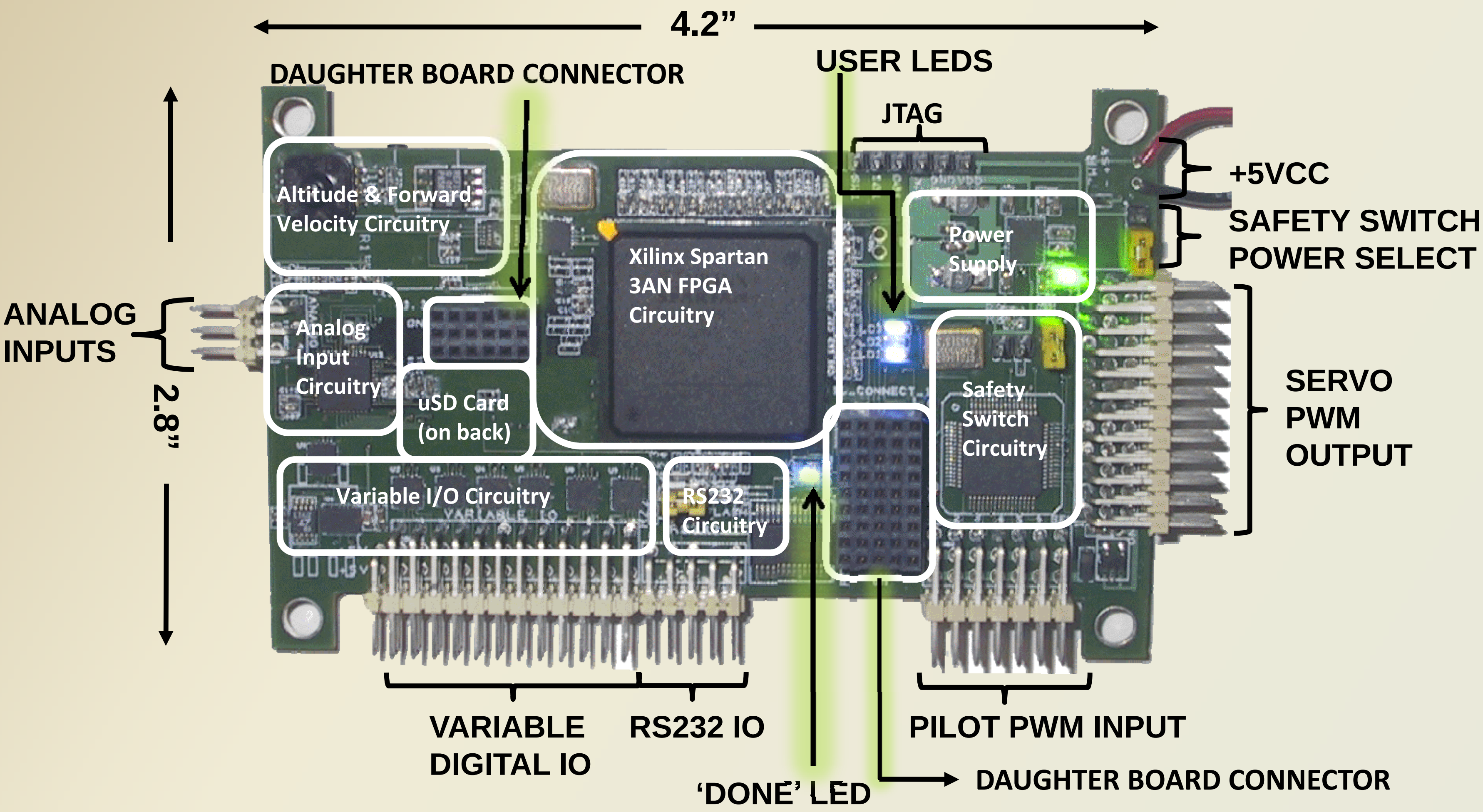
Portable, plug-in / plug-out 'across platform' navigation controllers. Chopper frames, Raptor 90 and Maxi Joker II.



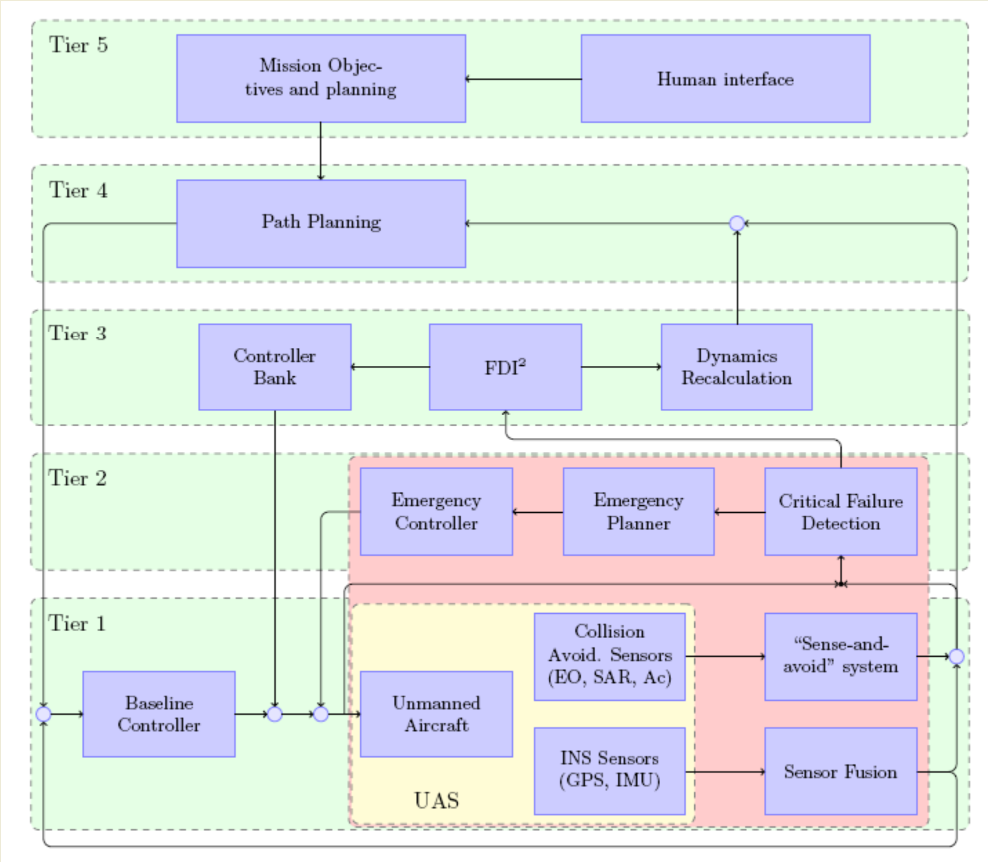
From paper-and-pencil design, to validation and verification, to actual implementation.

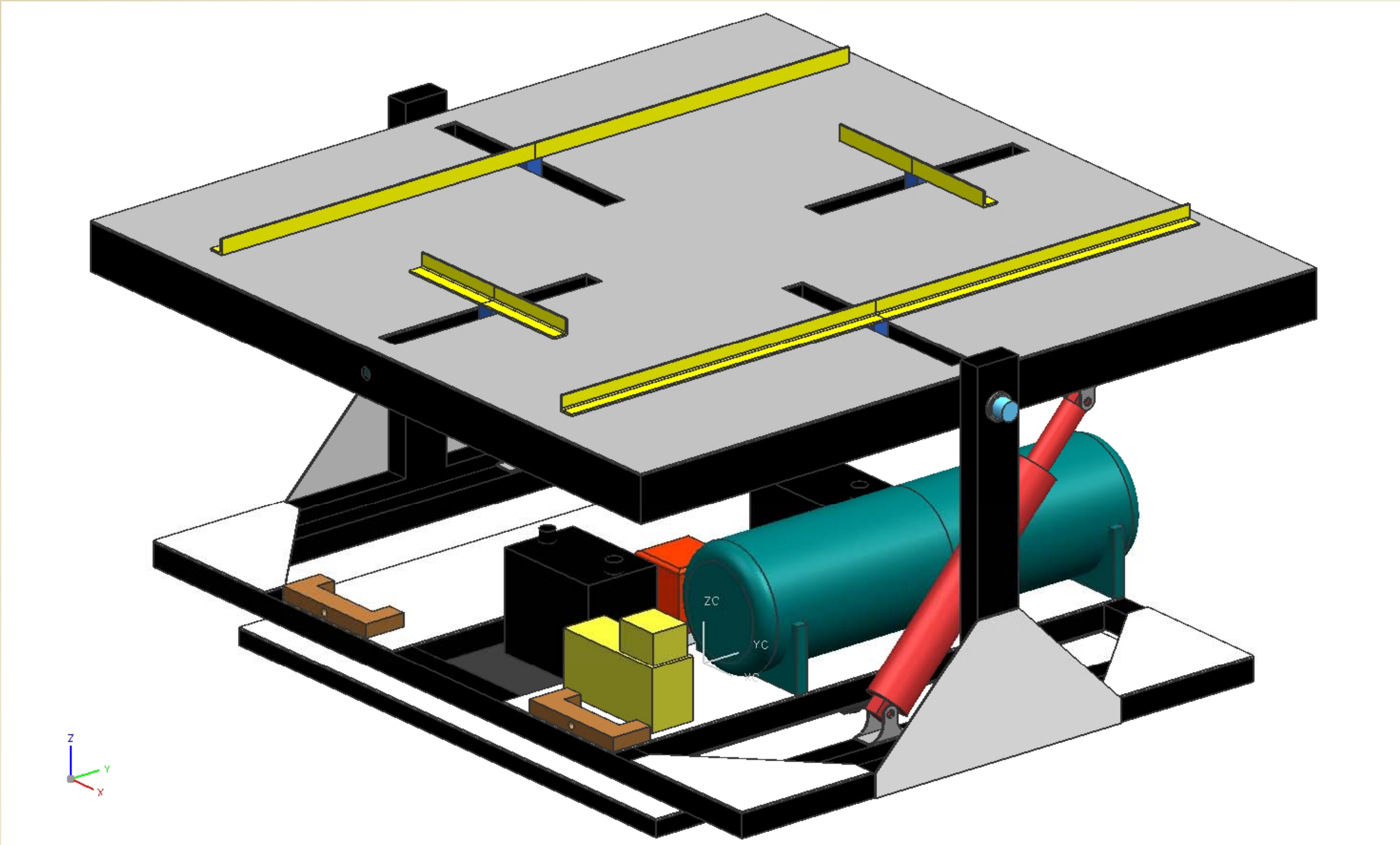


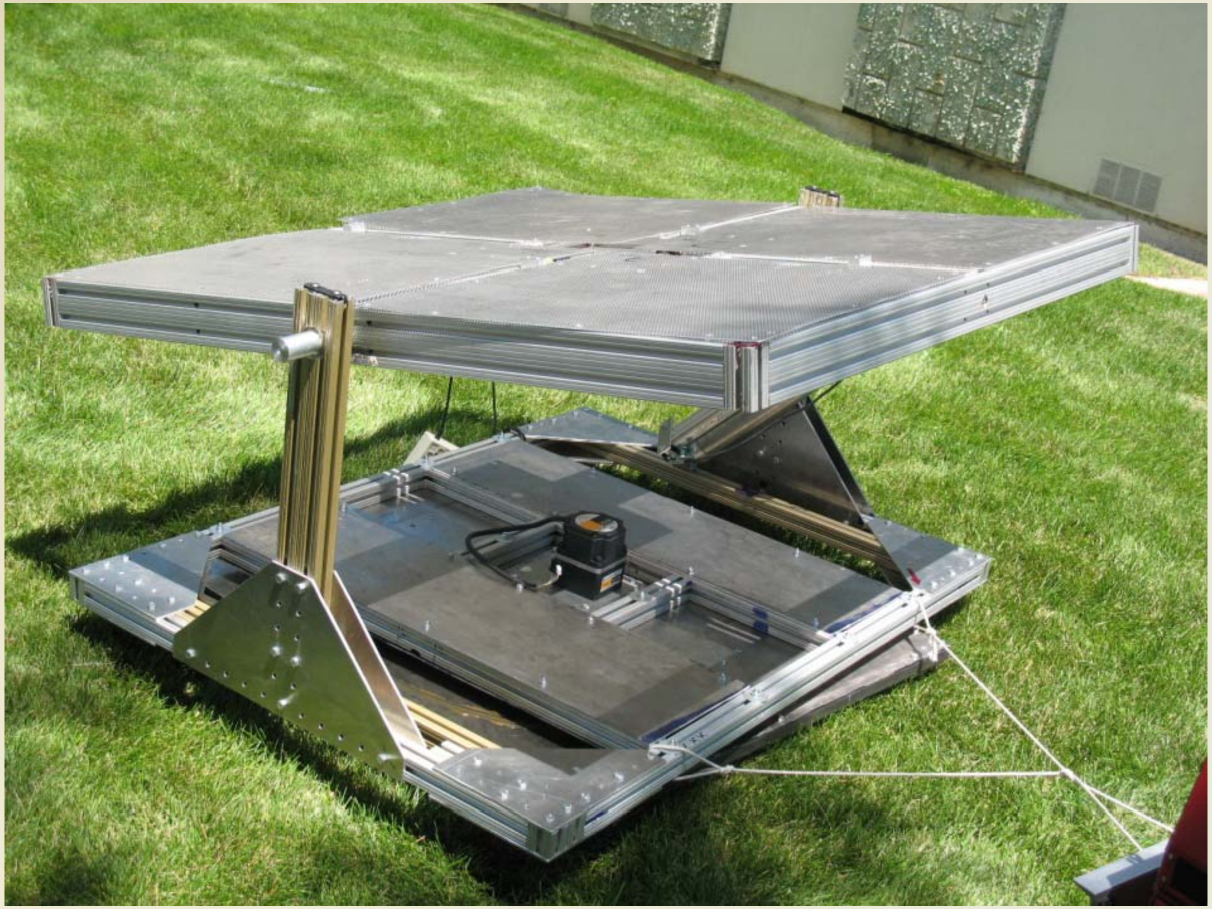
From paper-and-pencil design, to validation and verification, to actual implementation.

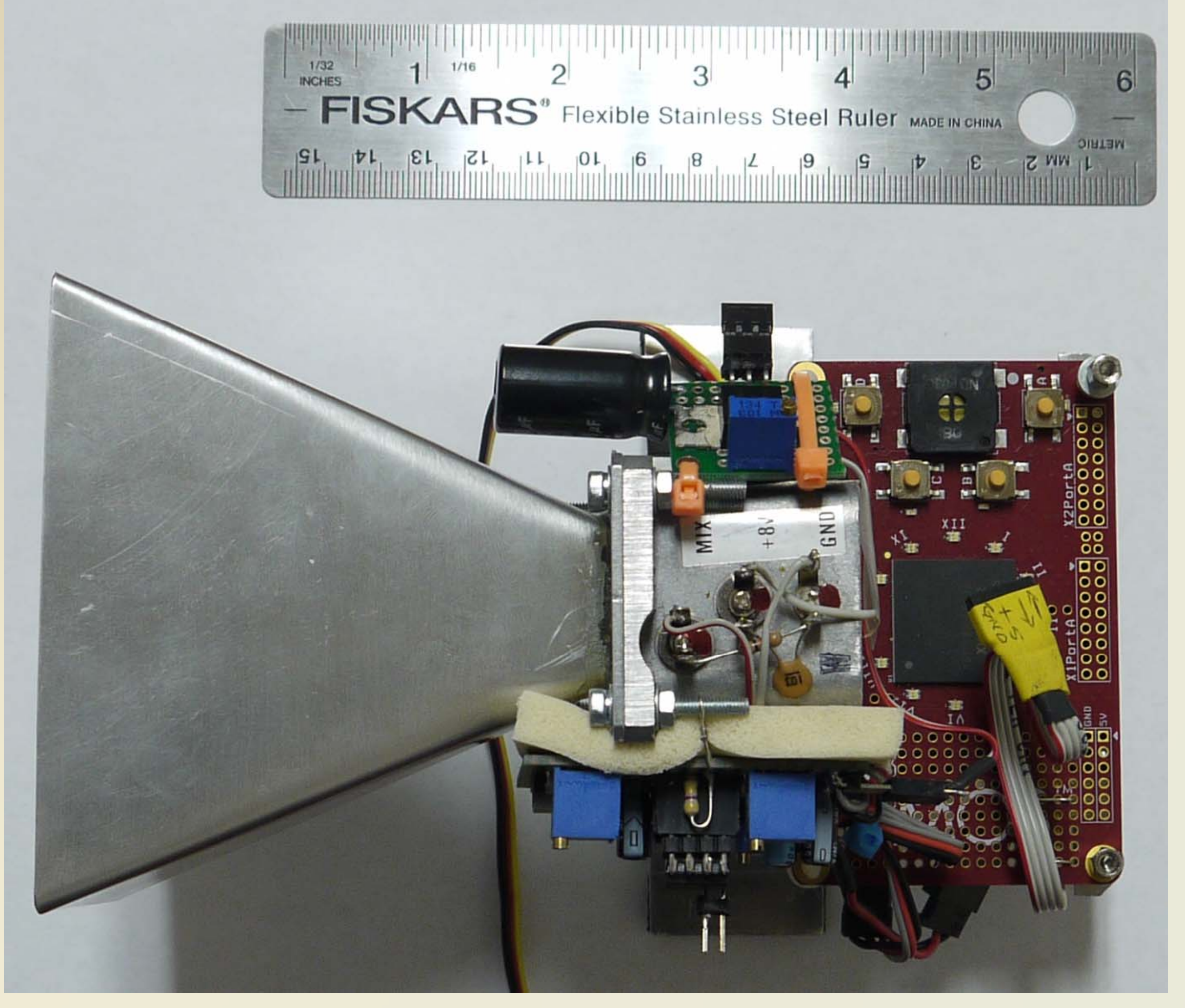

4.2”
DAUGHTER BOARD CONNECTOR
USER LEDS
JTAG
+5VCC
SAFETY SWITCH POWER SELECT
Altitude & Forward Velocity Circuitry
Xilinx Spartan 3AN FPGA Circuitry
Power Supply
ANALOG INPUTS
2.8”
Analog Input Circuitry
uSD Card (on back)
Safety Switch Circuitry
SERVO PWM OUTPUT
Variable I/O Circuitry
RS232 Circuitry
VARIABLE DIGITAL IO
RS232 IO
PILOT PWM INPUT
‘DONE’ LED
DAUGHTER BOARD CONNECTOR

- Miniature Autopilots
- Fail-safe emergency landing systems to comply with future safety requirements

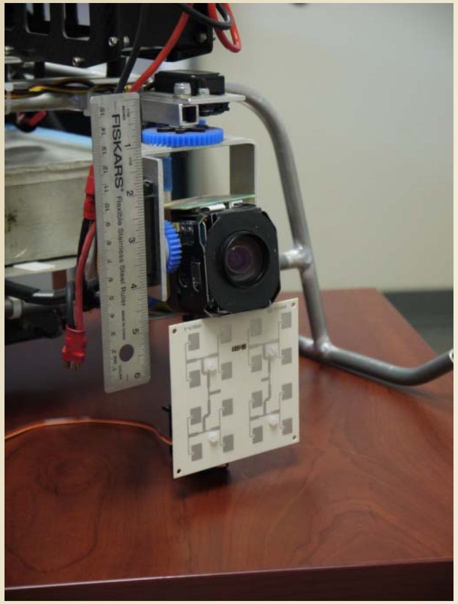


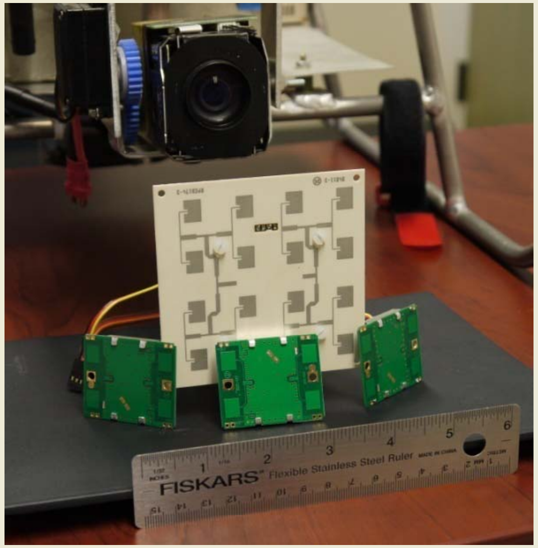

ZC
YC

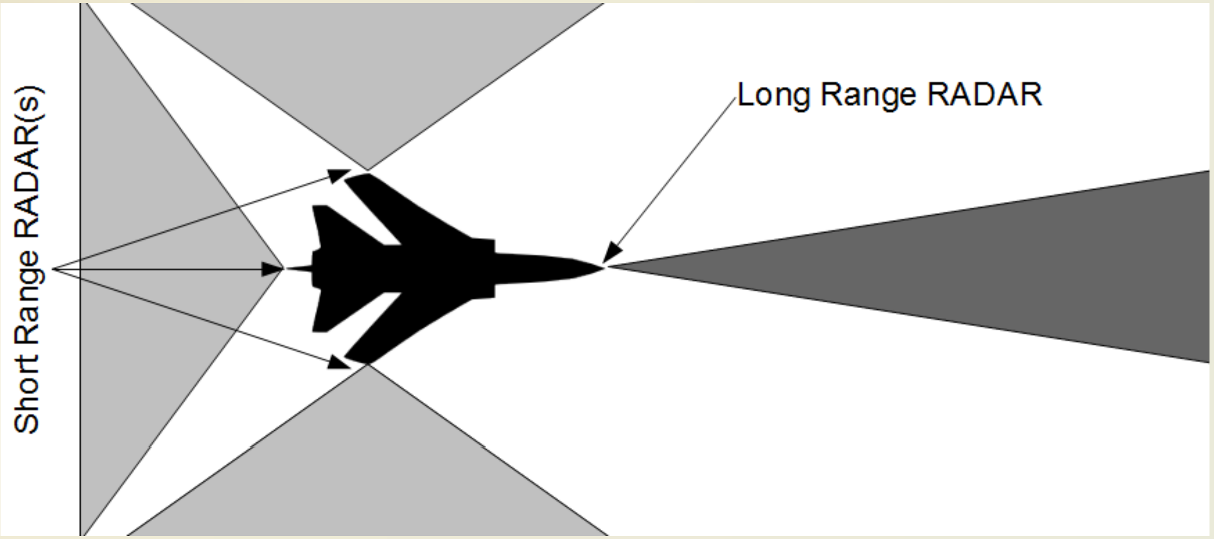




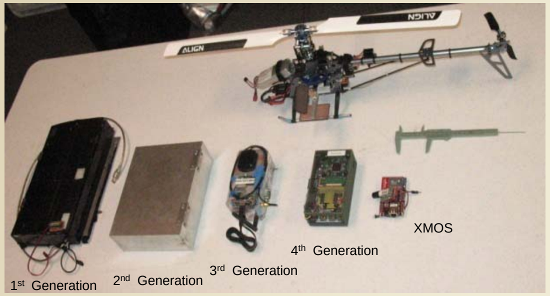
1/32 INCHES
1/16
FISKARS® Flexible Stainless Steel Ruler MADE IN CHINA
METRIC
MIX
+8V
GND
X2PortA
X1PortA

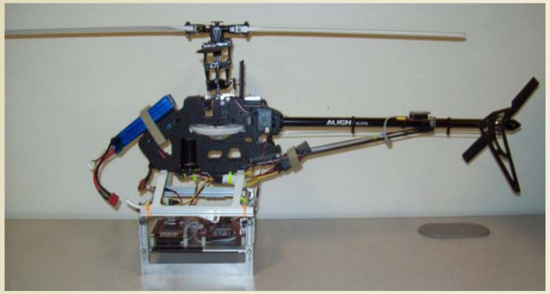

FISKARS

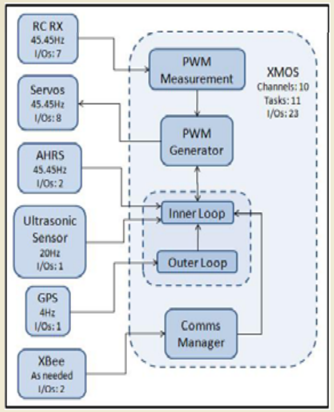

FISKARS Flexible Stainless Steel Ruler


Long Range RADAR
Short Range RADAR(s)

XMOS Based Controllers







Design Goals

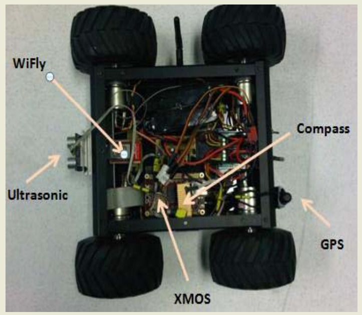
- Increase vehicle homogeneity using a common hardware platform
- Use of commercially available, off-the-shelf components to ensure reliability and low cost
- All-inclusive solution containing all hardware required for autonomous vehicle operation

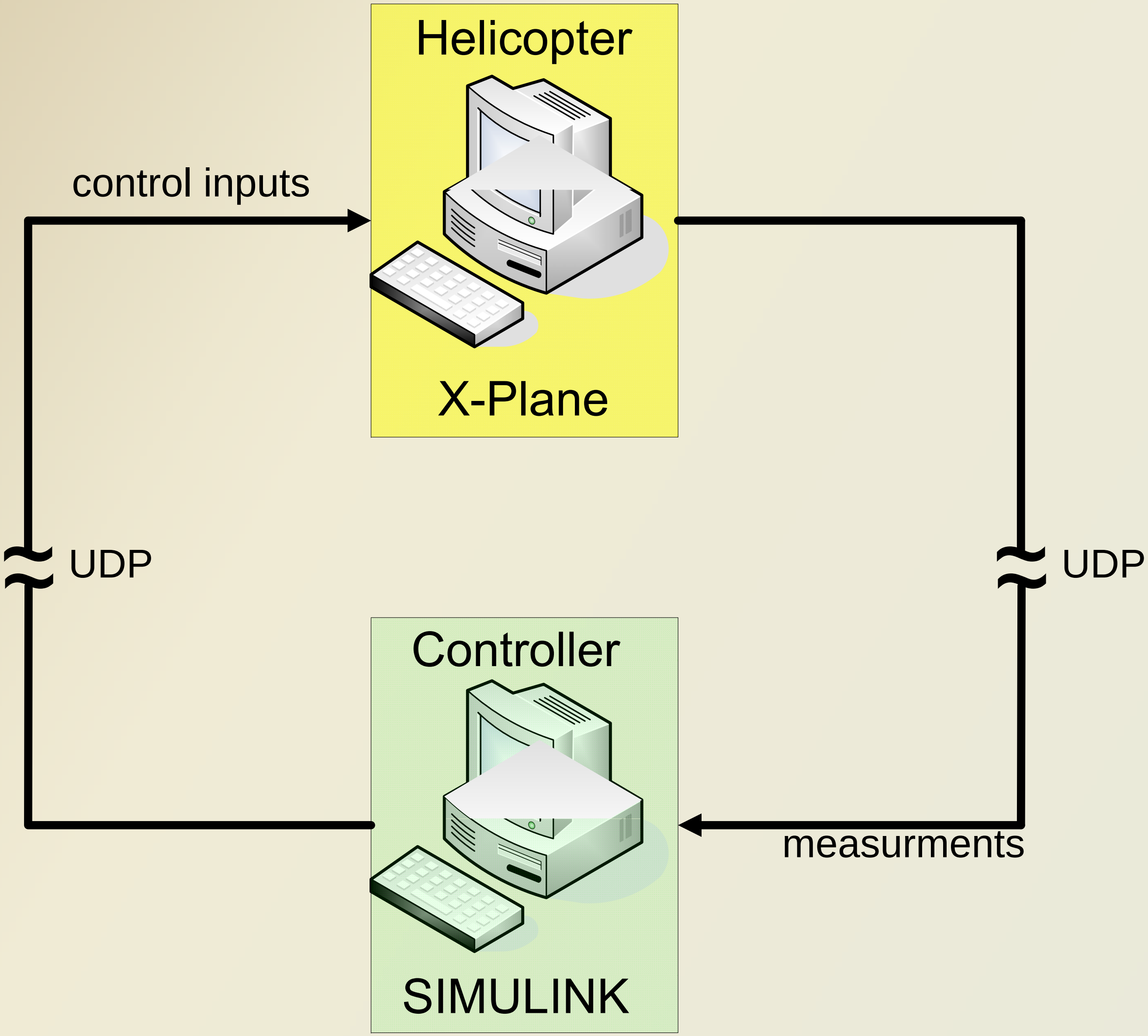
XMOS Characteristics

- Fast I/O interaction (10ns resolution)
- Real time ability (1Core can run 8 independent tasks)
- Scalability (add more cores through Xlink I/Os)
- Programming Languages: XC, C and C++

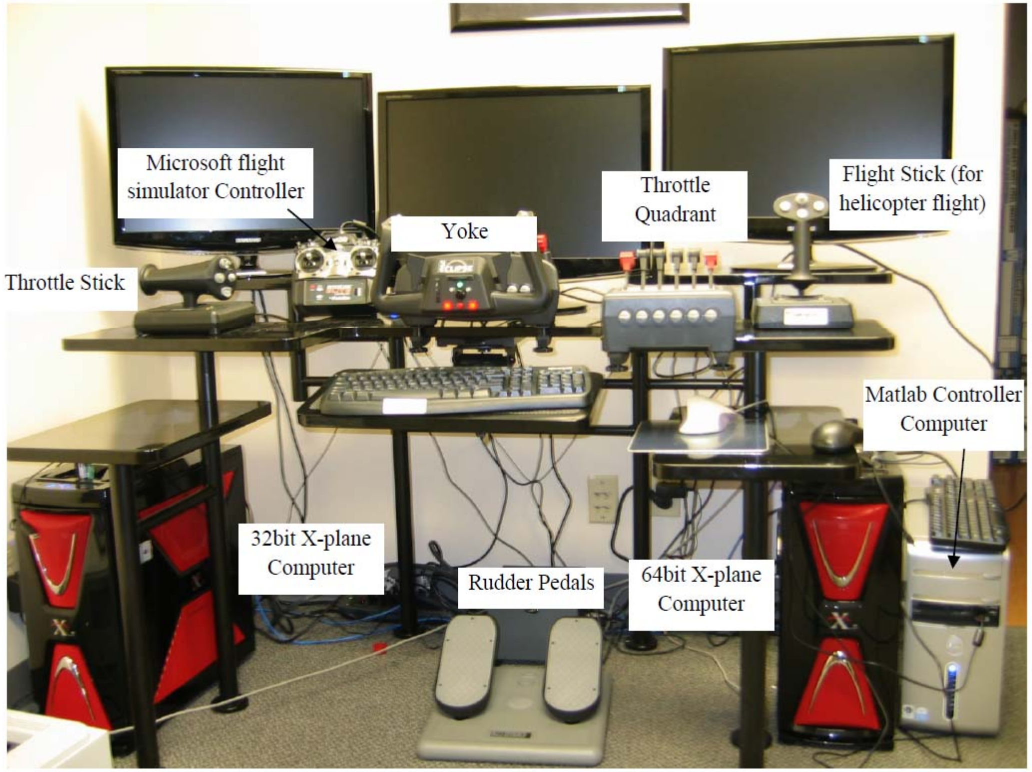
Applications

- Unmanned Aircraft Systems
- Unmanned Ground Vehicles
- Unmanned Underwater Vehicles
- Ground Control Stations




Helicopter
X-Plane
control inputs
UDP
UDP
Controller
SIMULINK
measurments

- ***Ability to demonstrate flight scenario feasibility of single/multiple UAS using X-Plane***
- ***Multiple UAS configuration is UNIQUE!***

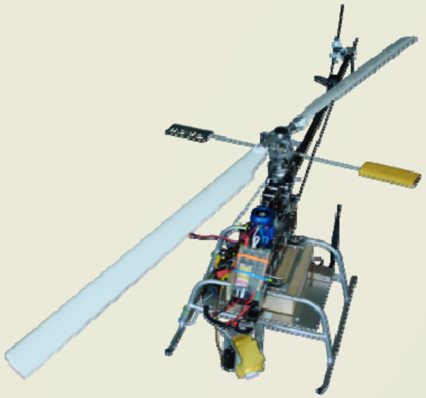

Microsoft flight simulator Controller
Yoke
Throttle Quadrant
Flight Stick (for helicopter flight)
Throttle Stick
Matlab Controller Computer
32bit X-plane Computer
Rudder Pedals
64bit X-plane Computer

Seeing is believing:

Traffic Monitoring-1
Traffic Monitoring-2
DOT_Heli_Traffic_11_29_06.wmv
Traffic-3
Traffic-4
Traffic-5
Tracking Ground Robots
PositionHold.wmv
Autonomous Flight-1
Autonomous Flight-2
UAV-UGV

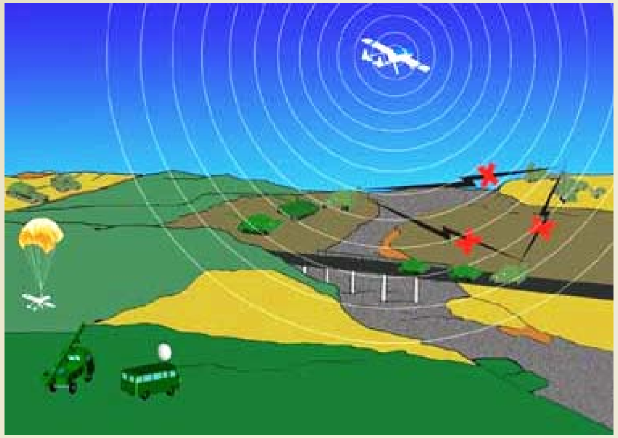
Challenges to overcome BEFORE any integration into the NAS (X-Plane based)
RunningLanding
TailFailure_V2

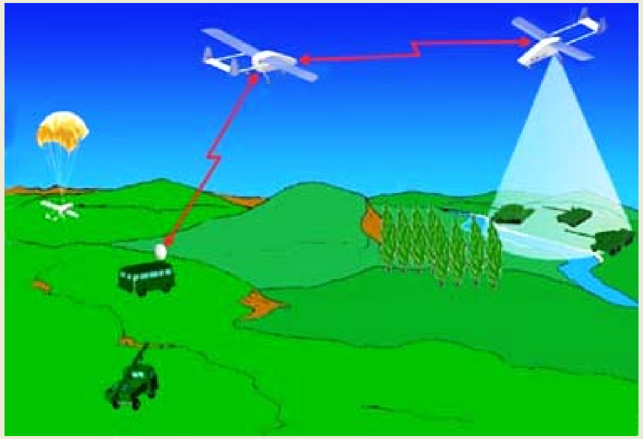
- What are we doing? Why? How? Final Objective?
    - Why Unmanned Rotorcraft (< 150 Kgr)?
- Control and Controller Design Challenges
- Linear and Nonlinear Controller Design
- Emergency Landing System
    - Nonlinear MPC + Recurrent NN
    - Autonomous vertical autorotation
- On integrating UAS into the NAS



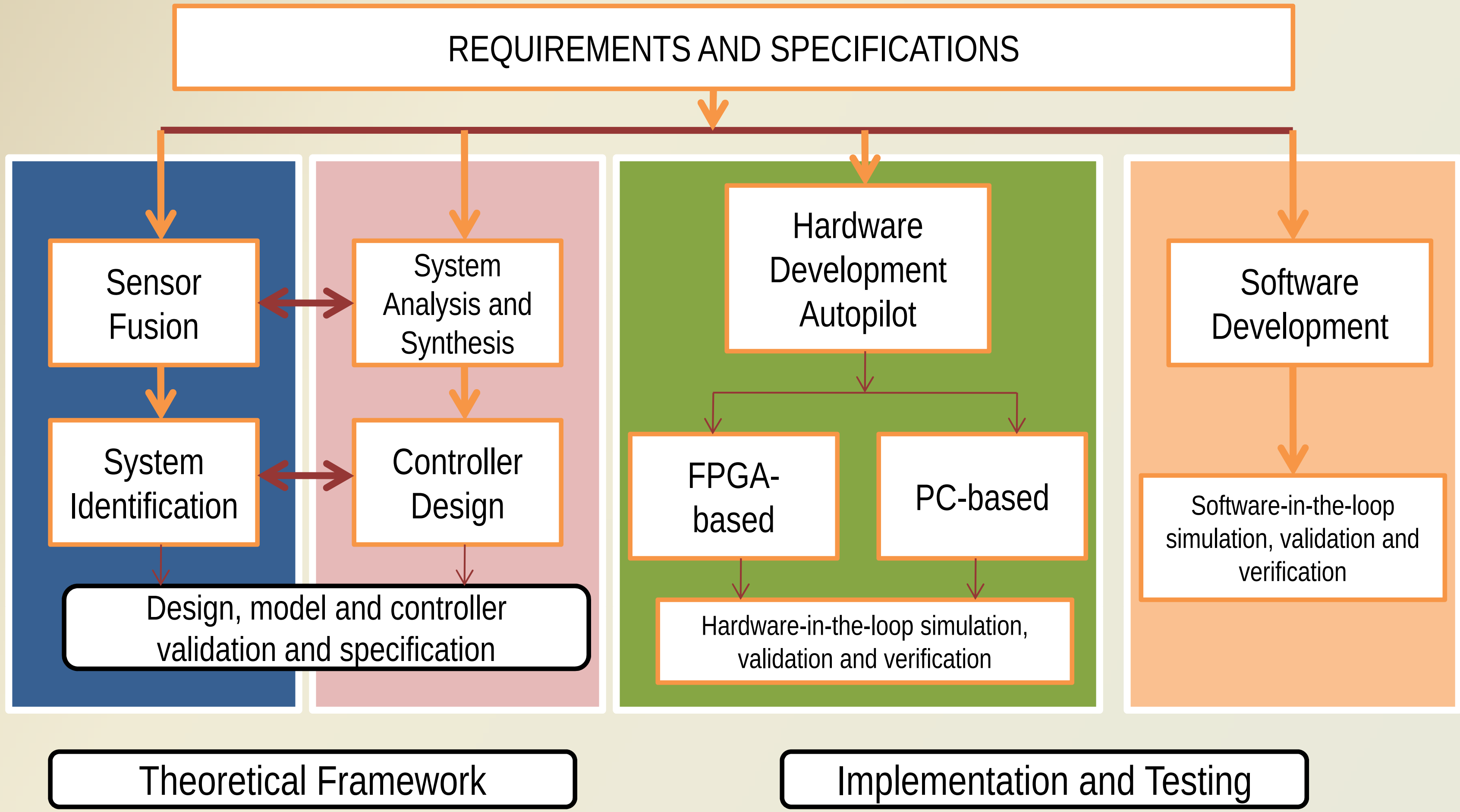
Focus on light rotorcraft, and be prepared for the new era of NAS operations

- ❑Design and build stable navigation controllers with fault tolerance
- ❑Design emergency systems to overcome failures in real-time
- ❑Develop experimentally proven and reliable technology
- ❑ Address safety issues through technology
    - ❑ Enhance onboard intelligence to overcome issues with lost communications
    - ❑ Enhance vision systems and alternative sensors to provide true see-and-avoid capability
- ❑ Obtain FAA experimental (and later on full) certification

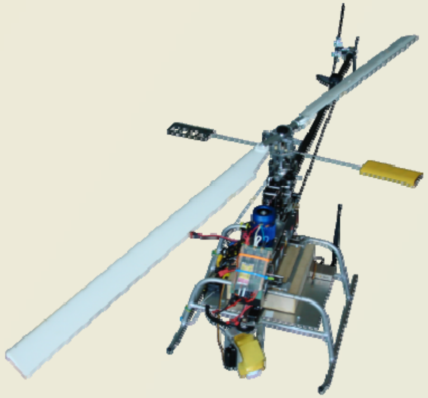




Concurrent Engineering Methodology

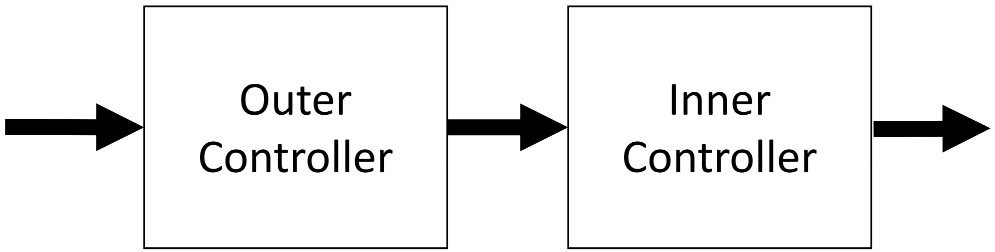


Challenges

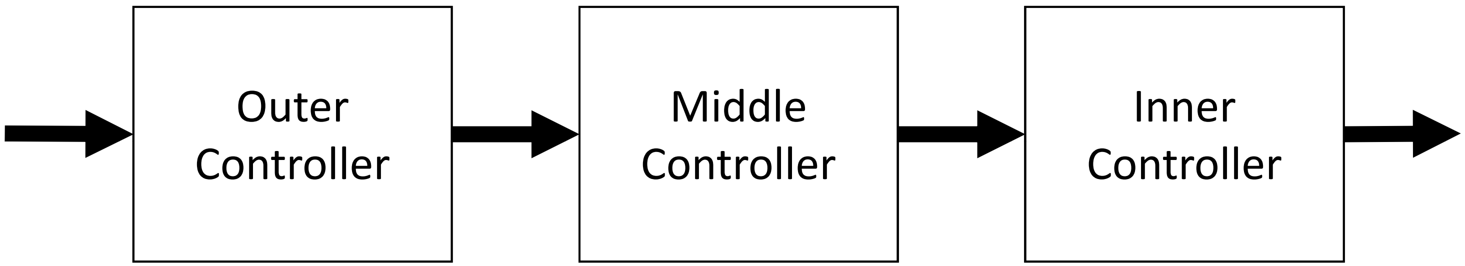


- Open-loop unstable (Planes fly, helis crash!)
  - E.g.: Hovering is open loop unstable
- High degree of coupling
  - Control channels have high interdependence
- Nonlinear behavior
  - Linearization works in small regions
- Dynamics spanning wide range of frequencies
- Fast dynamics
  - High sampling 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

TYPICAL FLIGHT CONTROL SYSTEMS ARCHITECTURE

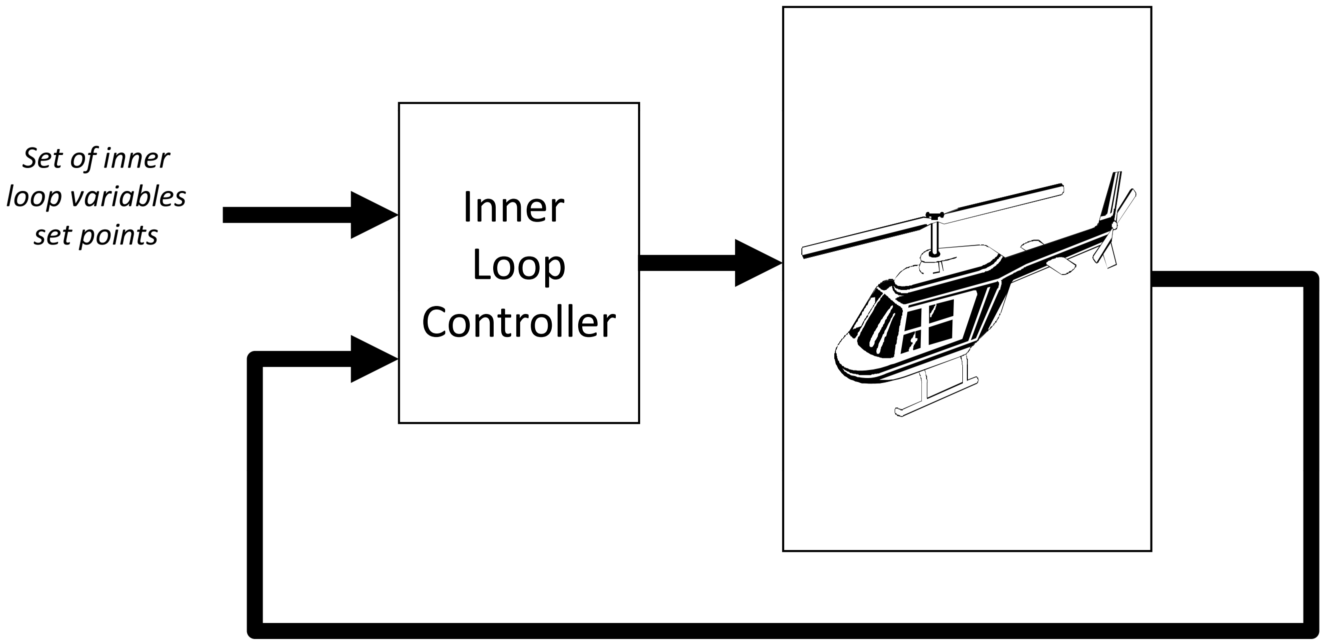


(a)

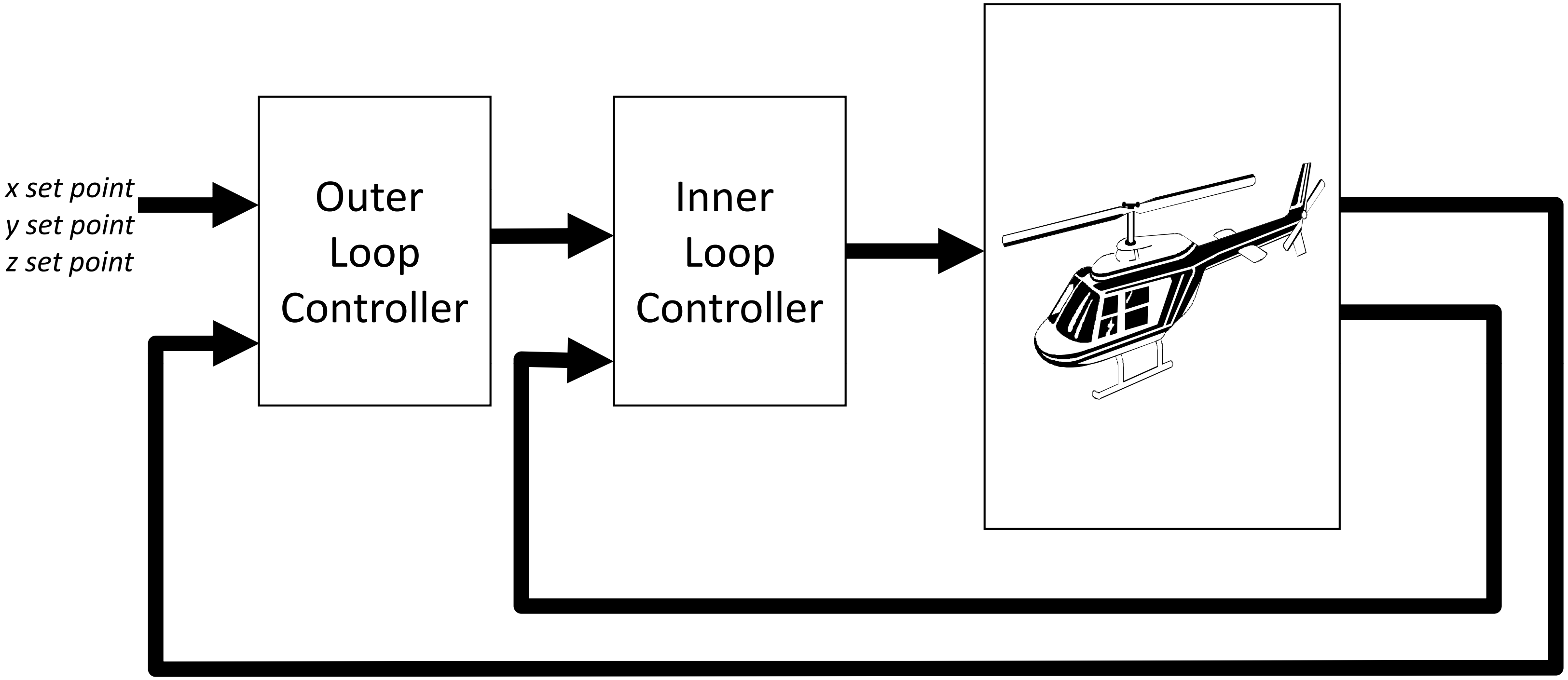


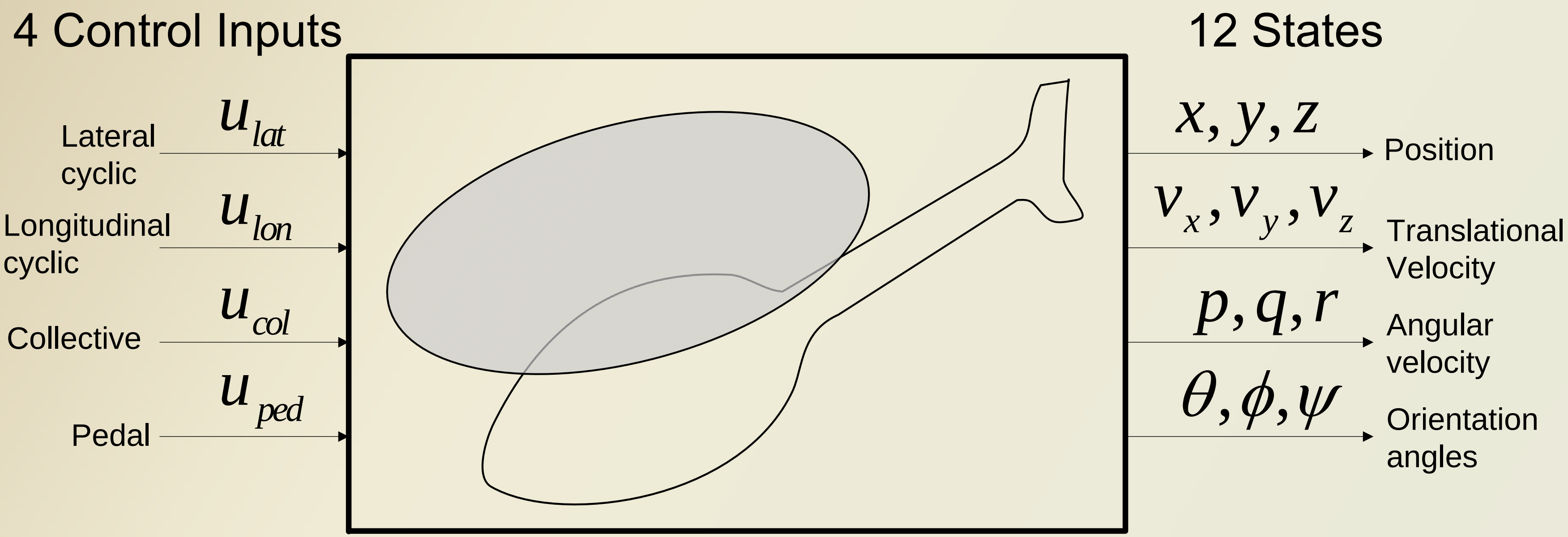
(b)

- **Inner Loop Controller**
  - This inner controller manipulates the helicopter's inputs and control the roll angle, the pitch angle, the yaw angle and the altitude.



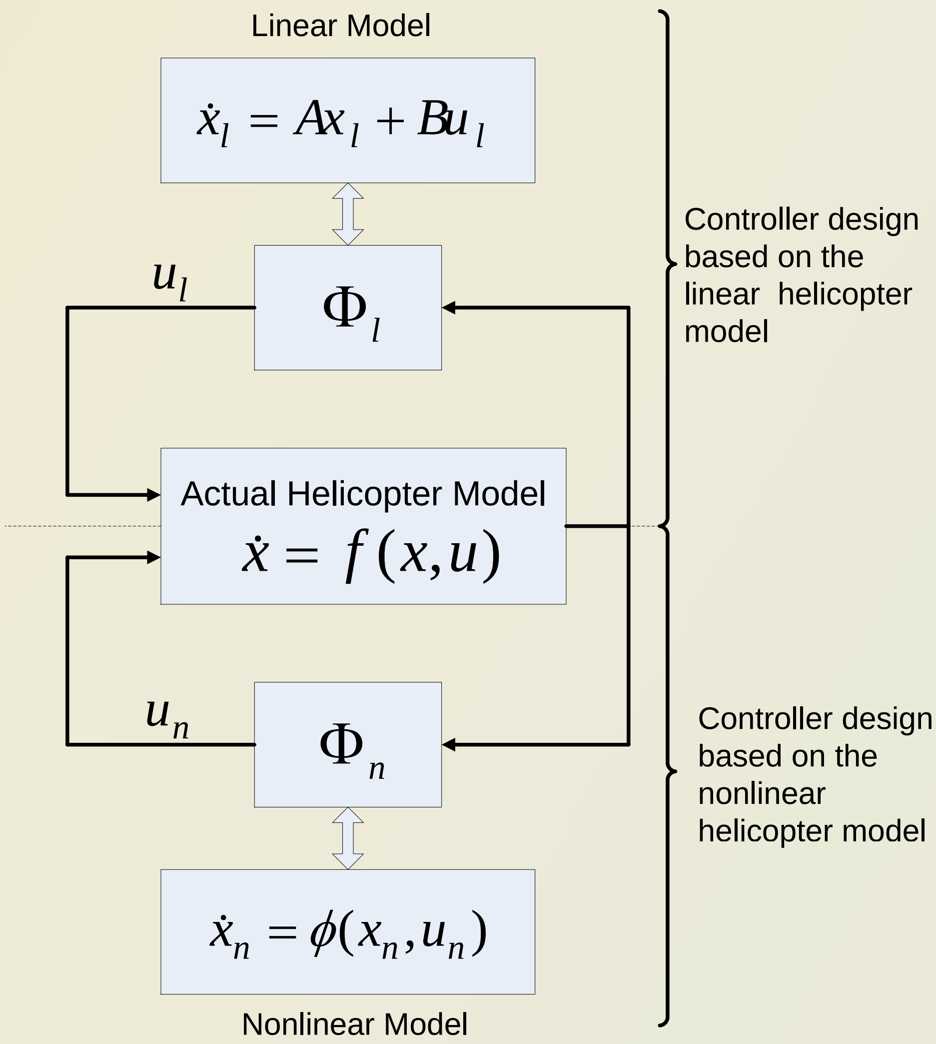
- **Outer Loop Controller**
  - The outer controller provides the set point of the inner controller.

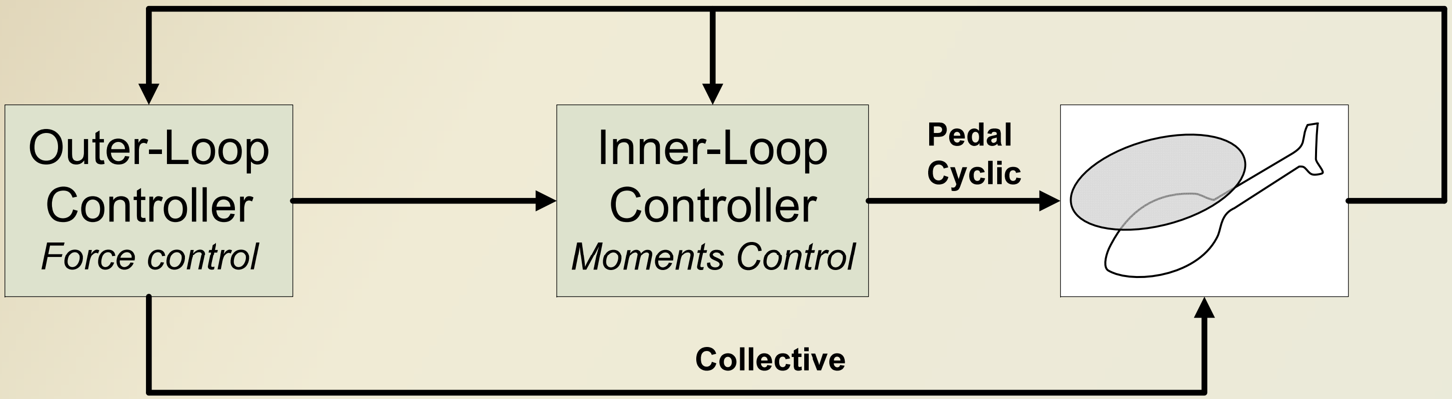




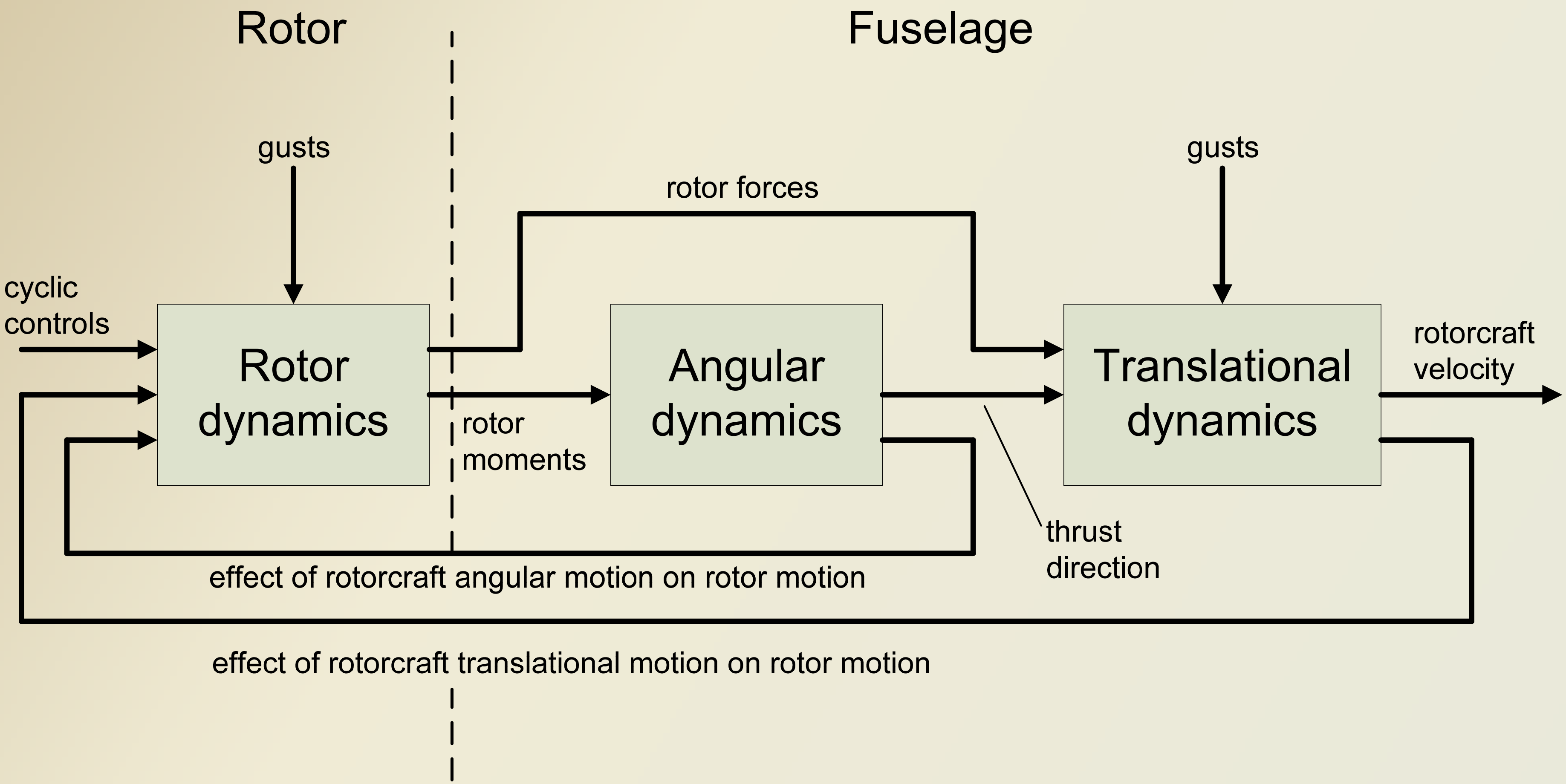
Helicopter as an Input-Output System

The two basic model based controller design approaches for unmanned rotorcraft

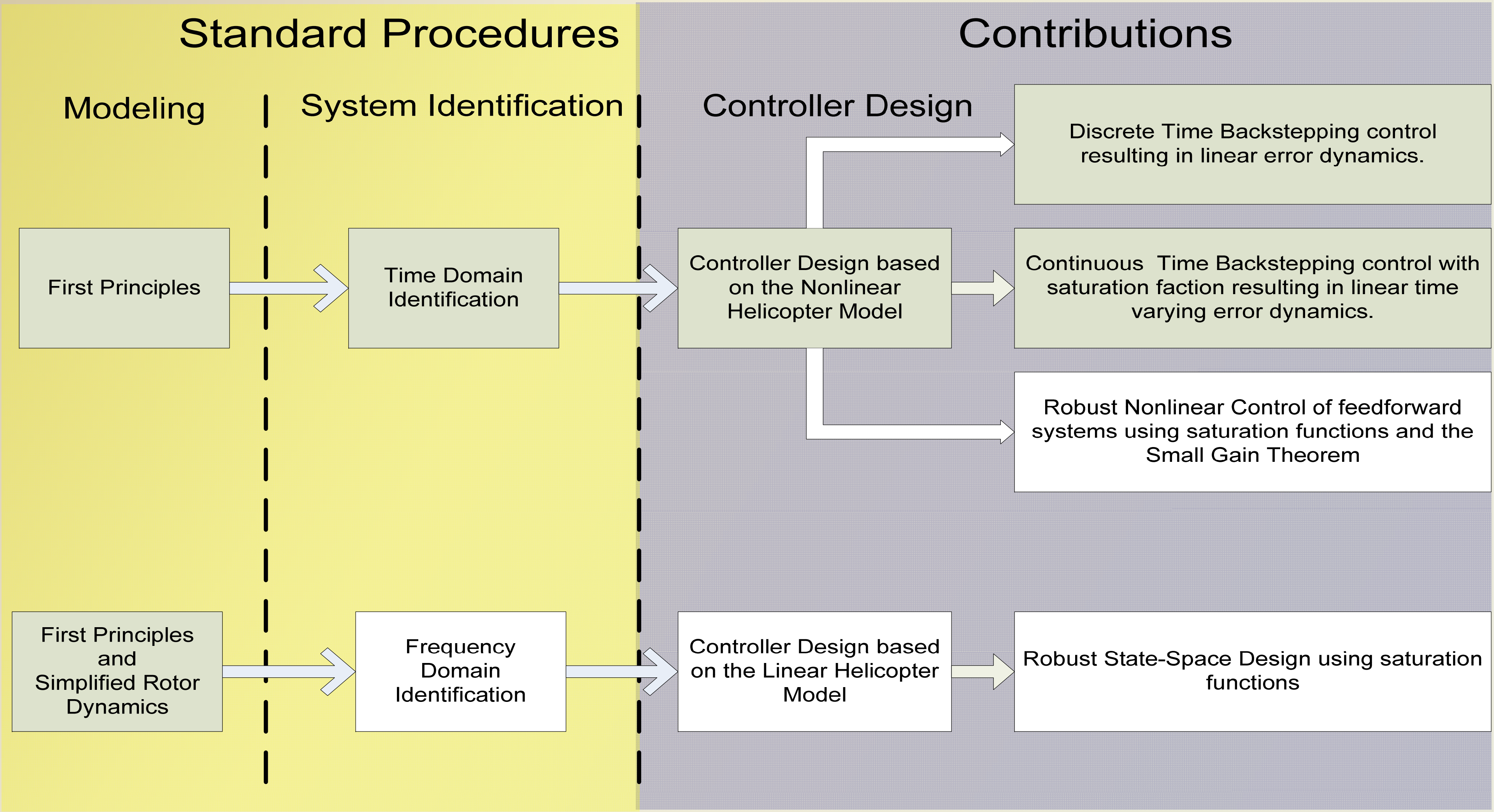




Typical Linear Controller Design



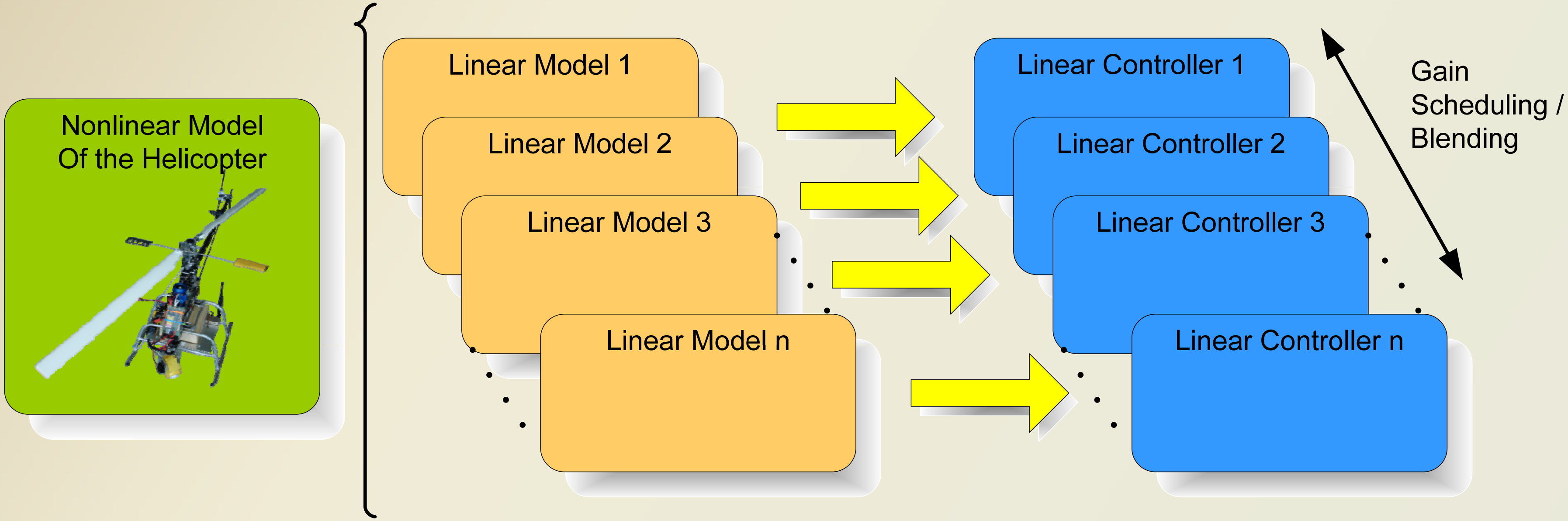
Rotorcraft Subsystem Block Diagram


Standard Procedures
Contributions
Modeling
System Identification
Controller Design
Discrete Time Backstepping control resulting in linear error dynamics.
First Principles
Time Domain Identification
Controller Design based on the Nonlinear Helicopter Model
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

	Advantages	Disadvantages
Linear Model	•Simpler controller design based on a variety of techniques for linear systems	•The controller is effective only for a region of an operating condition. Different controllers should be applied in each operating condition
Nonlinear Model	•It is a unique global model •It only requires the design of a single controller for all the operating conditions	•The controller design requires much more sophisticated tools.

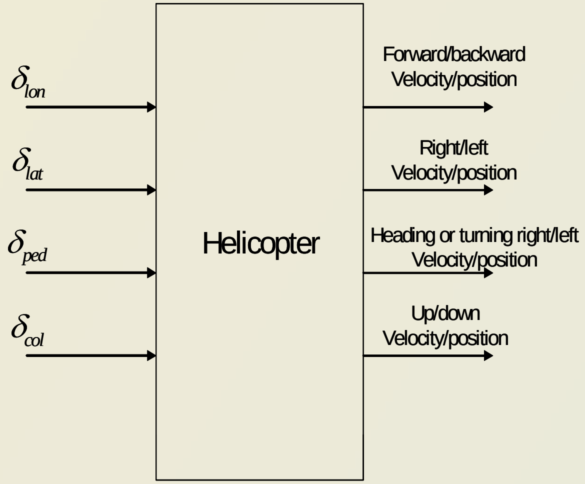
Controller design based on linear vs nonlinear model

Handling Nonlinearity through Linearization and Gain Scheduling



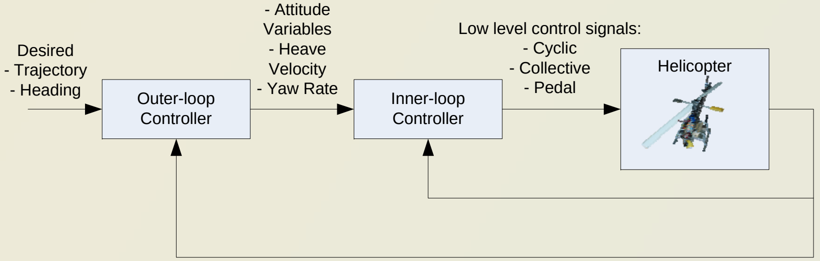
Considerations

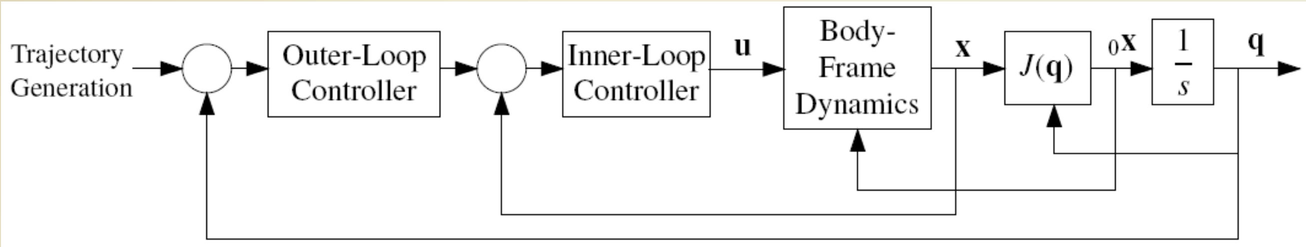
- Non-aggressive flight
  - Configuration space: change position in 3D and heading ($R^3 x S^1$).
  - Two regimes considered:
    - Hovering (includes slow motion).
    - Forward Flight.
  - Decomposition:
    - Outer loop: guidance
      - Velocity, position commands
    - Inner loop: control
     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



Input	**Output**
Lateral Cyclic Longitudinal Cyclic	Position in horizontal plane
Collective	Altitude
Pedal	Yaw

Inner/Outer Loop Decomposition





- 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 (ψ).

Mode 1	$\lambda_1 = 0.3061 \pm 0.0939i$
Mode 2	$\lambda_2 = -0.4007 \pm 0.0862i$
Mode 3	$\lambda_3 = -0.6078$
Mode 4	$\lambda_4 = -1.6977 \pm 8.1884i$
Mode 5	$\lambda_5 = -2.6605 \pm 11.5571i$
Mode 6	$\lambda_6 = -6.1981 \pm 8.1967i$
Mode 7	$\lambda_7 = -20.3125 \pm 4.7429i$

Mode 1	$\lambda_1 = 0$
Mode 2	$\lambda_2 = 0$
Mode 3	$\lambda_3 = -0.1220$
Mode 4	$\lambda_4 = -0.1550$
Mode 5	$\lambda_5 = -1.0100$
Mode 6	$\lambda 6 = -2.3247 \pm 8.8898i$
Mode 7	$\lambda_7 = -3.3662 \pm 12.3914i$
Mode 8	$\lambda_8 = -5.8500 \pm 7.3314i$
Mode 9	$\lambda_9 = -27.0718 \pm 7.0303i$

- Main modes that characterize system dynamics calculated and analyzed.
- To obtain the dynamic response unitary eigenvectors have been used as initial conditions to excite the specific modes and to obtain dynamic response.
- 7 modes for hovering, 9 for cruising

Controllability and Observability

- Controllability and observability matrices have numerical issues.
- Better: decompose the system into controllable and uncontrollable subspaces to count the number of controllable states.
  - Matlab ‘ctrfb’ command for controllability check
- Same approach for observability
  - Matlab ‘obsvf’ command for observability check
- Result: plant is controllable and observable
  - 13 controllable states
  - 13 observable states

Input-Output Pairing

- Best input-output pairing
  - Relative Gain Array analysis in DC

$$\lambda_{ij} = \left[\mathbf{G_o}(0)\right]_{ij}\left[\mathbf{G_o}^{-1}(0)\right]_{ji} \qquad \Lambda_3 = \begin{bmatrix} 0.8529 & 0.1471 & 0.0000 & -0.0000 \\ 0.1471 & 0.8529 & 0.0000 & -0.0000 \\ -0.0000 & 0.0000 & 1.0156 & -0.0156 \\ -0.0000 & 0.0000 & -0.0156 & 1.0156 \end{bmatrix}$$

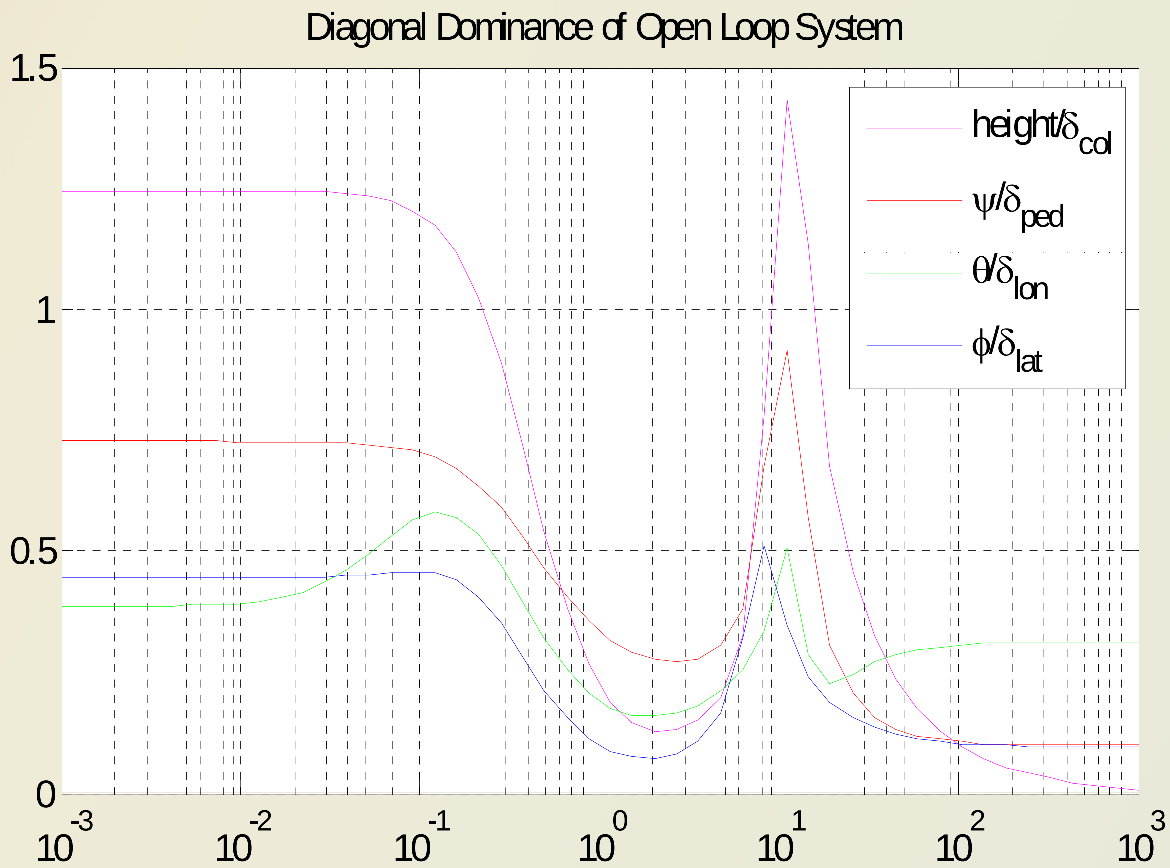
$$\delta_{\text{lat}} \to \phi \qquad \delta_{\text{lon}} \to \theta \qquad \delta_{\text{ped}} \to r \qquad \delta_{\text{col}} \to w$$

  - Also matches physical characteristics of helicopter
  - Interpretation:
    - Lateral control is associated with the roll
    - Longitudinal control is associated with pitch
    - Pedal control changes the yaw rate
    - Collective control changes the heave velocity

Diagonal Dominance, Open-Loop

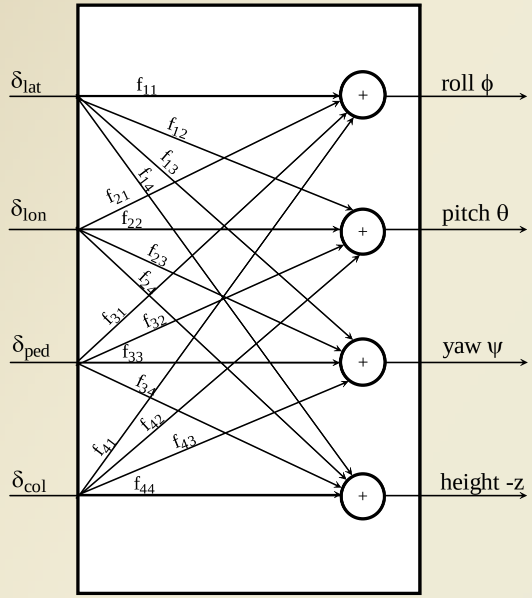
$$\phi_c(j\omega) = \frac{\sum_{\substack{r=1 \\ r \neq c}}^{n} \left| z_{rc}(j\omega) \right|}{\left| z_{cc}(j\omega) \right|}$$

- Calculated for all of the inner loop variables.
- Yaw, pitch and roll all below required value.
- Results indicate that maximum diagonal dominance for the height/collective is approximately 1.5. This is only slightly above recommended limit
- Inner loop control to be treated as four SISO controllers.

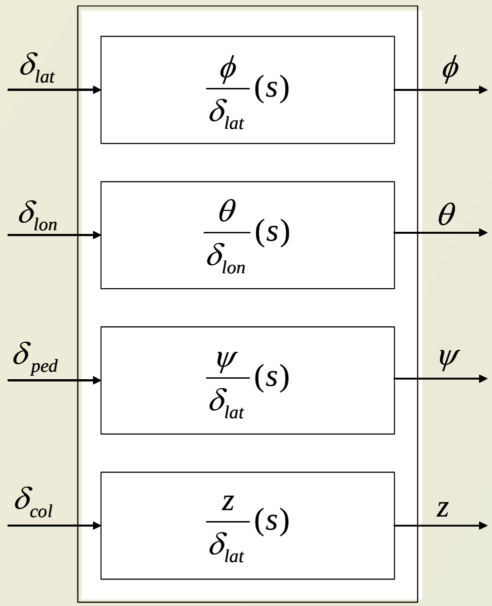


Decentralized Control

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

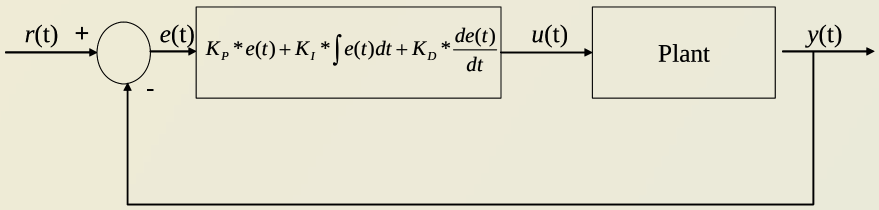
PID Controllers

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

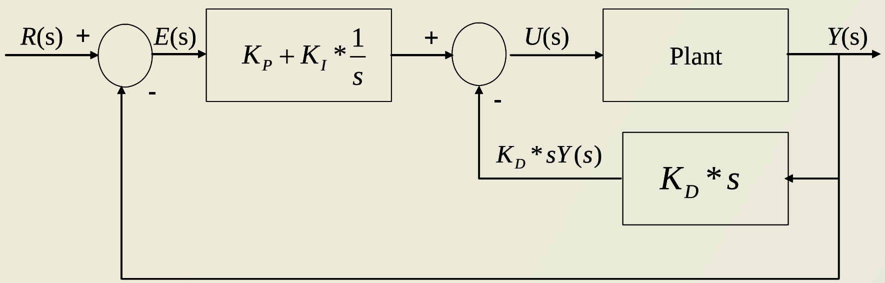
$$u(t) = K_P * e(t) + K_I * \int e(t)dt + K_D * \frac{de(t)}{dt}$$

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

- 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.



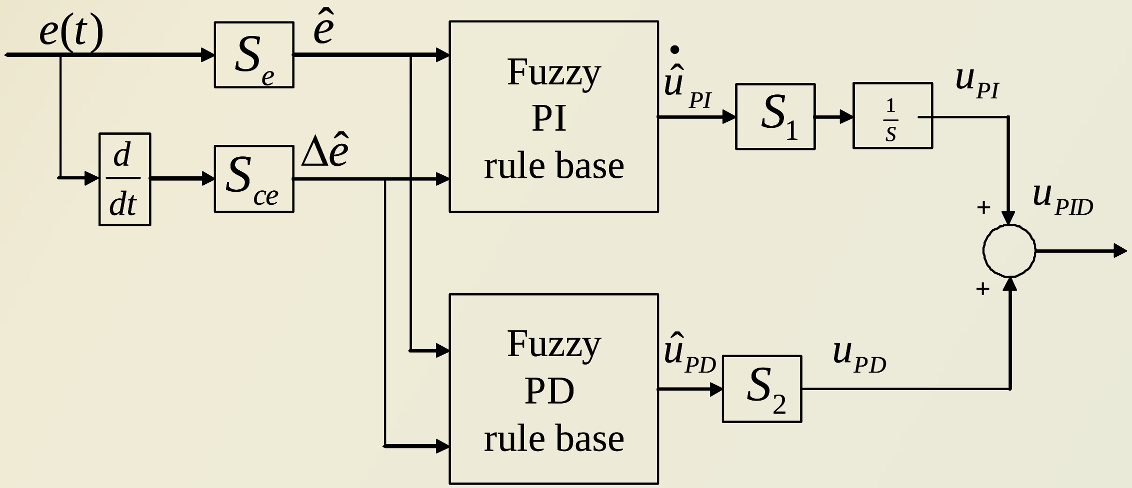
SISO PID closed loop control



Rate feedback PID control

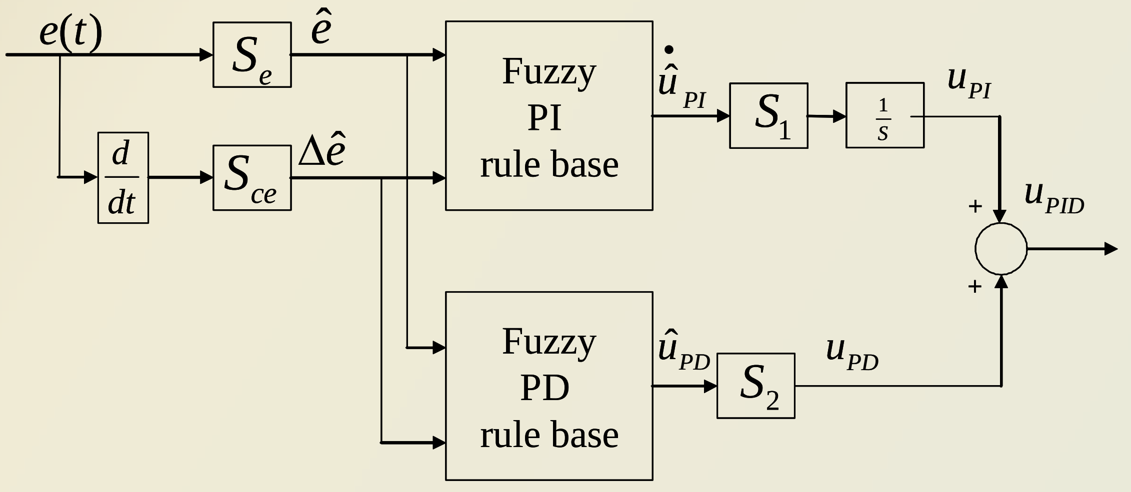
PD-like Fuzzy Logic Controller

- The error *e*(t) is defined as the difference between the desired signal value (set point) and the real value of the controlled variable
- Δ*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..



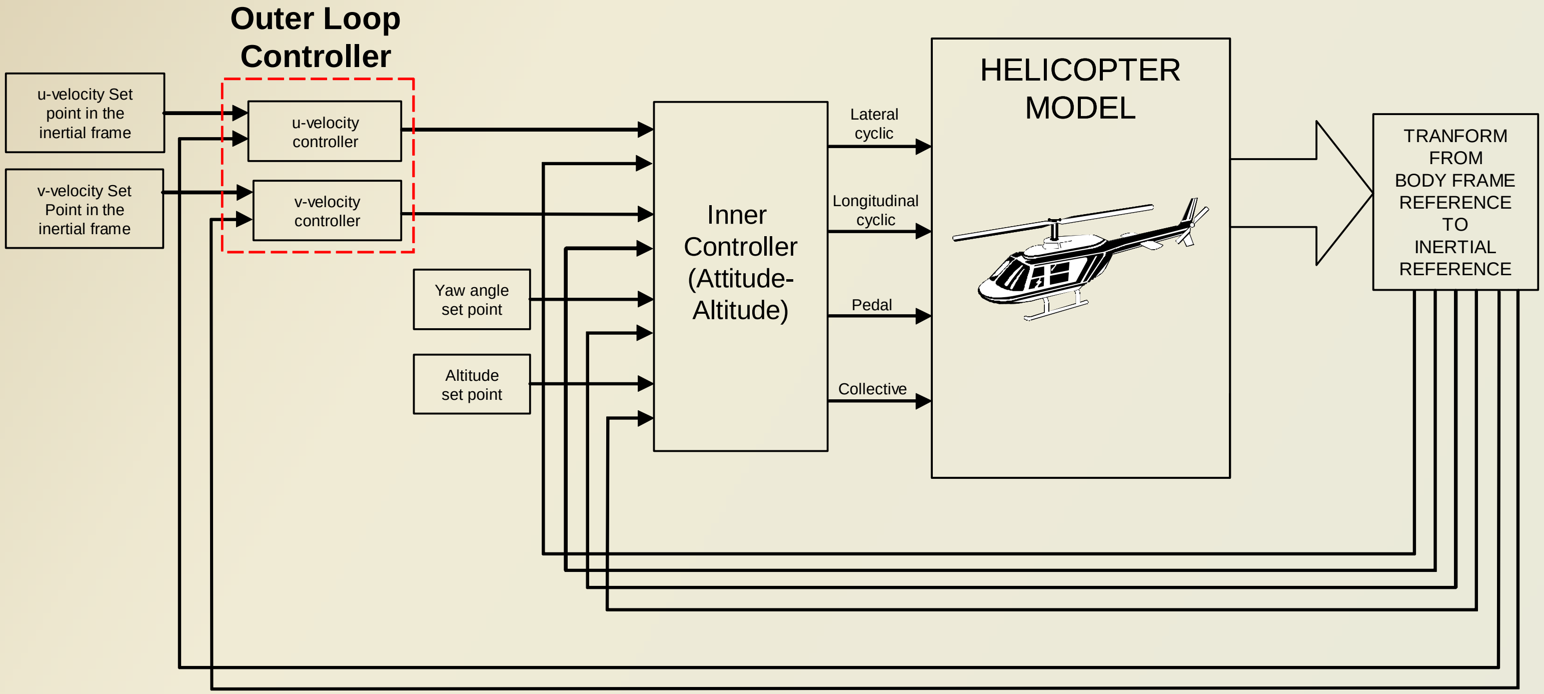
PID-like Fuzzy Logic Controller

- The error e(t) is defined as the difference between the desired signal value (set point) and the real value of the controlled variable.
- Δe(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.



Implementation

- The Control System implemented consists of
  - A Attitude-Height (Inner Controller)
  - A Inertial Position (Outer Controller)



Optimization Based Controller Design

- Based on results of diagonal dominance analysis, MIMO model may be treated as a set of multiple independent SISO systems.
- Helicopter controller implemented sing a set of SISO controllers.
- Because of complexity of transfer functions obtained for each of independent SISO systems, optimized-based controller was implemented.
- An iterative approach followed to obtain parameters of the Height, Yaw, Pitch and Roll Controllers.

Optimization

- The objective function used was the Integral of the Absolute Error (IAE)

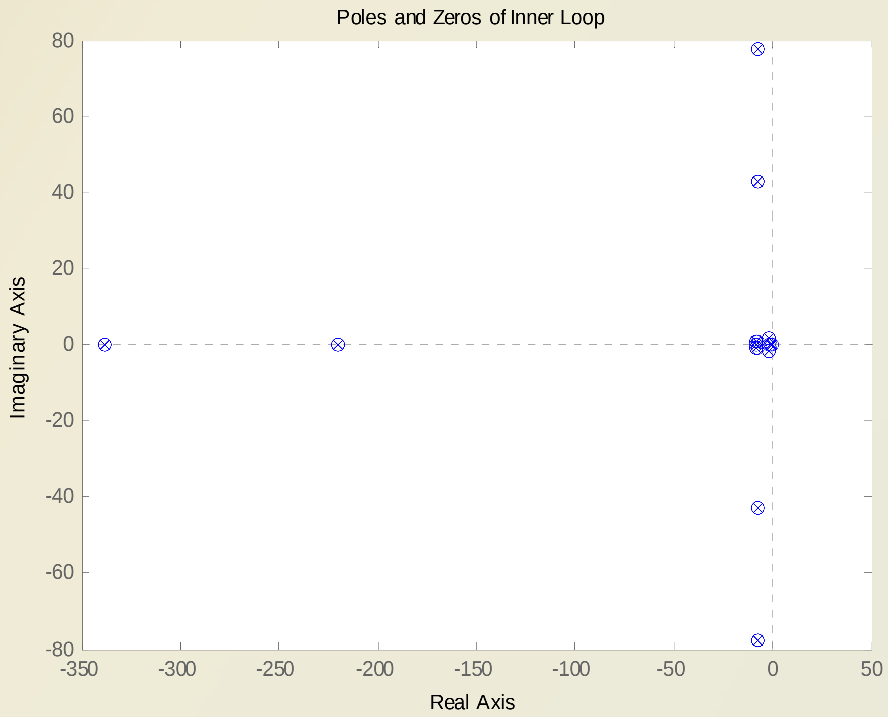
$$\mathrm{IAE}=\int |e(t)|\,dt$$

- Each controller was optimized when the other controllers had a fixed set point.

- The optimization was implemented using Matlab Optimization toolbox.

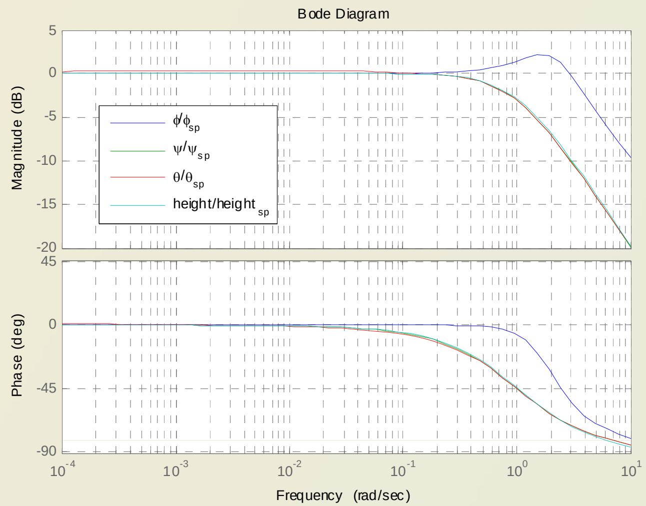
Inner Loop Stability

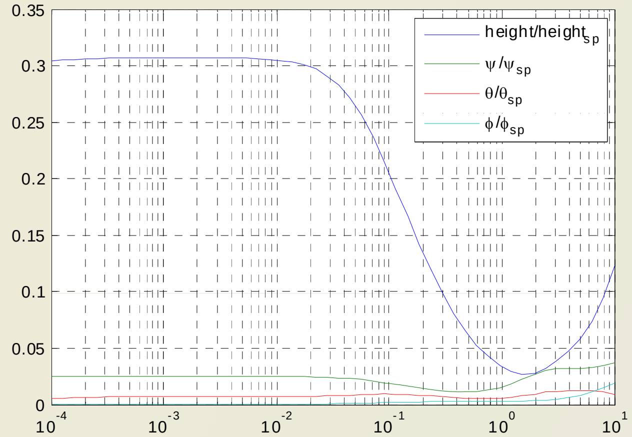
- The system is stable as confirmed by all roots being in the left half s-plane



Diagonal Dominance of Inner Loop

- Closed inner loop transfer functions become outer loop open loop transfer functions.
- Diagonal dominance checked.
- First BW determined for inner loop system determined to be approximately 3.5 rad/sec.
- Diagonal dominance calculated over bandwidth.
- Height had the greatest degree of coupling.





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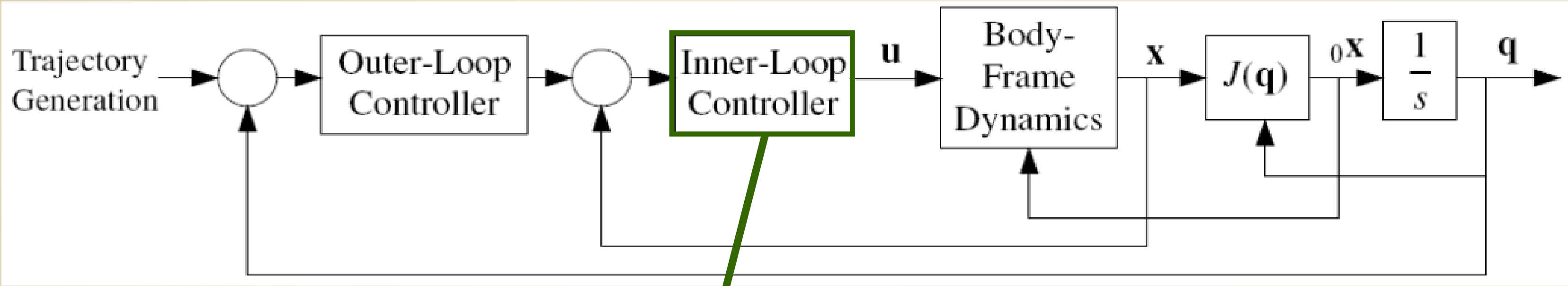
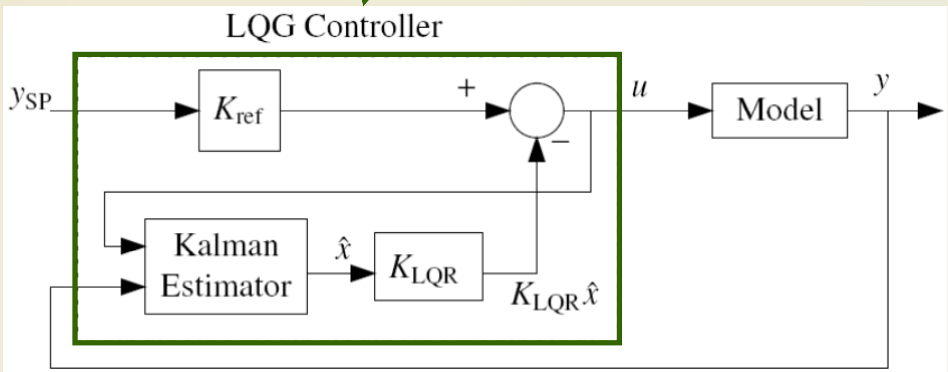
Linear Quadratic Control Techniques

- Helicopter is a "good candidate" for application of linear quadratic control techniques:
  - Highly coupled MIMO system
  - Open-loop unstable in hovering mode
  - Instrumentation requires sensor fusion and filtering techniques
- It provides analytical bounds for relative stability, robustness and tracking error.
- It may provide better performance than initial SISO design approaches
- There are computational tools readily available
  - MATLAB's Control Toolbox
  - MATLAB's Robust Control Toolbox

Control Strategy

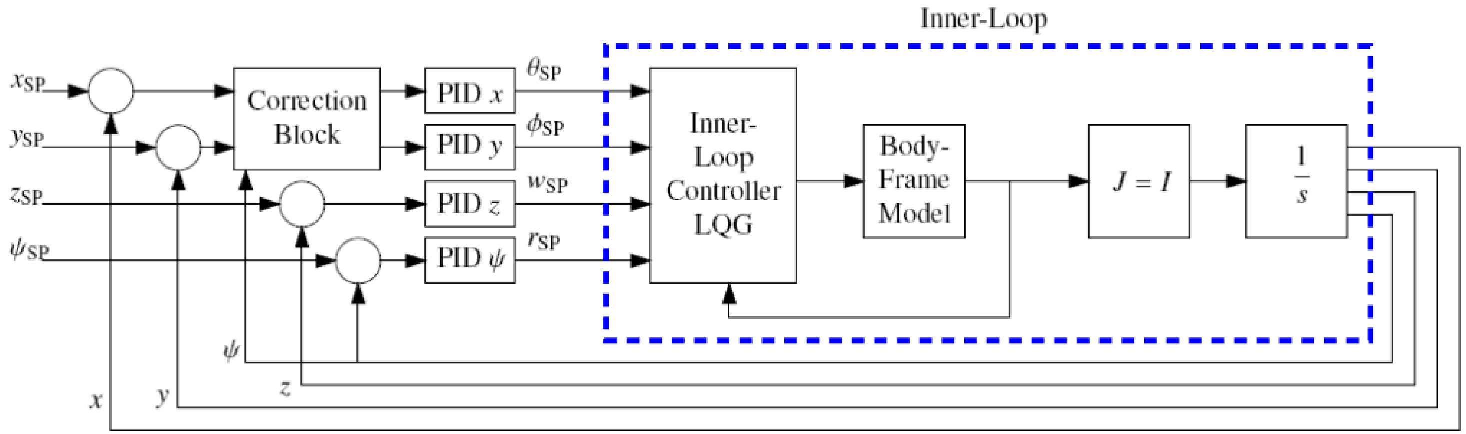
Cascaded Control Structure





Outer-Loop Control Design

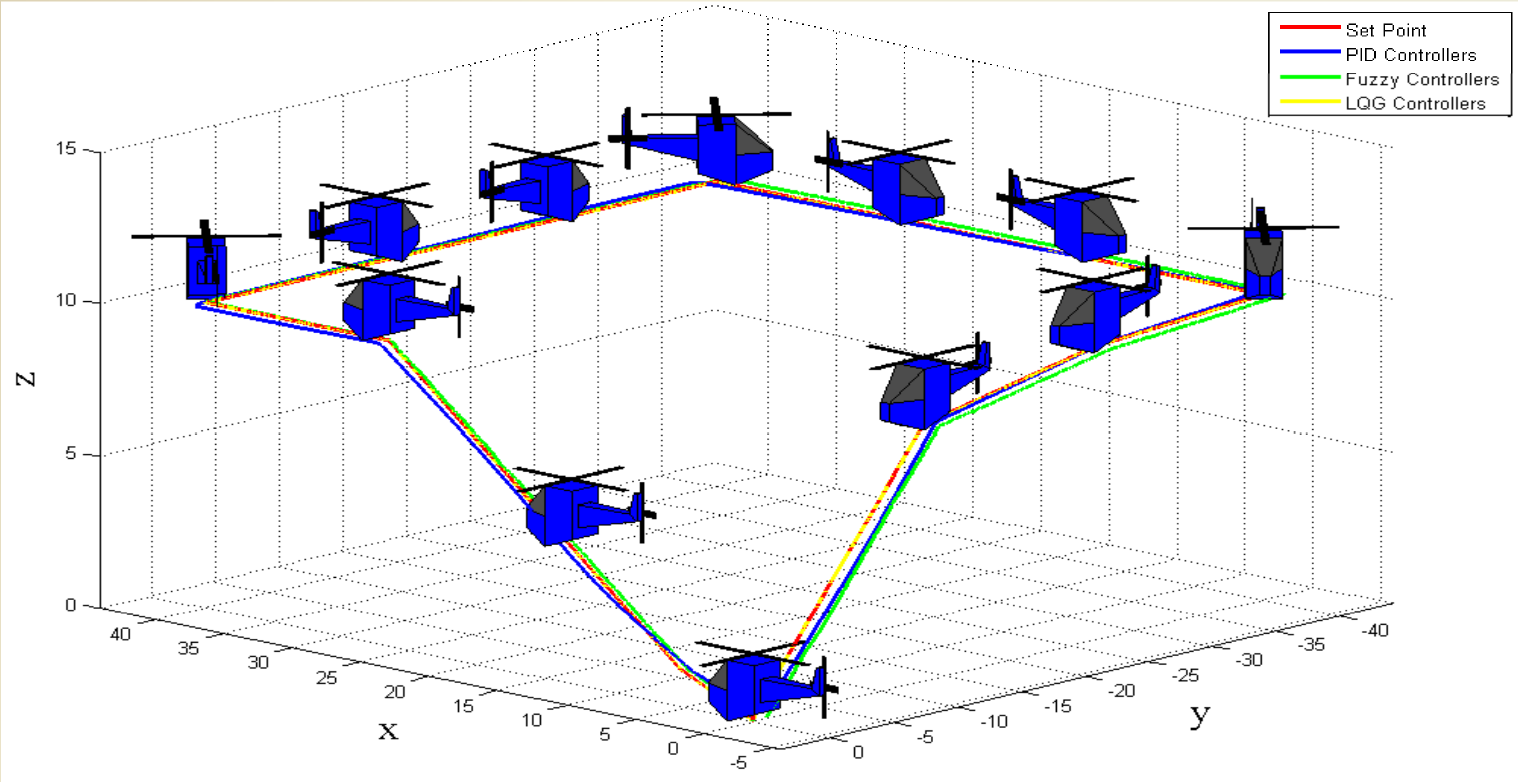
- Inner-loop reduction
- Outer loop handled by 4 PID controllers and a correction block for trajectory input.



- PID controllers can be designed by SISO approximation using classical control techniques.
- For now just manual tuning.

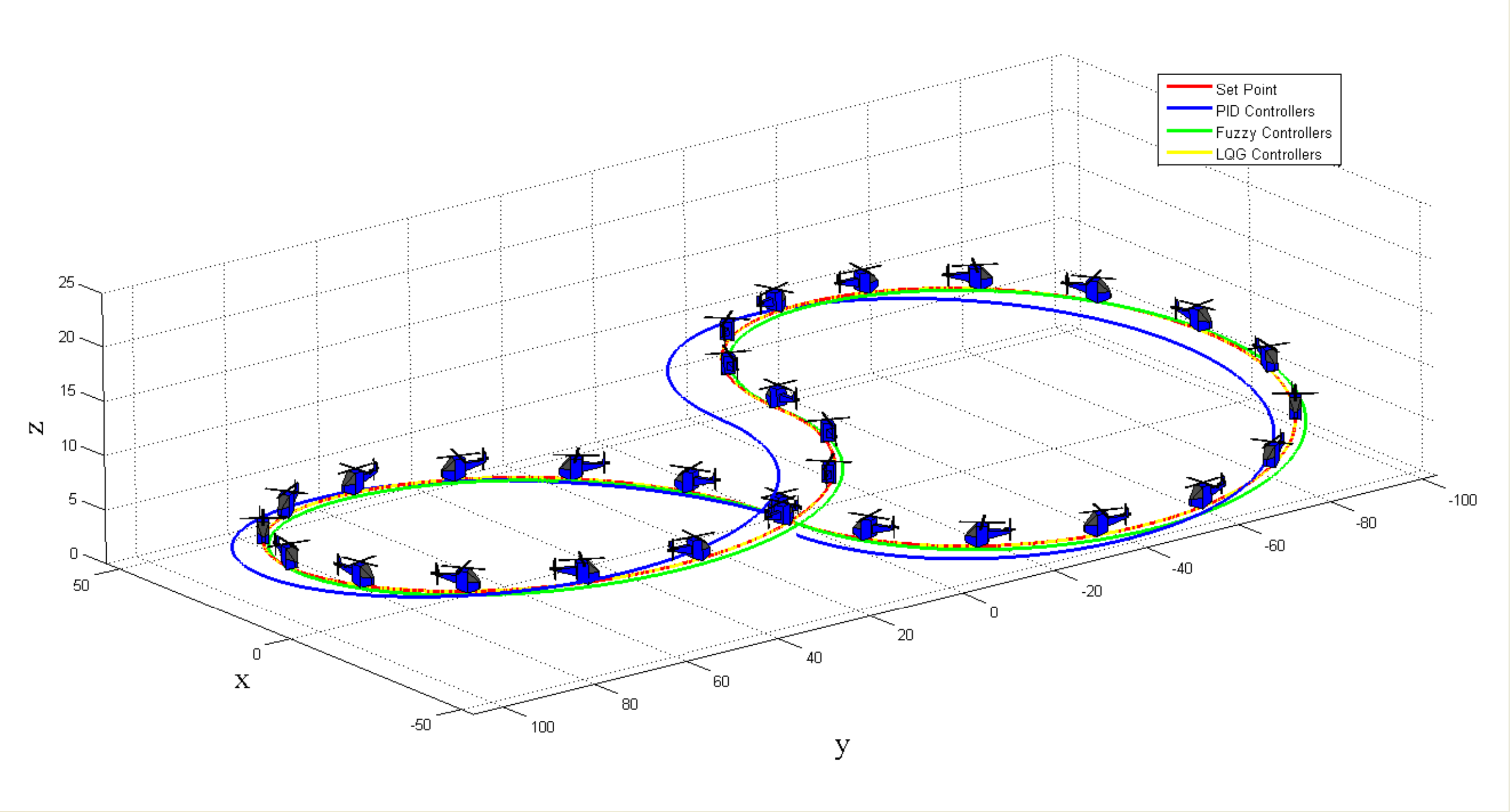
Comparison: PID vs Fuzzy vs LQG

Reference Tracking



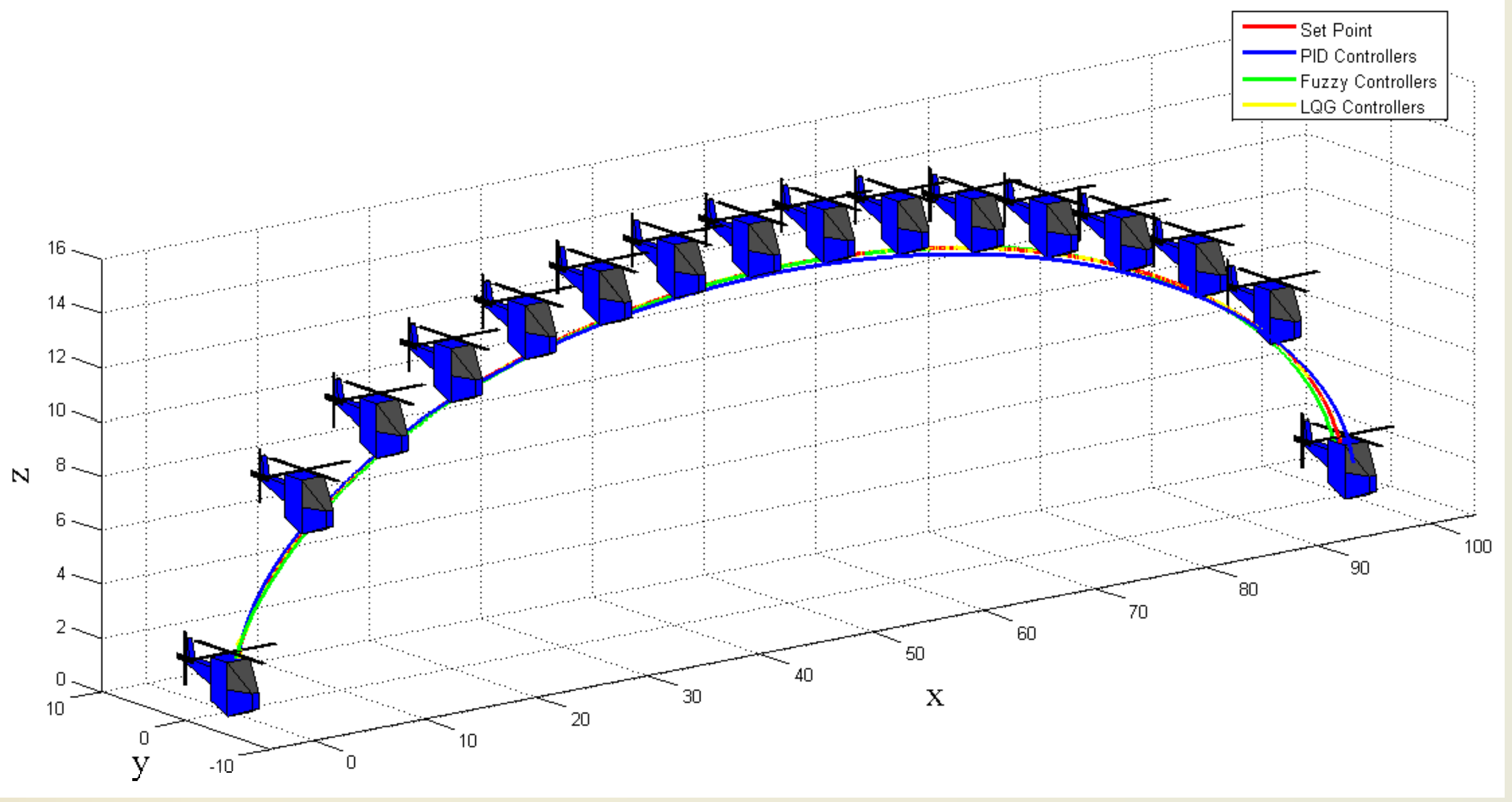
Rectangular Trajectory

Reference Tracking



Double CircleTrajectory

Reference Tracking

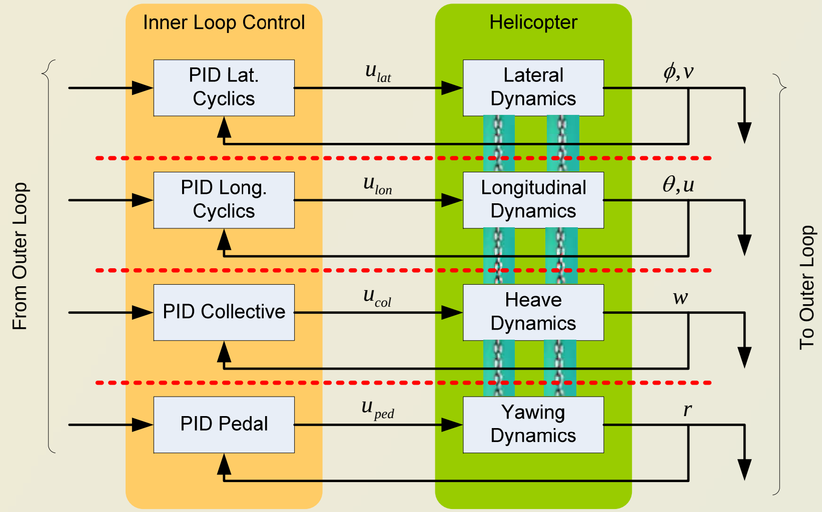


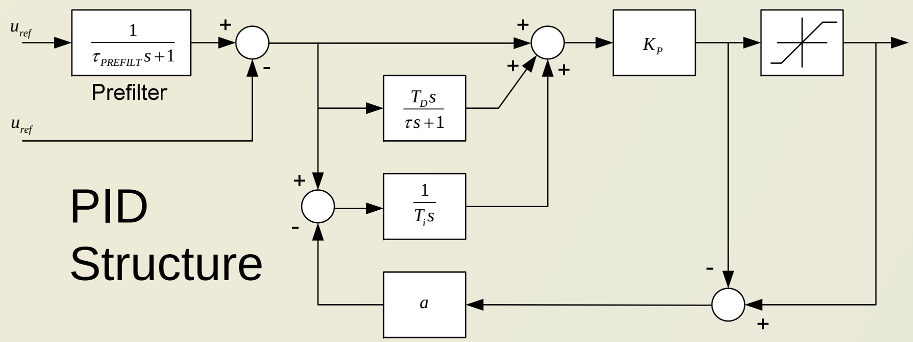
Take-off and Landing

Second Phase

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.

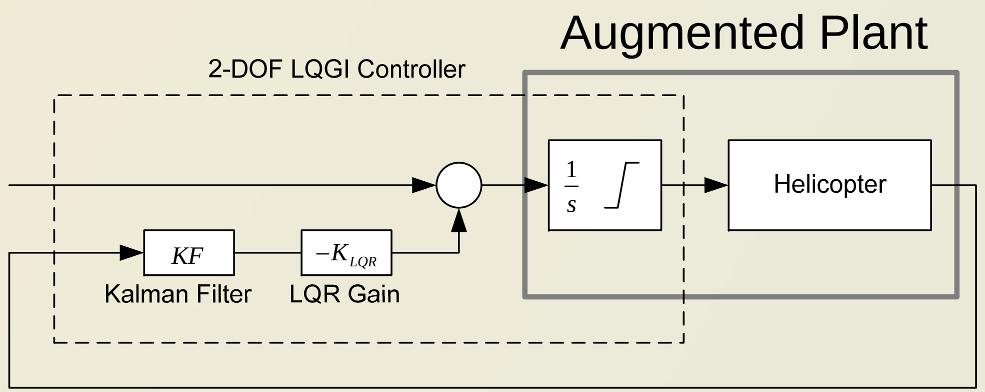




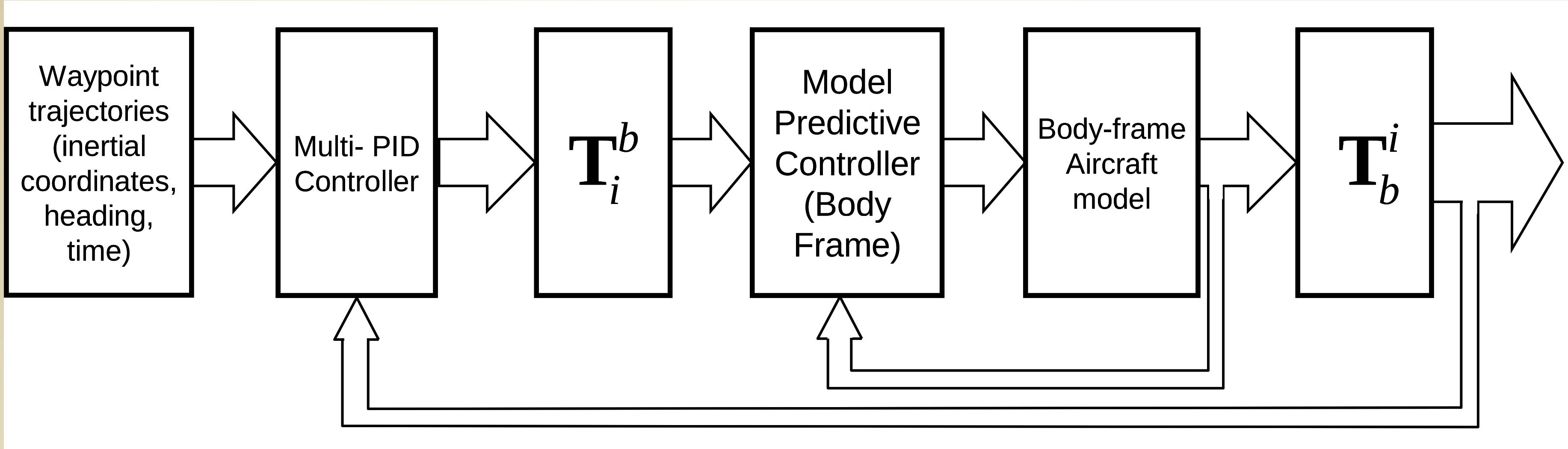
PID Structure

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



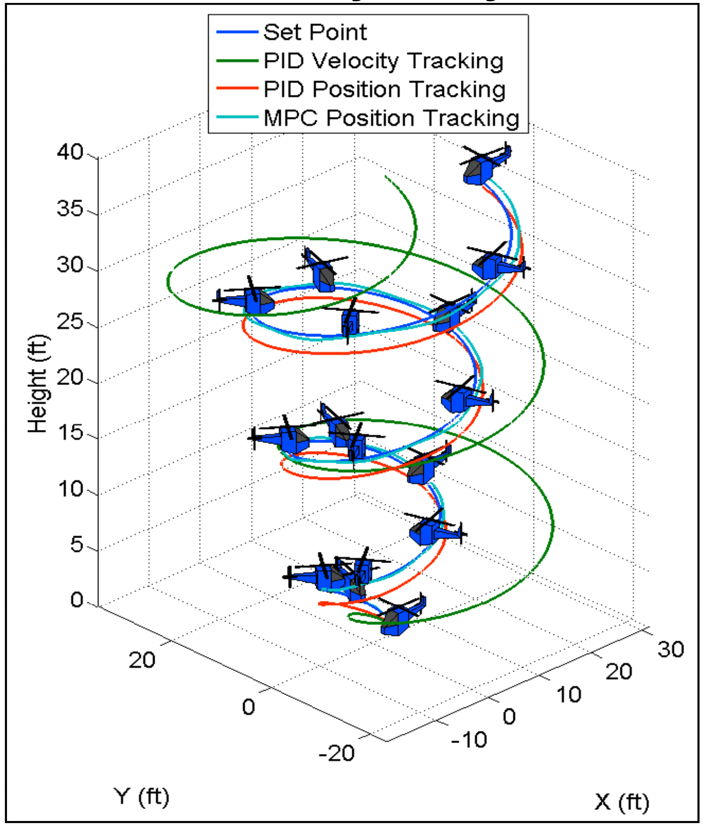
MPC Control Position Tracking System



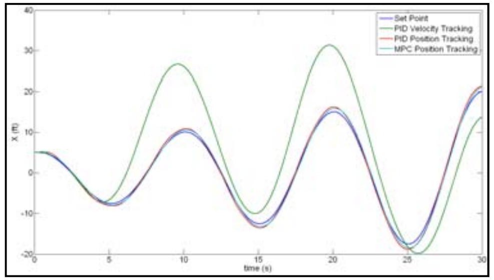
where: $$\mathbf{T}_i^b = \begin{bmatrix} c\theta c\psi & c\theta s\psi & -s\theta \\ s\phi s\theta c\psi - c\phi s\psi & s\phi s\theta s\psi + c\phi c\psi & s\phi c\theta \\ c\phi s\theta c\psi + s\phi s\psi & c\phi s\theta s\psi - s\phi c\psi & c\phi c\theta \end{bmatrix}$$ **and** $$\mathbf{T}_b^i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

Ascending Spiral

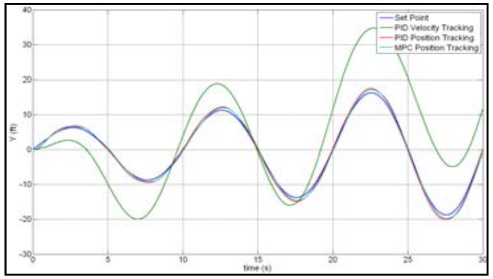
3D trajectory



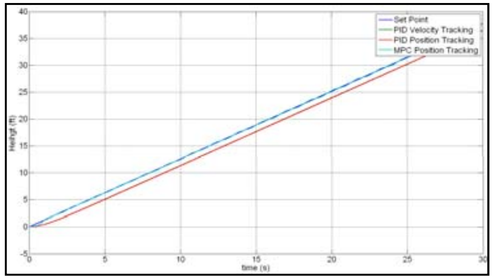
x responses



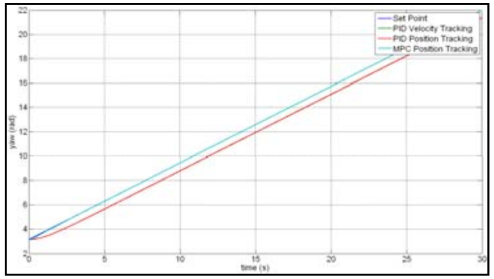
y responses



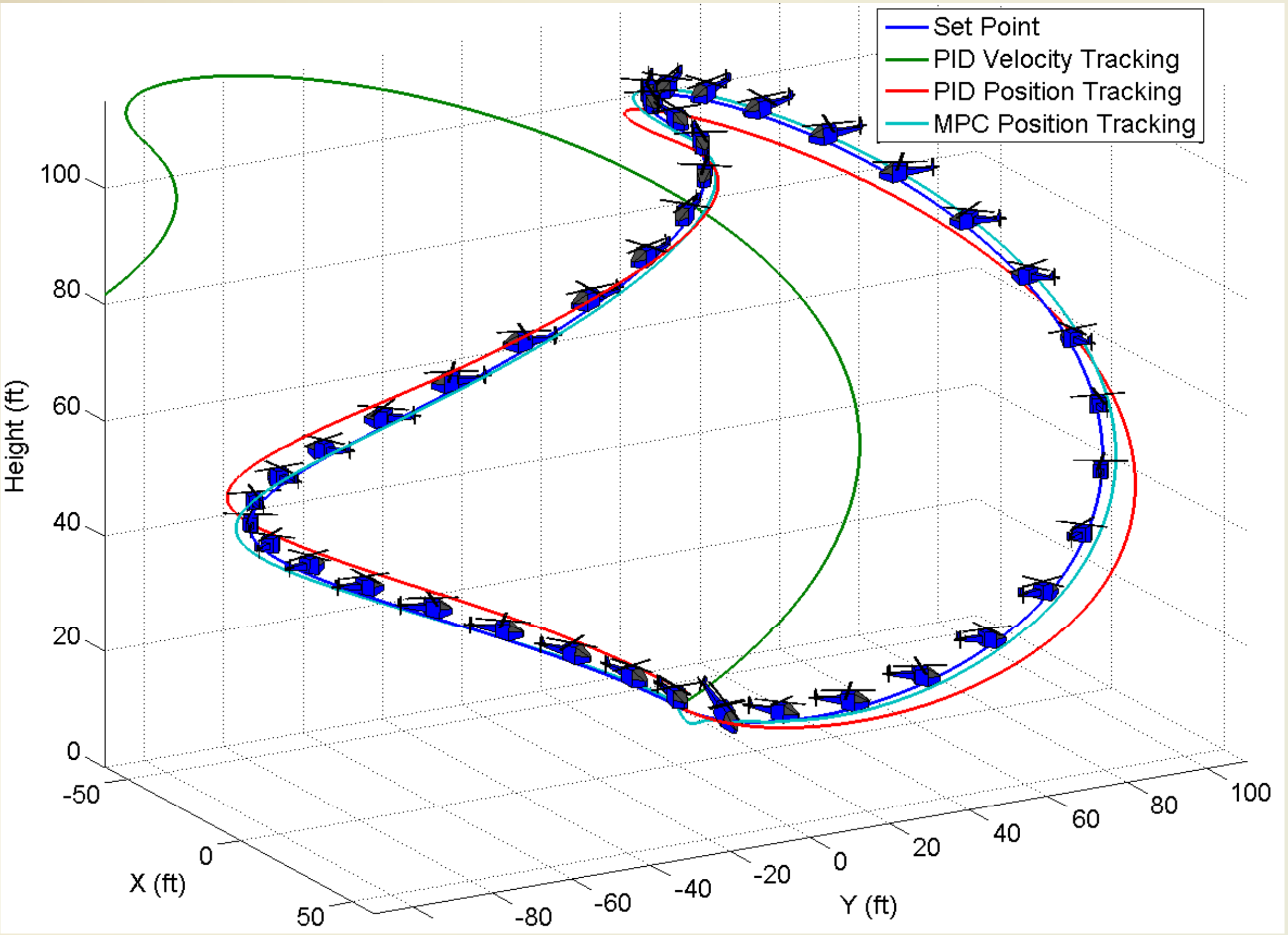
z responses

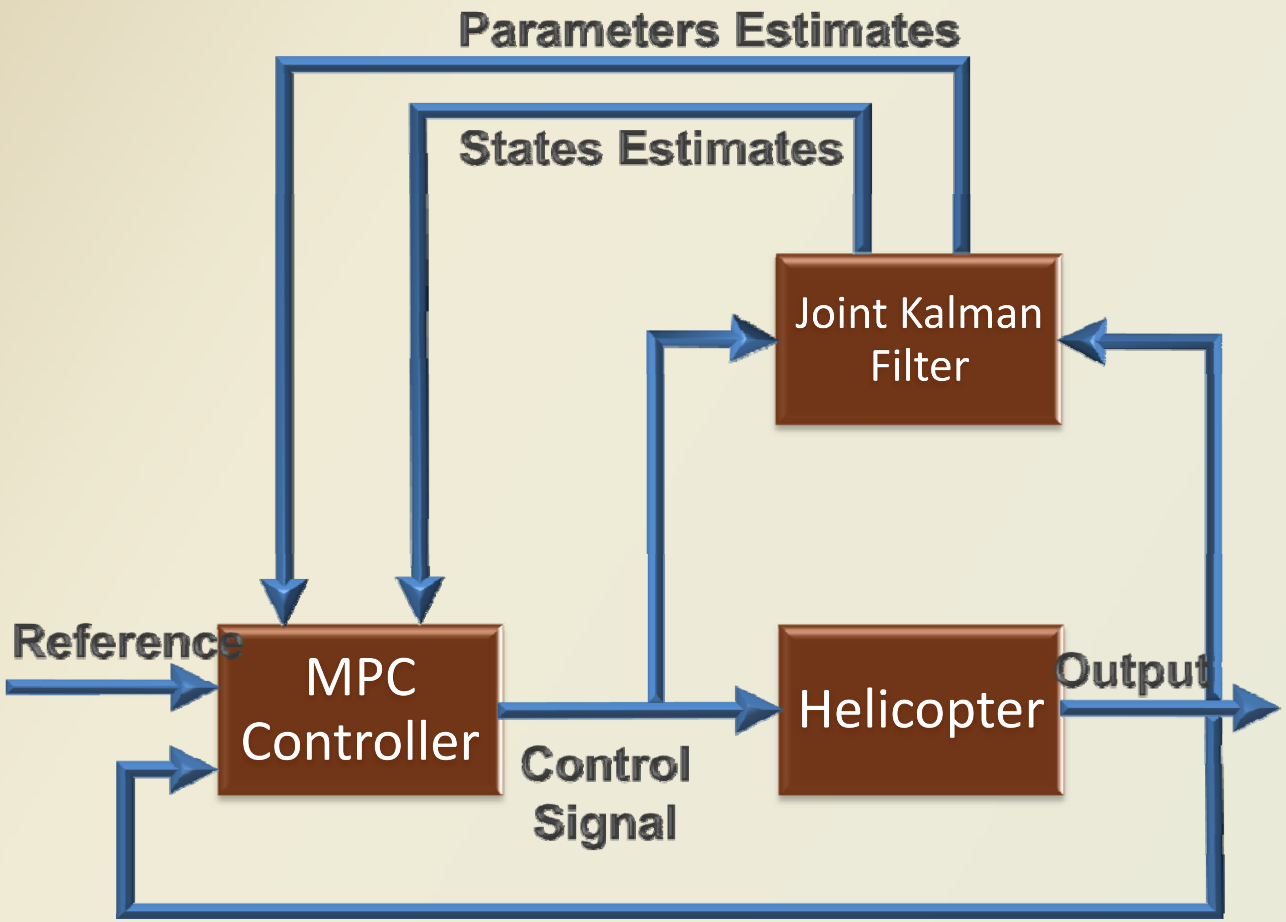


Heading responses

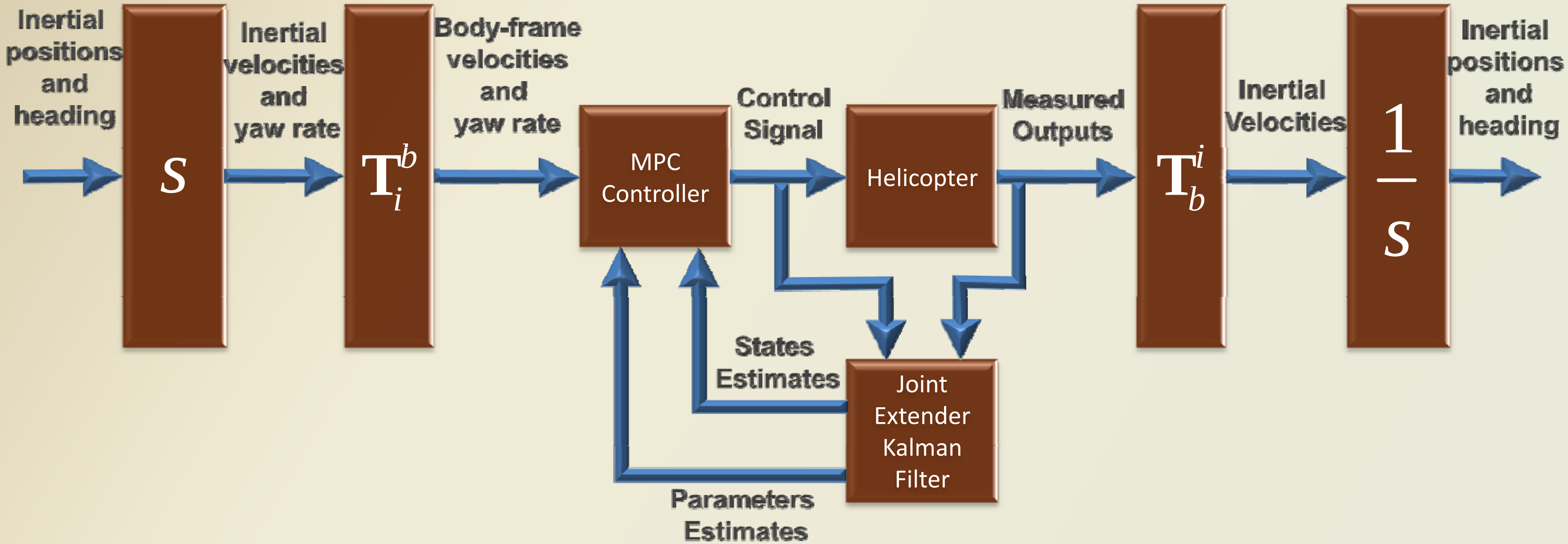


Double Circle with Variable Height

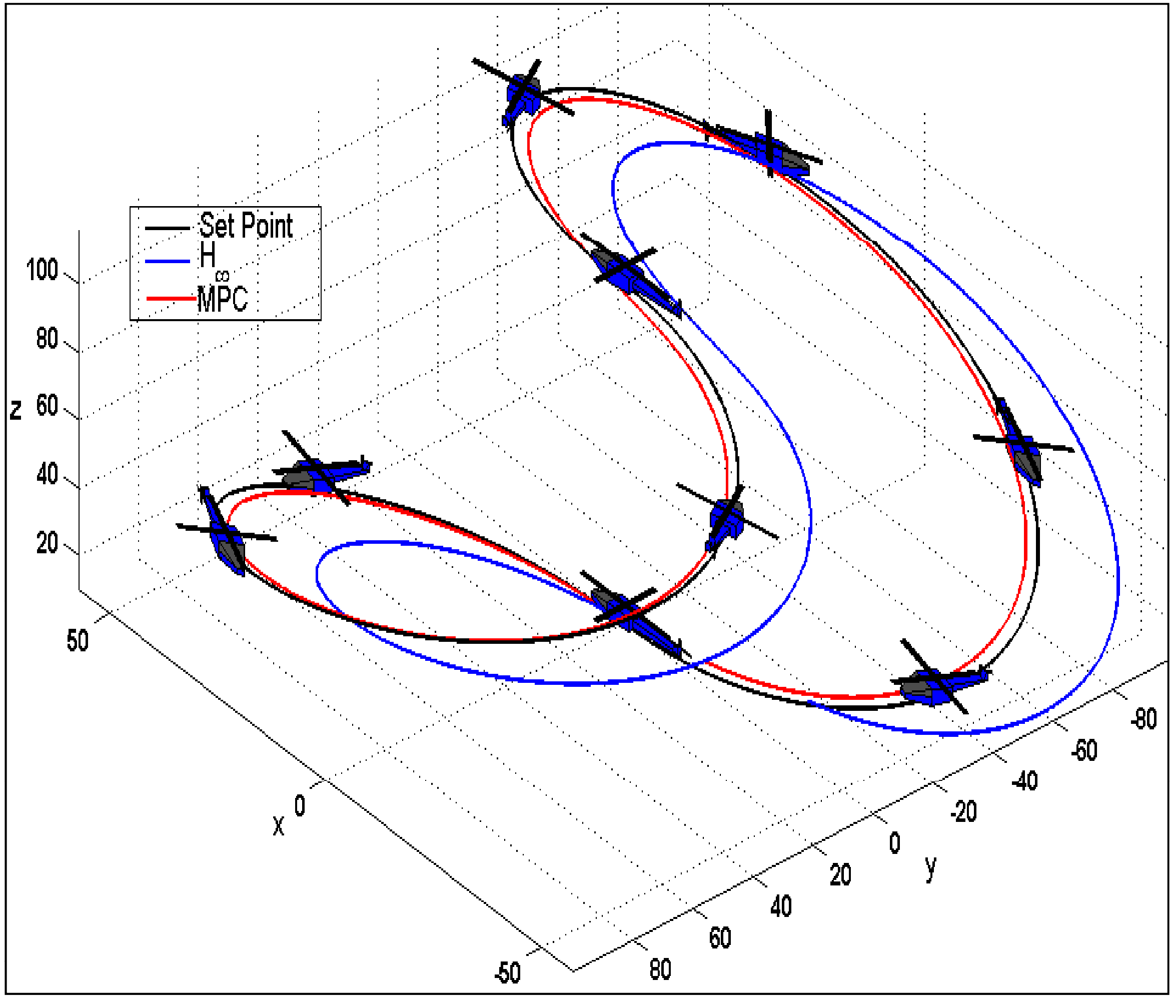



Parameters Estimates
States Estimates
Joint Kalman Filter
Reference
MPC Controller
Helicopter
Output
Control Signal

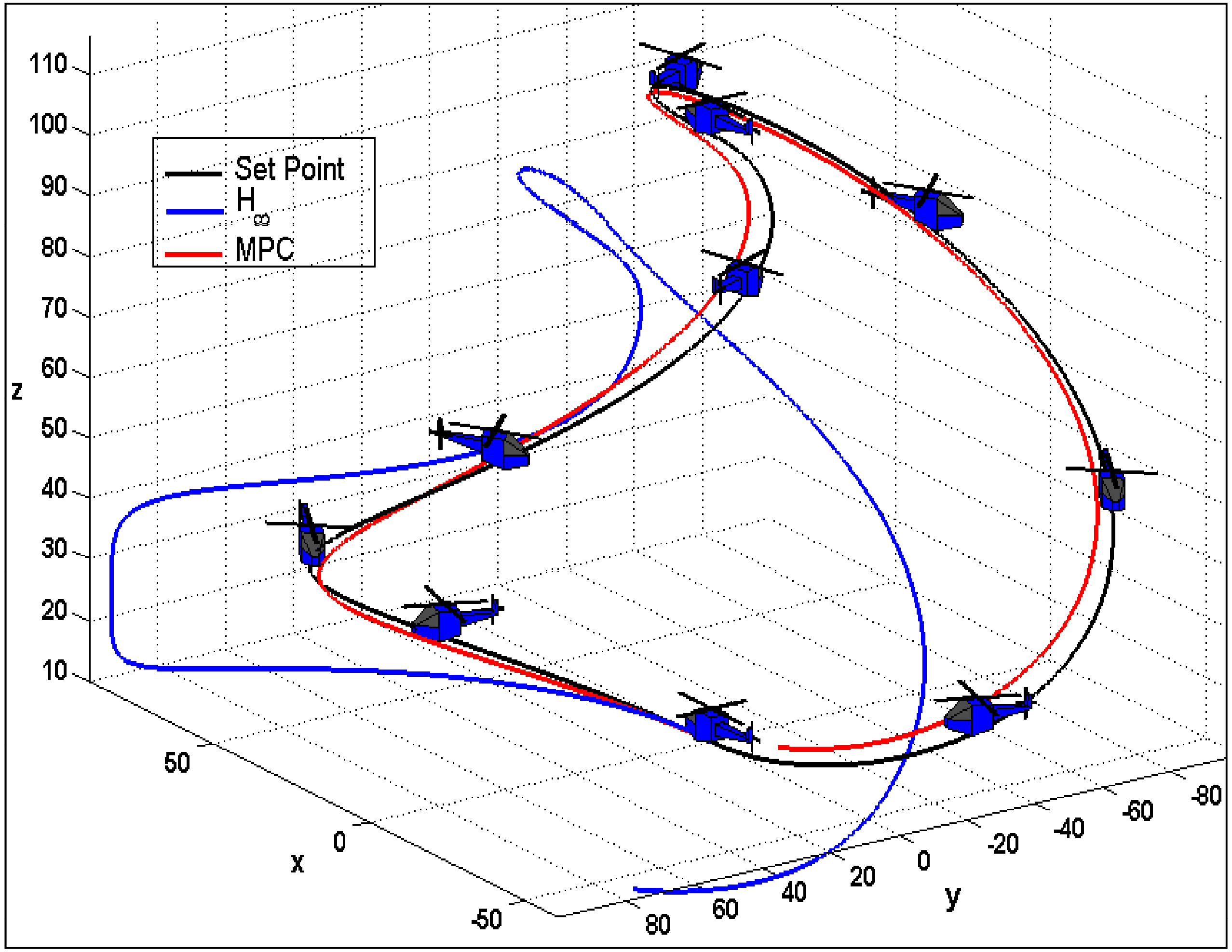
FLIGHT CONTROL IMPLEMENTATION



PERFORMANCE COMPARISON – FLIGHT TRAJECTORY

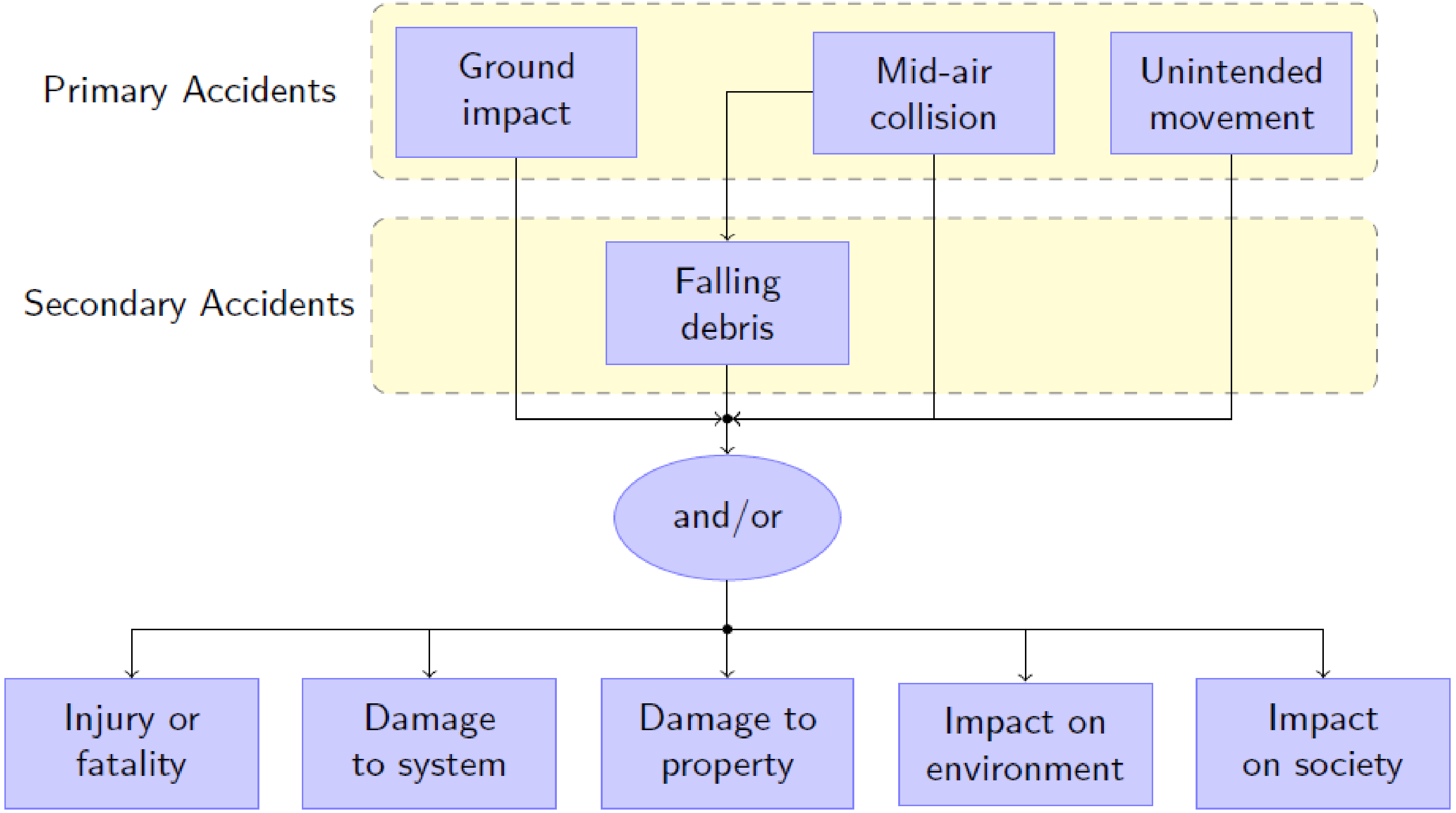


PASSIVE FAULT TOLERANCE TEST (ROBUSTNESS)



UAS & THEIR INTEGRATION INTO THE NAS

Accidents and damages



UAS & THEIR INTEGRATION INTO THE NAS

		Catastrophic[a]	Hazardous[b]	Major [c]	Minor [d]	No safety effect
Frequent	$> 10^{-3}/hr$					
Probable	$< 10^{-3}/hr$					
Remote	$< 10^{-4}/hr$					
Extremely remote	$< 10^{-5}/hr$					
Extremely Improbable	$< 10^{-6}/hr$					

[a] Uncontrolled flight and/or uncontrolled crash, which can potentially result in a fatality. Potential fatality to UAV crew or ground staff.
[b] Controlled-trajectory termination or forced landing potentially leading to the loss of the UAV where it can be reasonably expected that a fatality will not occur. Potential serious injury to UAV crew or ground staff.
[c] Emergency landing of the UAV on a predefined site where it can be reasonably expected that a serious injury will not occur. Potential injury to UAV crew or ground staff.
[d] Slight reduction in safety margins or functional capabilities and slight increase in UAV crew workload.

Fig. 4.1: UAV operations risk reference system (the grayed areas signify unacceptable risk). Source: [43]

UAS & THEIR INTEGRATION INTO THE NAS

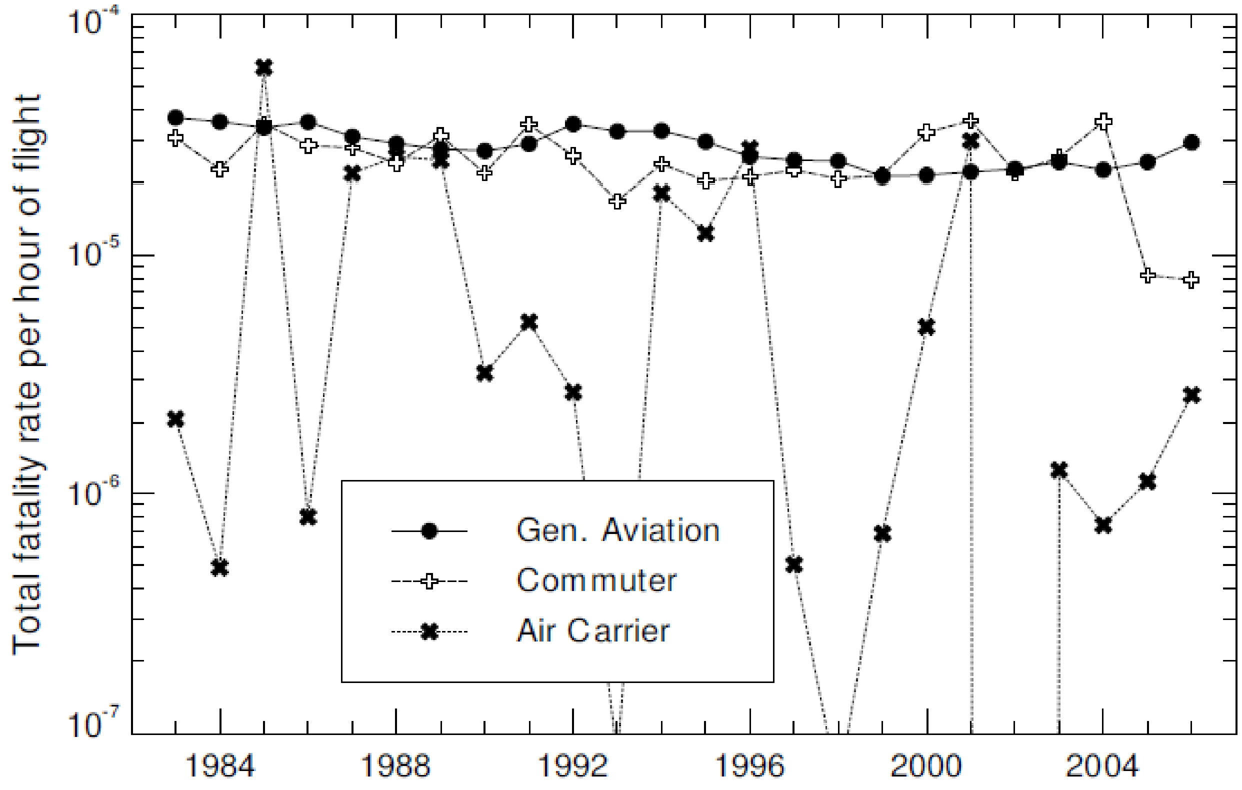


Fig. 5.2: Fatality rates from general aviation, commuter and air carrier accidents as a function of time. Based on analysis of NTSB accident data [15] between 1983 and 2006.

UAS & THEIR INTEGRATION INTO THE NAS

Table 5.3: Fatality rates for accidents where an in-flight collision with obstacles (e.g. birds, trees, powerlines) occurred. Based on analysis of NTSB accident data [14] between 1983 and 2006.

Rates per hour	Air Carrier	Commuter	General Aviation	Total
Accident	1.34×10^{-7}	3.22×10^{-6}	1.33×10^{-5}	8.17×10^{-6}
Fatalities aboard	9.67×10^{-7}	2.67×10^{-6}	6.27×10^{-6}	4.25×10^{-6}
Ground fatalities	5.97×10^{-9}	3.81×10^{-8}	5.73×10^{-8}	3.93×10^{-8}
Total fatalities	9.73×10^{-7}	2.71×10^{-6}	6.32×10^{-6}	4.29×10^{-6}

Table 5.4: Fatality rates for accidents where a mid-air collision with another aircraft occurred. Based on analysis of NTSB accident data [14] between 1983 and 2006.

Rates per hour	Air Carrier	Commuter	General Aviation	Total
Accident	None	2.76×10^{-7}	5.90×10^{-7}	3.74×10^{-7}
Fatalities aboard	None	6.96×10^{-7}	1.04×10^{-6}	6.82×10^{-7}
Ground fatalities	None	1.91×10^{-8}	2.86×10^{-8}	1.87×10^{-8}
Total fatalities	None	7.15×10^{-7}	1.07×10^{-6}	7.01×10^{-7}

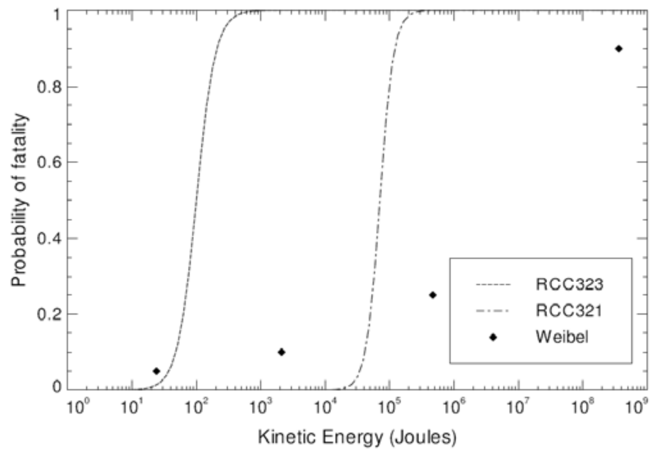


Fig. 5.4: The probability of fatality as a function of kinetic energy impact as estimated by Weibel [20] and models derived in RCC321 [18] and RCC323 [17].

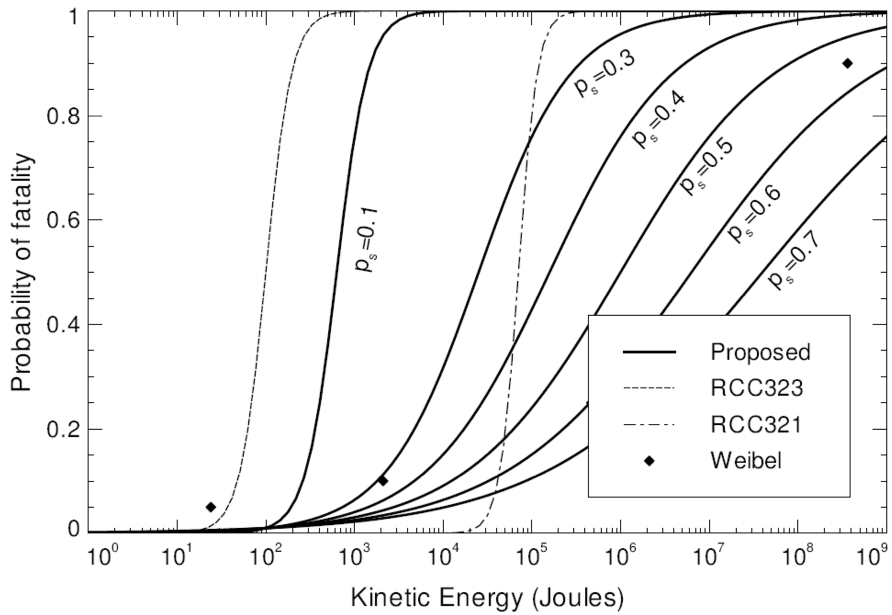


Fig. 5.5: The probability of fatality as a function of kinetic energy impact for the proposed model with $\alpha = 10^6$J, $\beta = 100$J and for several values of p_s. For comparison purposes the estimates of Weibel [20] as well as the models of RCC321 [18] and RCC323 [17] are given.

Equivalent levels of safety - study

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

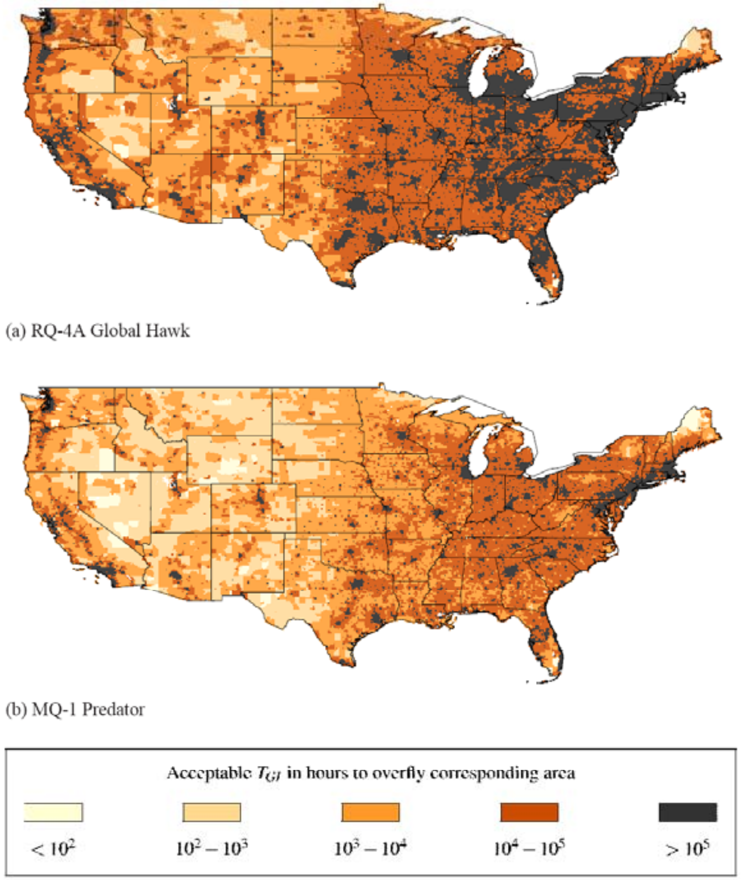


Fig. 5.6: The areas of the US, the RQ-4A Global Hawk and the MQ-1 Predator UAS are allowed to loiter over based on their reliability with respect to ground impact occurrence frequency.

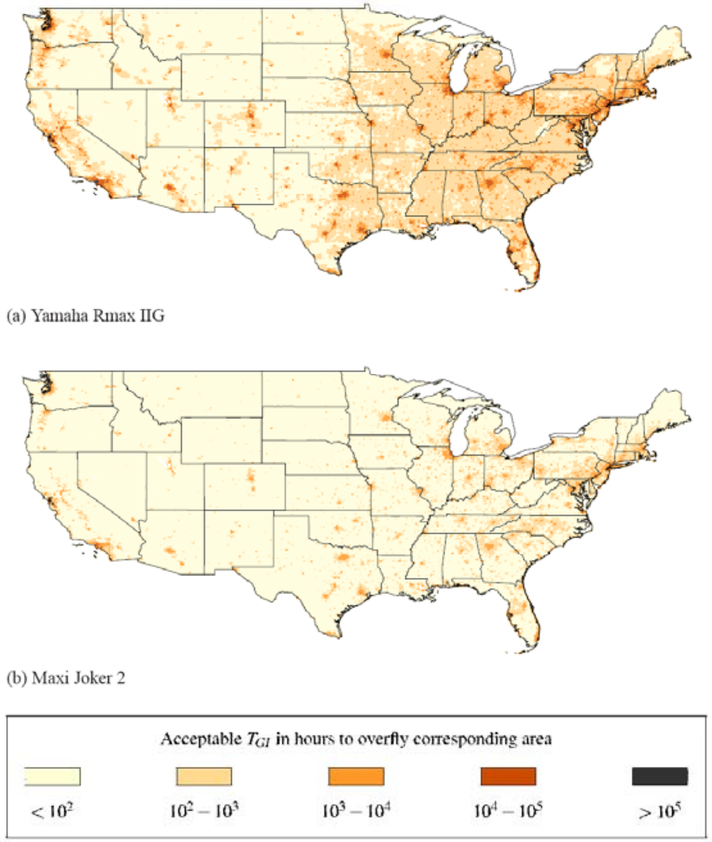


Fig. 5.8: The areas of the US, the Yamaha Rmax IIG and Maxi Joker 2 helicopters are allowed to loiter over based on their reliability with respect to ground impact occurrence frequency.

Case Study % of Europe– Flying over

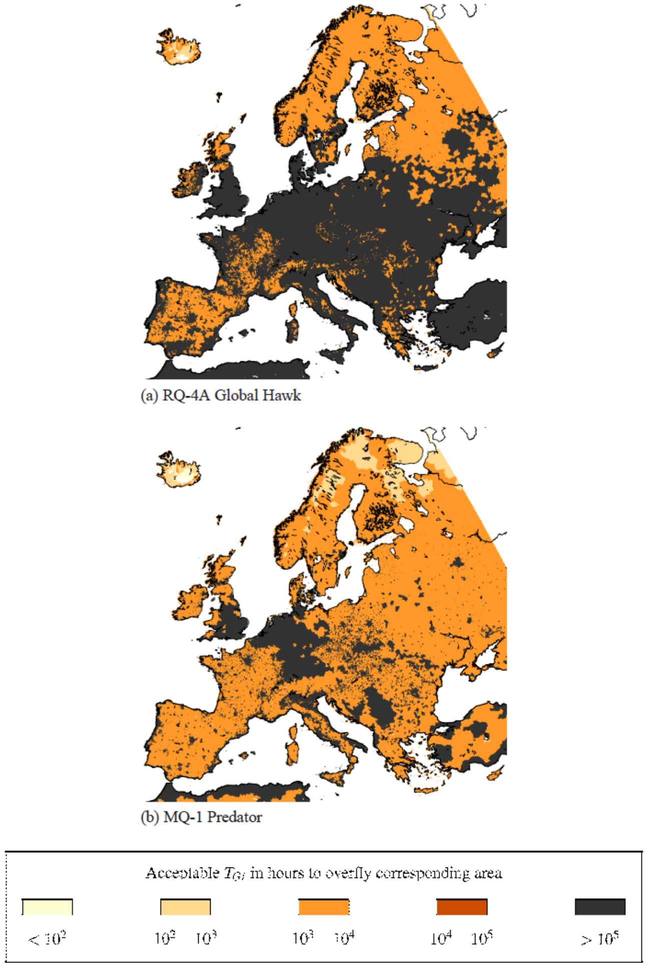


Fig. 5.9: The areas of Europe, the RQ-4A Global Hawk and the MQ-1 Predator UAS are allowed to loiter over based on their reliability with respect to ground impact occurrence frequency.

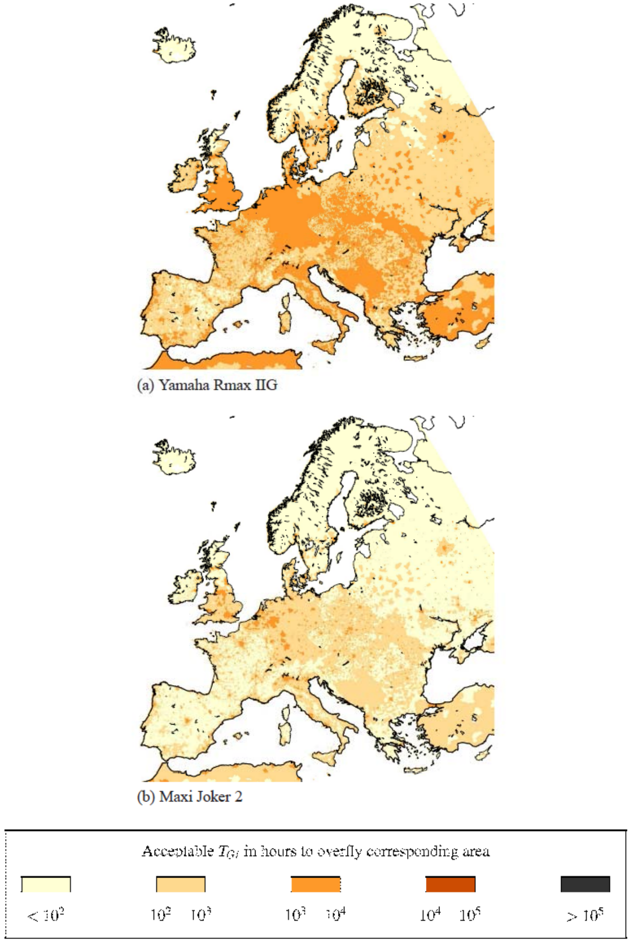
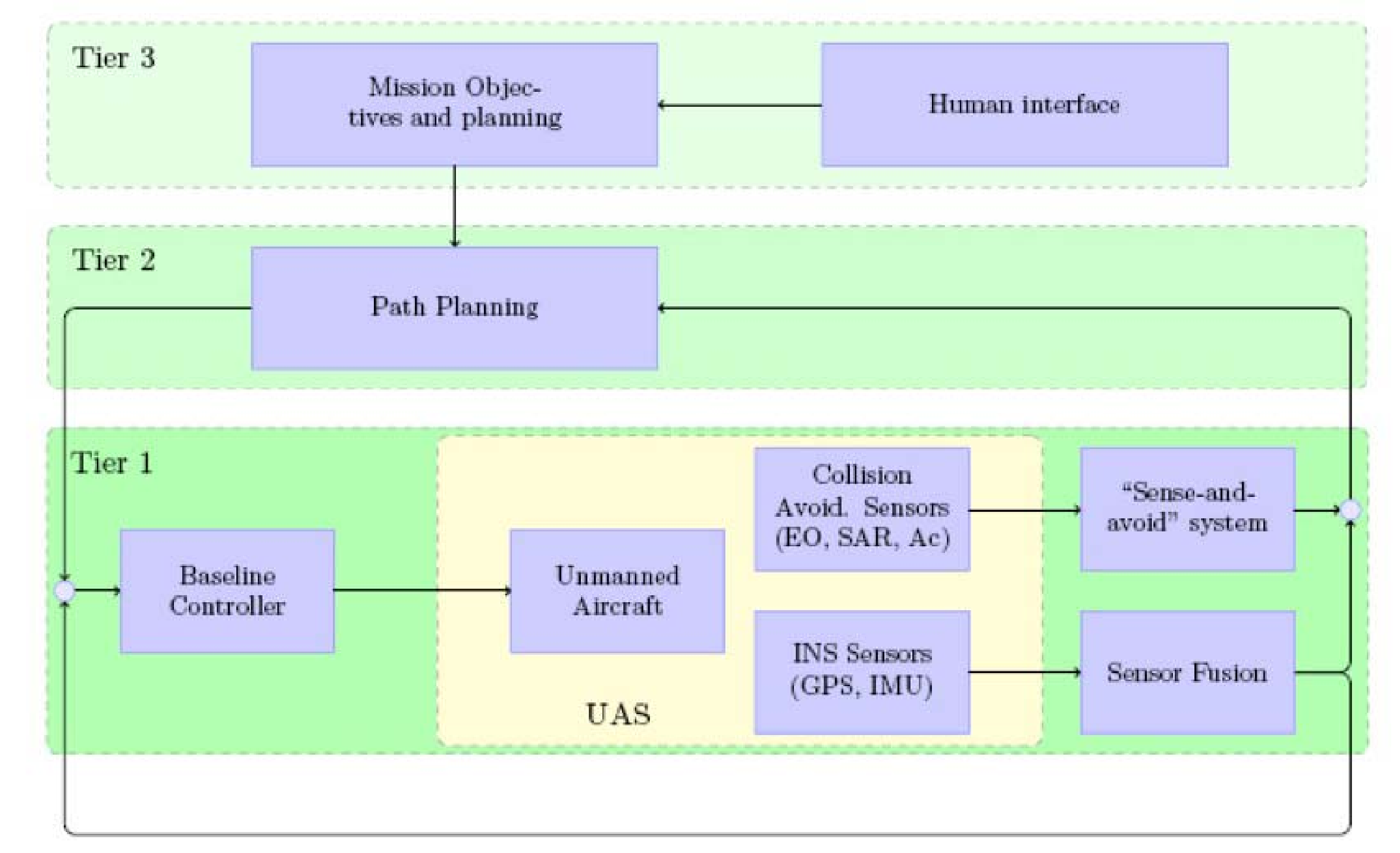
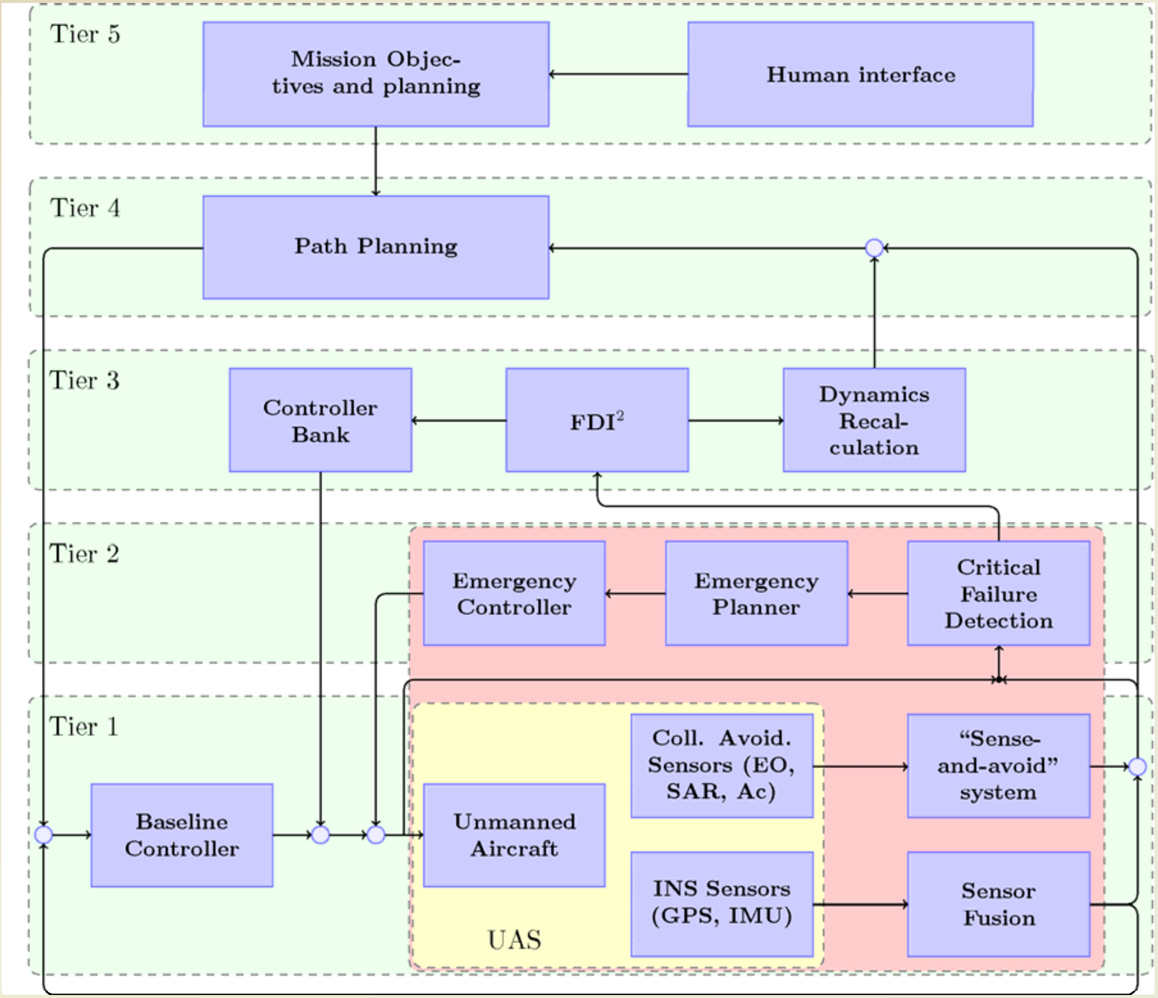


Fig. 5.11: The areas of Europe, the Yamaha Rmax IIG and Maxi Joker 2 helicopters are allowed to loiter over based on their reliability with respect to ground impact occurrence frequency.

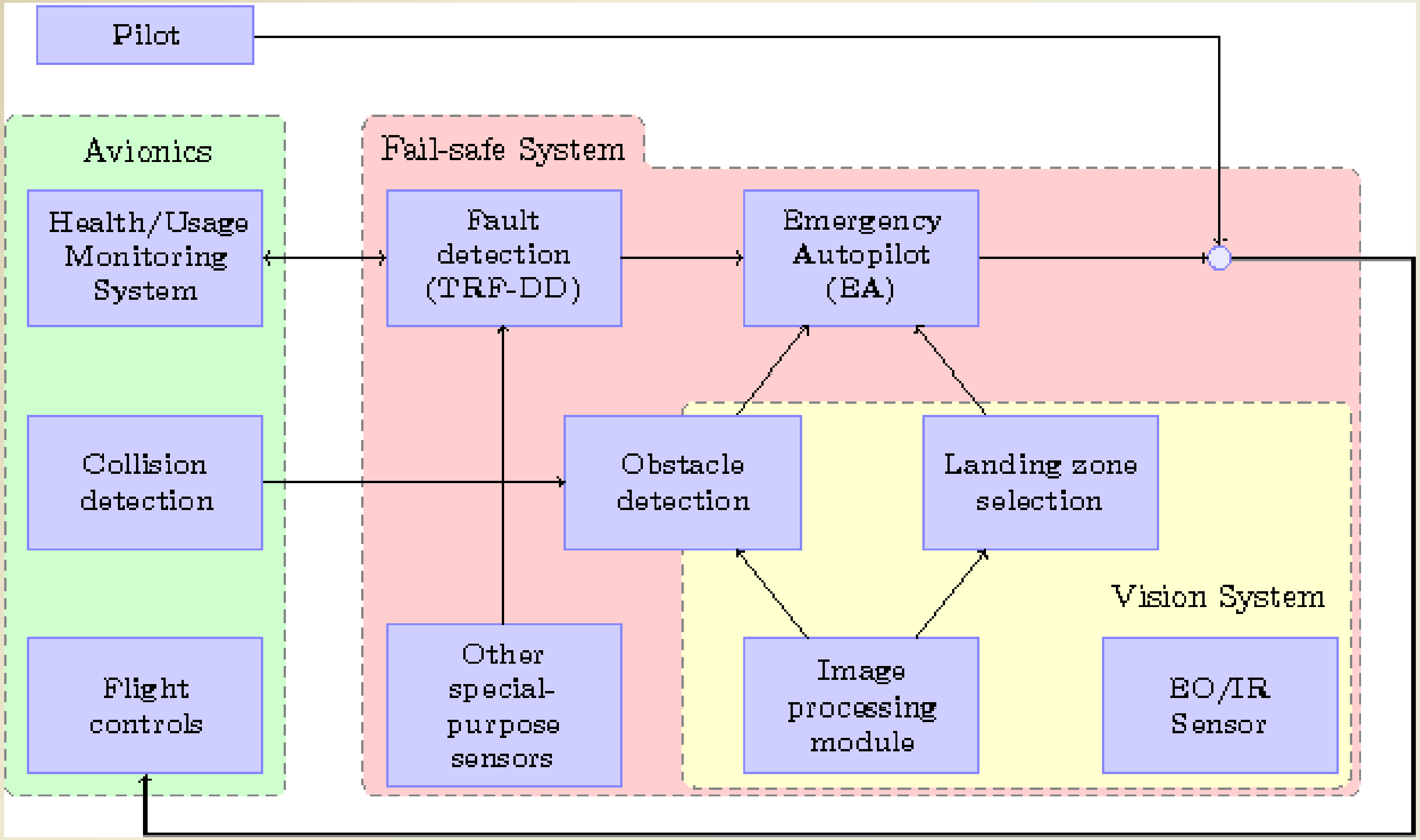
ADDED SAFETY: THE CURRENT STATE



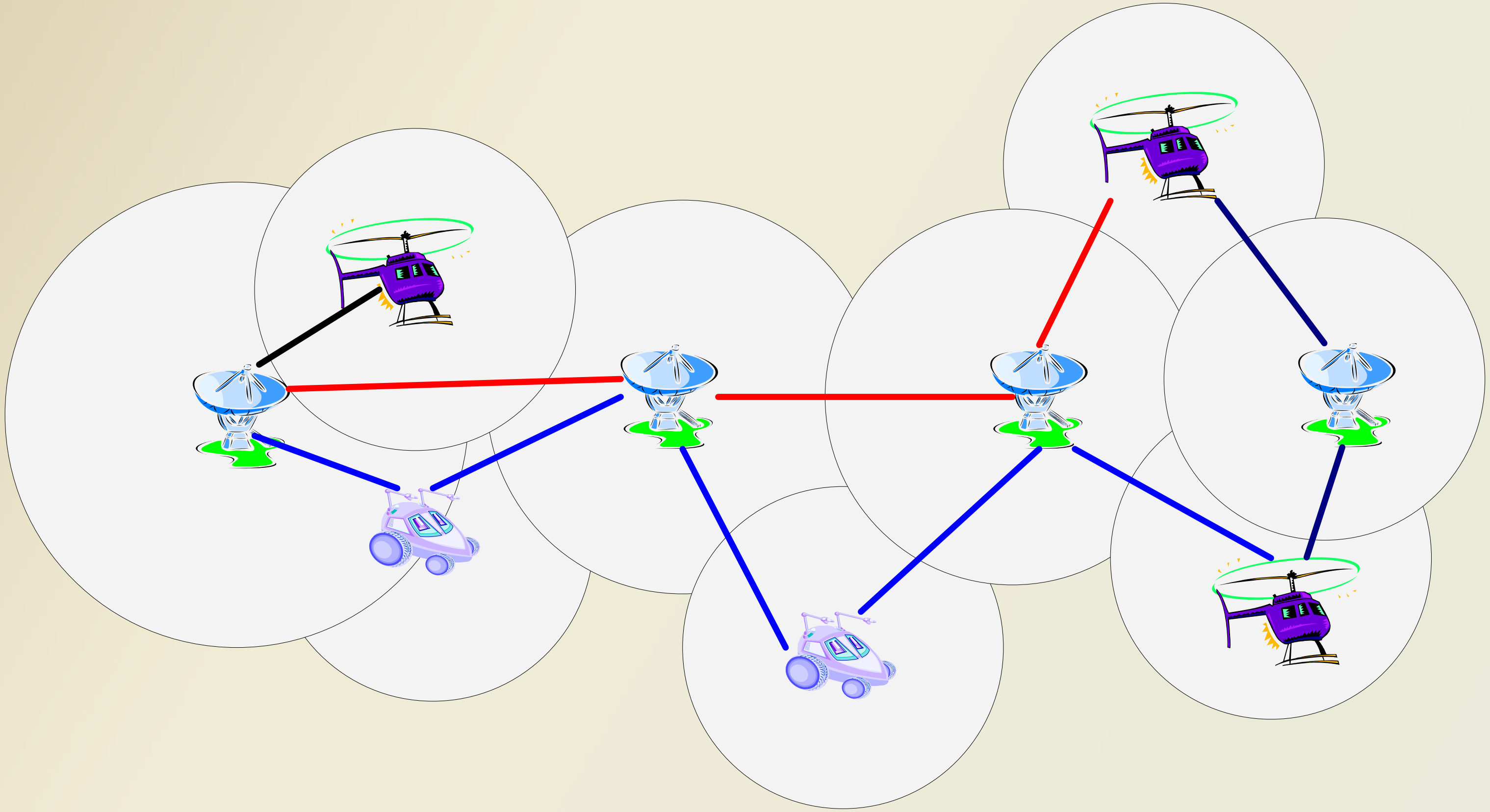


THE PROPOSED SYSTEM

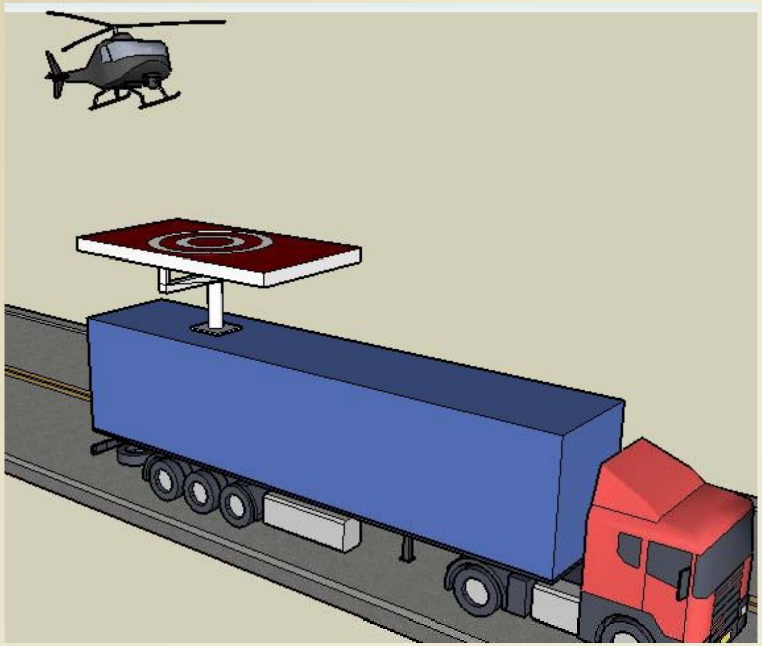
THE 'AUGMENTED' SYSTEM FOR MANNED HELICOPTERS

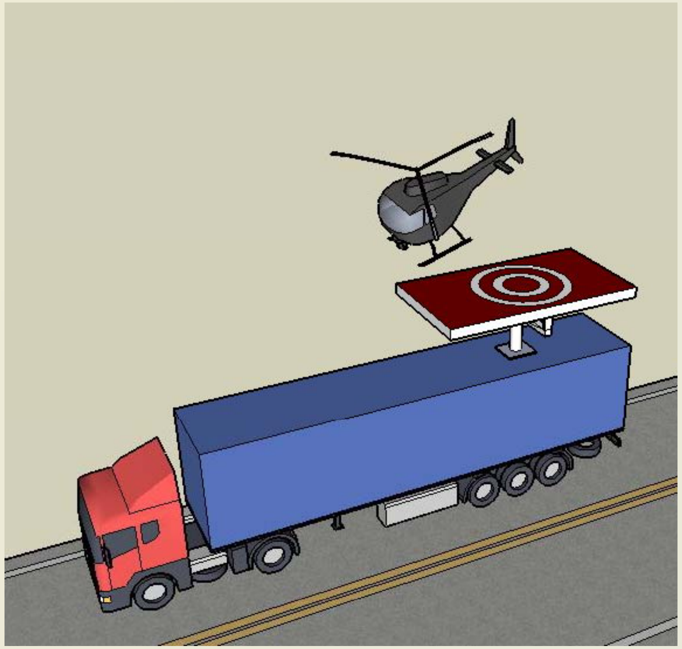


A Long Term Concept Objective



Idea of launching and recovering on the move





CONCLUSIONS

A LOT HAS ALREADY BEEN DONE, AND CONSIDERABLE PROGRESS HAS BEEN MADE IN

- *Controller Design*
- *Navigation Systems*
- *Sensors*
- *Integration*

BUT,

THE LOAD IS STILL VERY LONG!!!!!