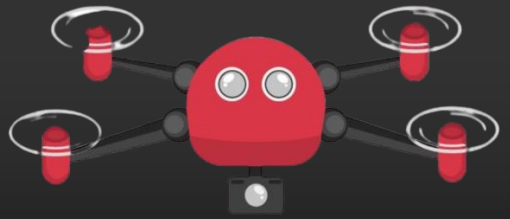

smARTflight : An Environmentally-Aware Adaptive Real-Time Flight Management System

Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

Anam Farrukh

Richard West

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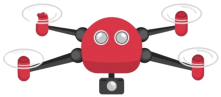
Drones: Cyber-Physical Systems



- The technology that is fundamentally changing the way we live.

Disinfection

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Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

Drones: Cyber-Physical Systems

- The technology that is fundamentally changing the way we live.

Disinfection

Remote Package Delivery

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Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

Drones: Cyber-Physical Systems

- The technology that is fundamentally changing the way we live.

Disinfection

Remote Package Delivery

Monitoring & Patrolling

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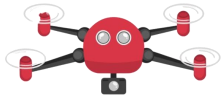
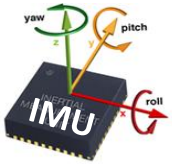
Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

Drones: Cyber-Physical Systems



Sensing



\+

Mag

GPS

Sonar

Camera

Barometer

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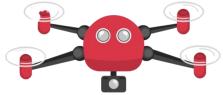
Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

Drones: Cyber-Physical Systems



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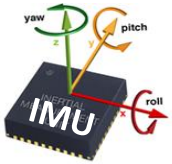

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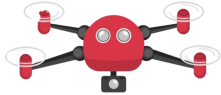
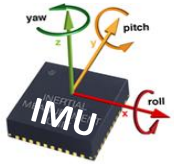


Sensing → **Processing + Control** → **Actuation**



+ Mag

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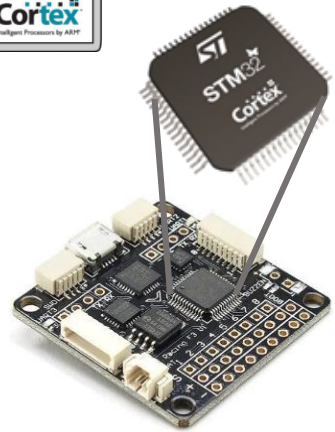

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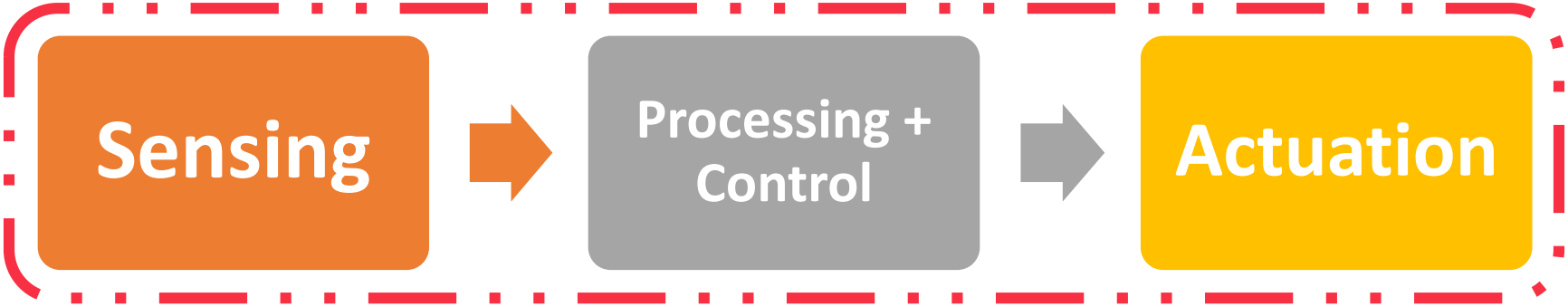

Flight Management System (Autopilot)

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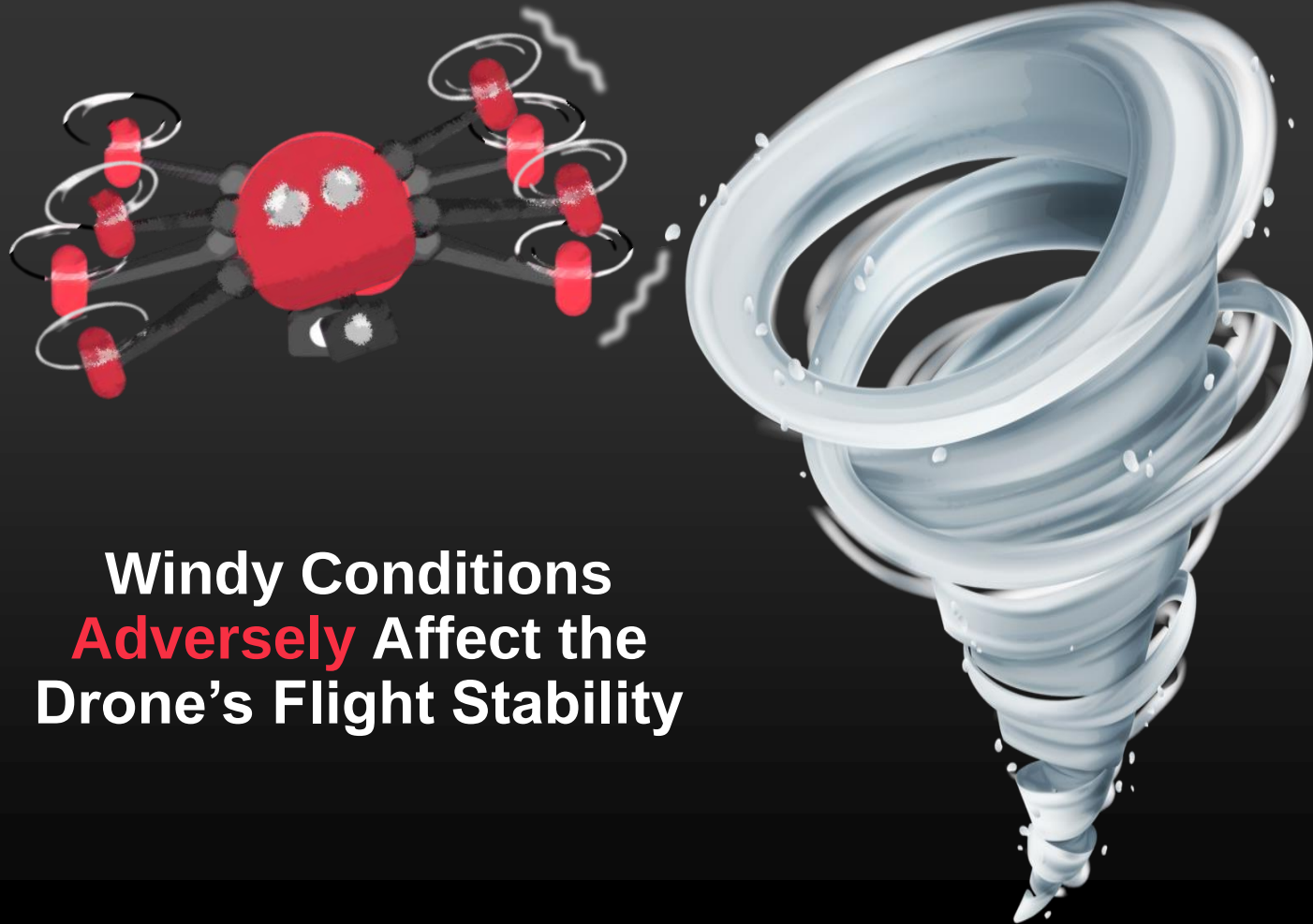
Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html



Windy Conditions Adversely Affect the Drone's Flight Stability

Attitude : 3D Orientation

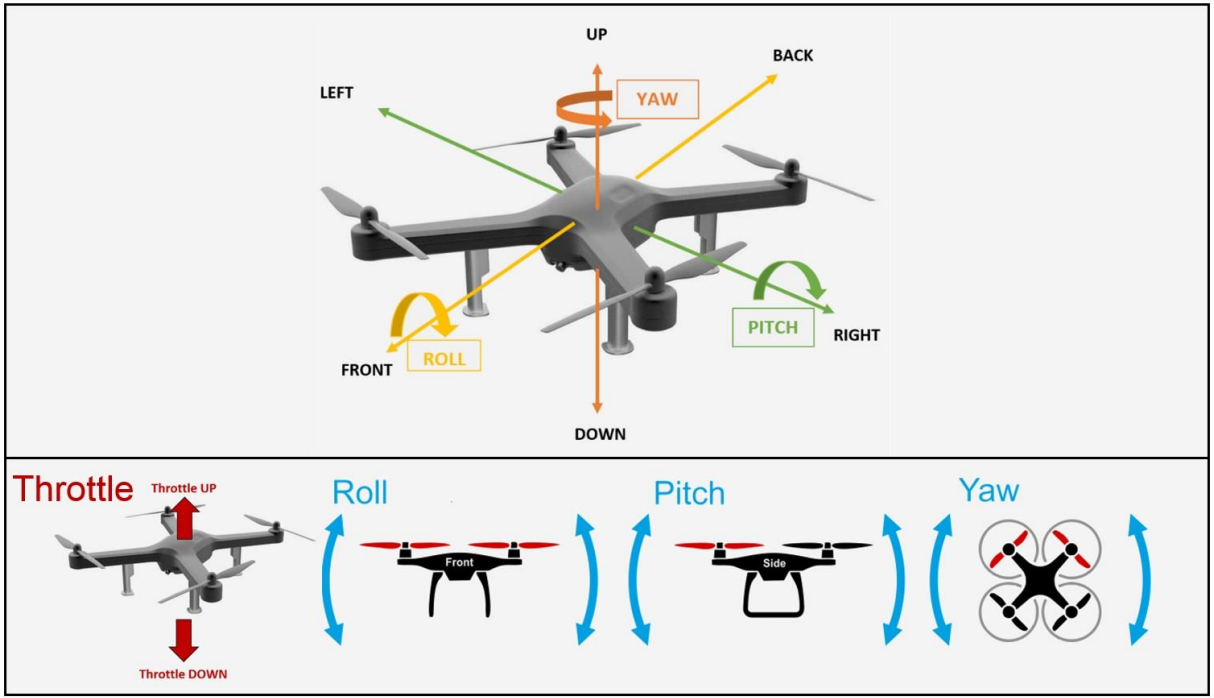
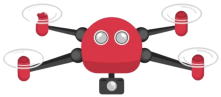


Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

State-of-Art Flight Management Systems: Problems



- Have low reactivity & slow response times

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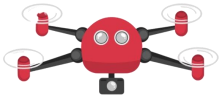
State-of-Art Flight Management Systems: Problems



- Have low reactivity & slow response times
- Are highly sensitive to external environmental dynamics leading to fight inaccuracy and instability

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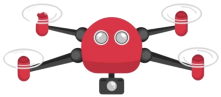

- Have low reactivity & slow response times
- Are highly sensitive to external environmental dynamics leading to fight inaccuracy and instability
- Are unable to continue flight & require emergency landing
  - Manual override
- Execute flight control tasks at the maximum possible frequencies all the time in adverse conditions!
  - Loosely “periodic” executions => soft time period bounds
  - Statically defined

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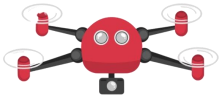
Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

Challenges



- Lack of system adaptability to changes in environment
- Lack of timing predictable behavior
- Inefficient use of limited battery power

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Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

smARTflight Contributions to Challenges

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Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

smARTflight Contributions to Challenges

- Lack of system adaptability to changes in environment
  - ✓Introduce **criticality-awareness** within the system
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System Criticality ≙ directly reflects influence of environment on the system

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Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

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Criticality ≙ Measure of severity of the consequences to the system in case of unpredictable behavior

System Criticality ≙ directly reflects influence of environment on the system

Task Criticality ≙ function of task's importance to maintenance of flight.

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Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

smARTflight Contributions to Challenges

- Lack of system adaptability to changes in environment
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- Lack of system adaptability to changes in environment
  - ✓Introduce **criticality-awareness** within the system
  - ✓**Dynamic adaptation of execution rates** of critical flight controller tasks

- Lack of timing predictable behavior
  - ✓Introduce **real-time** (RT) **task** execution constraints enforced by a **real-time scheduler –** deterministic flight

- Inefficient use of limited battery power

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Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

Challenges
✓ smARTflight Contributions

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- Lack of timing predictable behavior
  - ✓Introduce **real-time** (RT) **task** execution constraints enforced by a **real-time scheduler –** deterministic flight
- Inefficient use of limited battery power
  - ✓**Low** execution rates of tasks in **stable flying conditions**

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Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

Autopilots

BETAFLIGHT

ARDUPILOT

CLEANFLIGHT

INAV

PX4 autopilot

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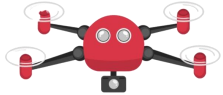
Autopilots



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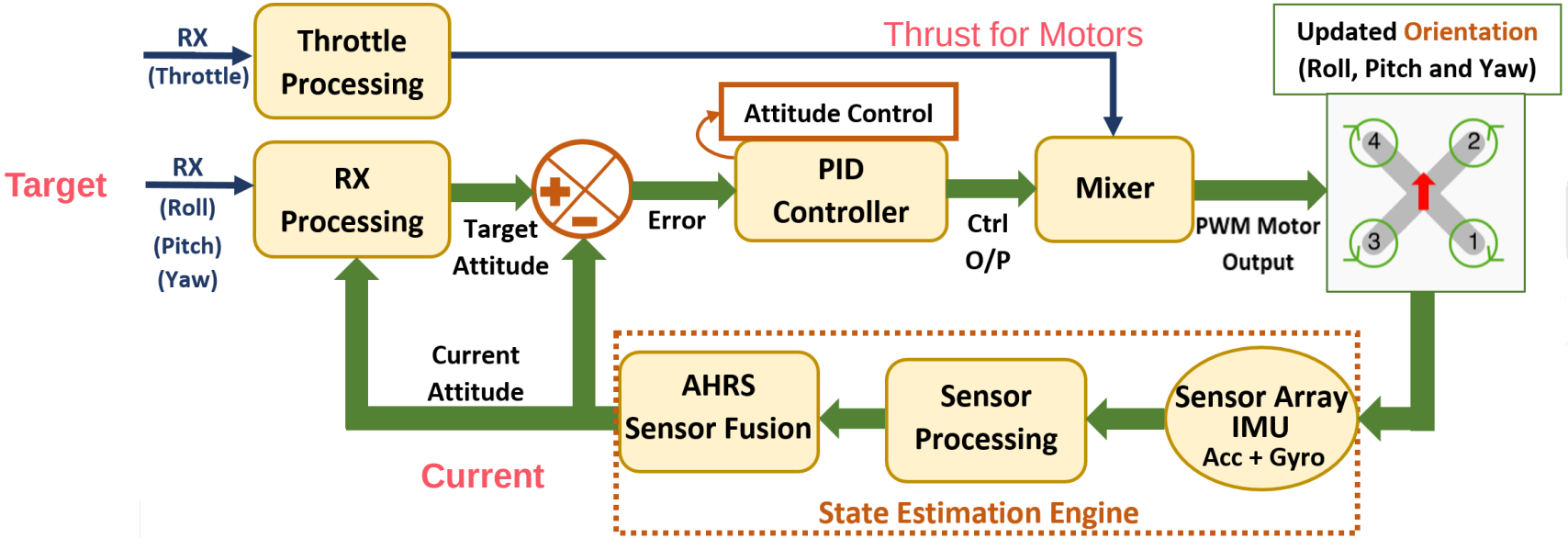
Autopilot Flight Control



Low-level attitude stabilization: classical linear feedback control loop

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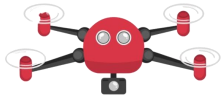
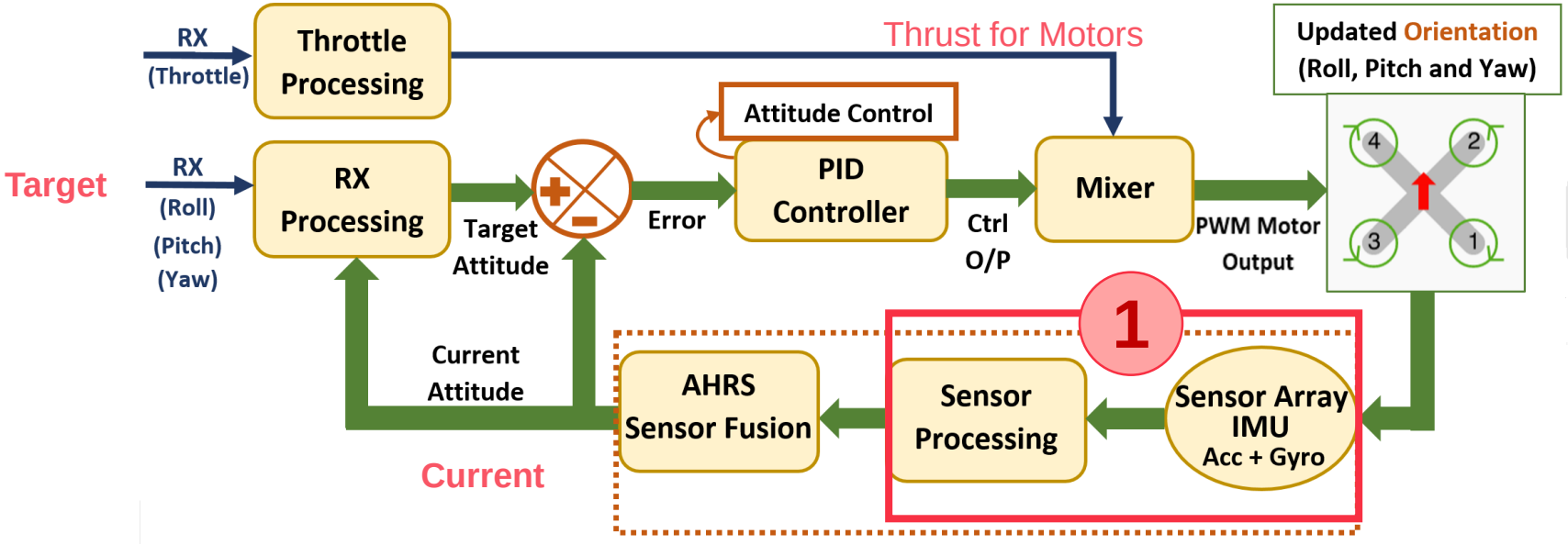
Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

Autopilot Flight Control





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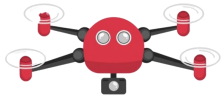

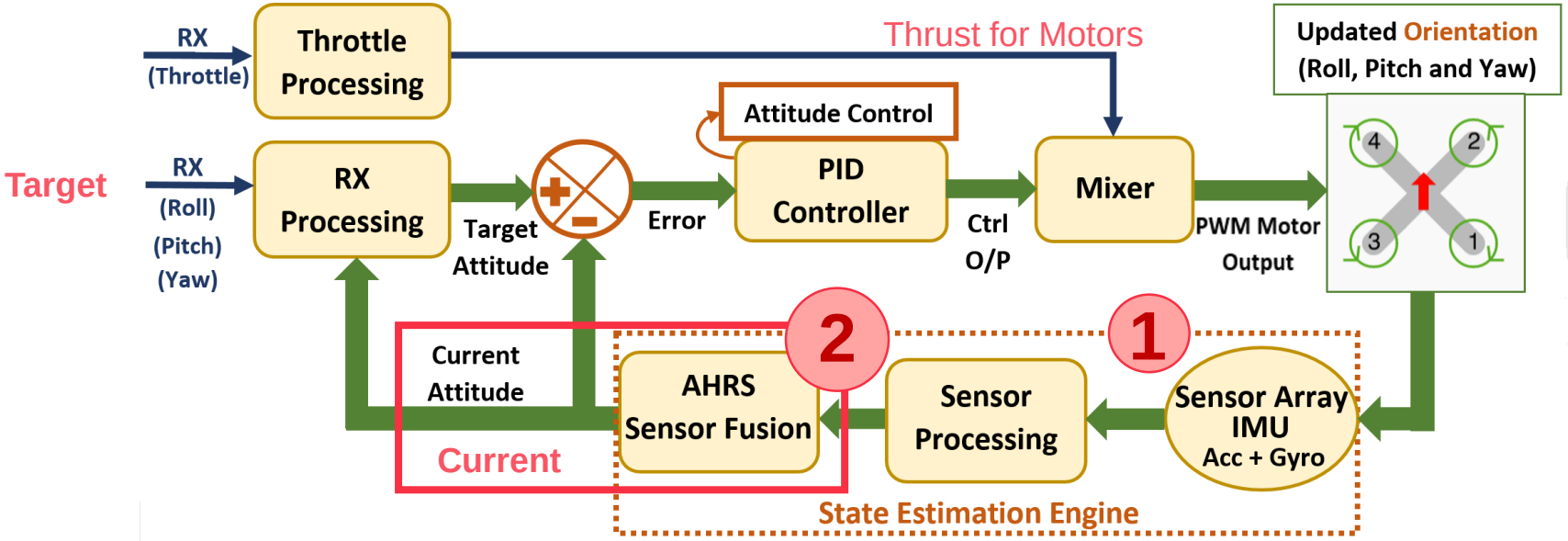

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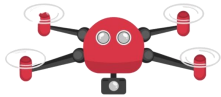

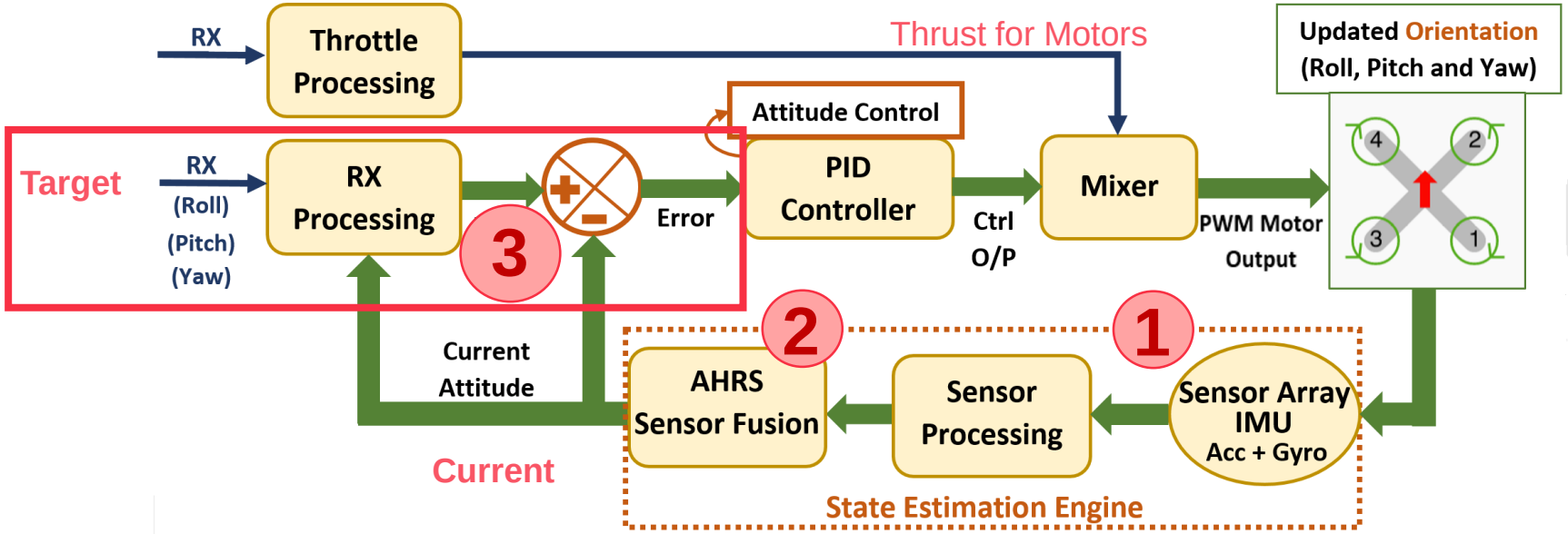

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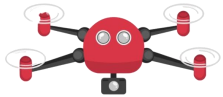

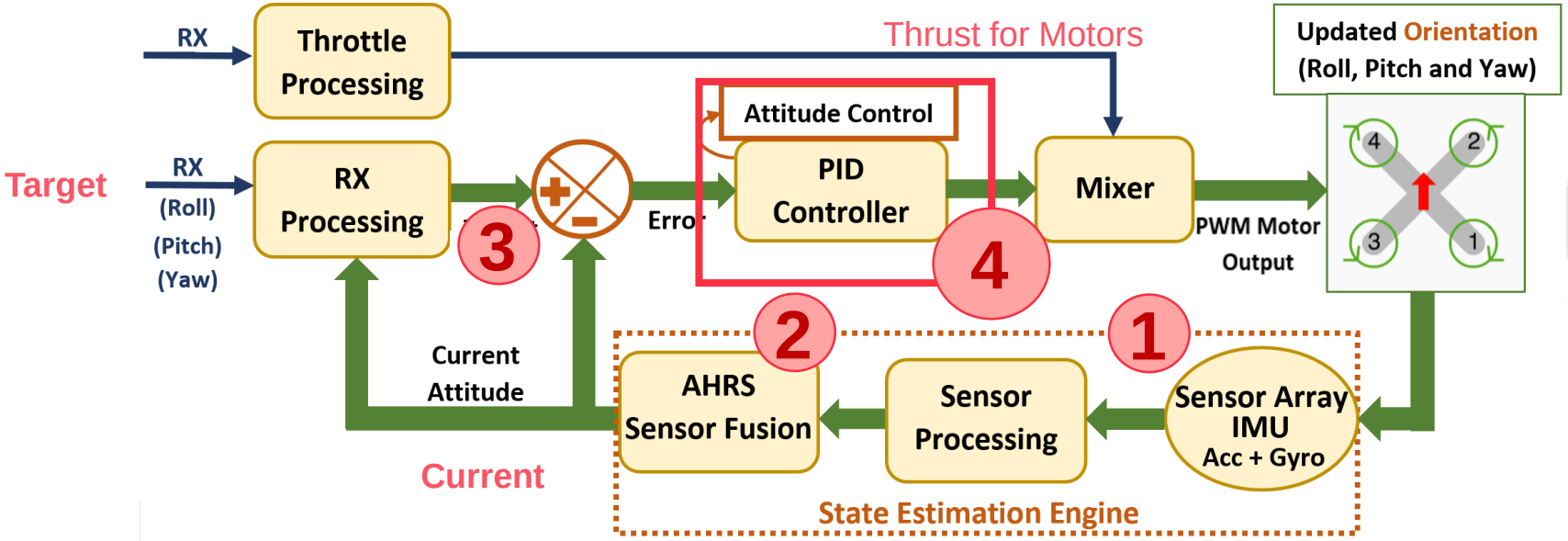

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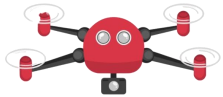

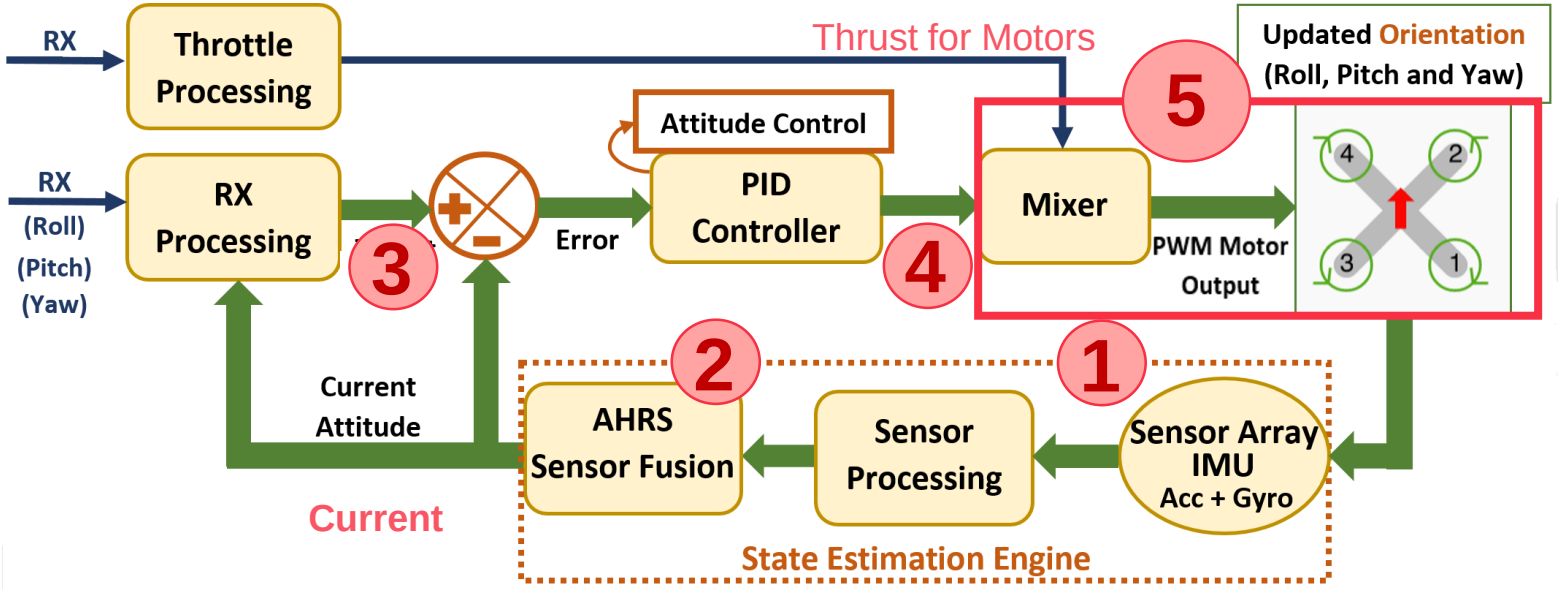

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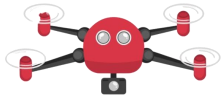

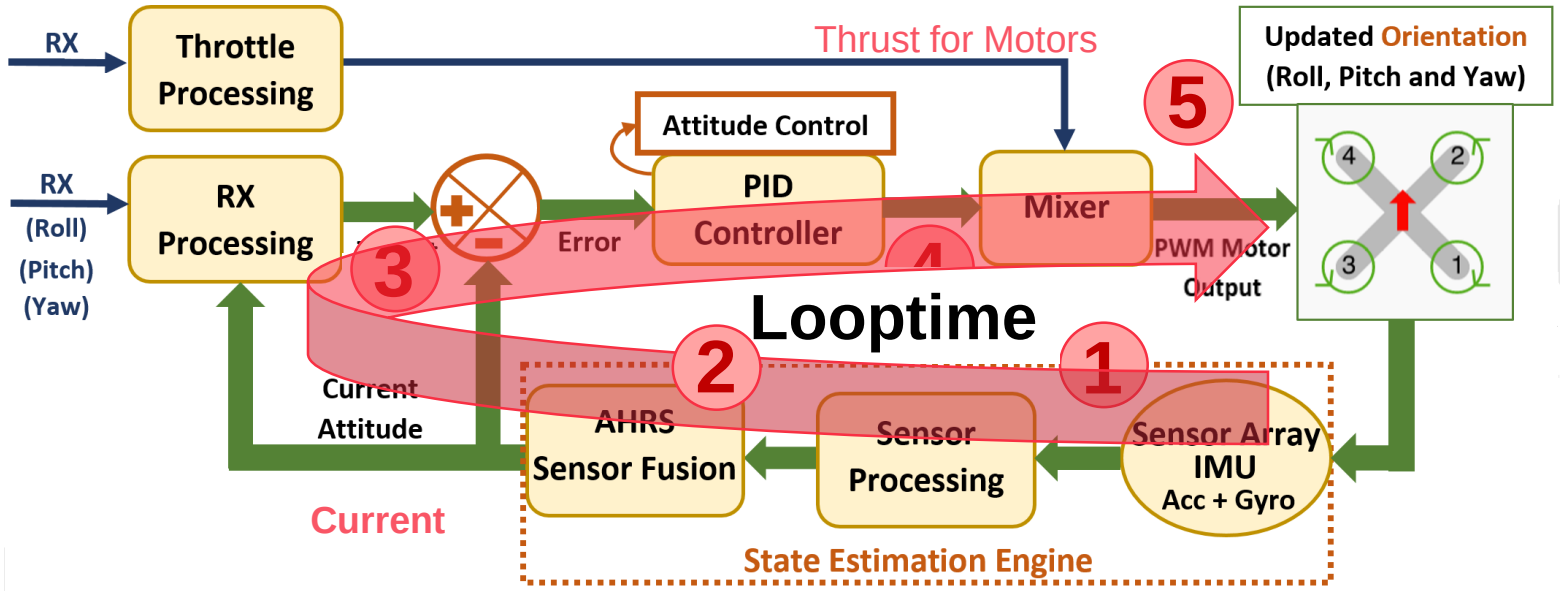

Low-level attitude stabilization: classical linear feedback control loop

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Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

KEY Observation

Flight Performance

translates

Rates of Execution of Critical Flight Controller Tasks

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Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

smARTflight Dual Criticality Semantics

- System Criticality
  Dynamic
  - HI (Adverse)
  - LO (Calm)

Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

smARTflight Dual Criticality Semantics

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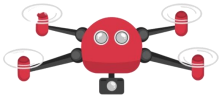

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Task Model

$$\{C_i,\ [T_i(\text{LO}), T_i(\text{HI})],\ [D_i(\text{LO}), D_i(\text{HI})],\ L_i,\ [p_i(\text{LO}), p_i(\text{HI})]\}$$

Budget **Periods** **Deadlines** **Task Criticality** **Task Priority**

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Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

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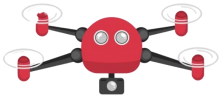

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Budget **Periods** **Deadlines** **Task Criticality** **Task Priority**

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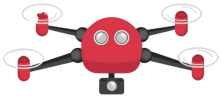
smARTflight Tasks



Task Name	Time Period (μs) Cleanflight	Execution Frequency (Hz)	Static Priority (Vanilla CF)	Criticality (smARTflight)	Description
TASK_SYSTEM	100,000	10	Med-High	LO	Report system statistics
TASK_BAT_VOLT	20,000	50	Medium		Sample battery voltage
TASK_GYROPID (Looptime)	**4,000 / 2,000 / 1,000**	**250 / 500 / 1,000**	**Real-Time** (highest)	**HI**	**Sample Gyroscope + PID-based motor control**
TASK_ACCEL	**1,000**	**1,000**	**Medium**		**Sample Accelerometer data**
TASK_ATTITUDE	**10,000**	**100**	**Medium**		**Calculate current attitude**
TASK_RX	20,000	50	High	LO	Process receiver commands
TASK_SERIAL	10,000	100	Low		Serial communication with the ground computer

Execution rates (default)

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smARTflight : System Mode Changes

- System mode changes are asynchronous events
  - Triggers: attitude change with respect to Euler angle thresholds
  - Attitude task registers the change and propagates the mode change flag to the scheduler
  - smARTflight scheduler:

LO Criticality Tasks	HI Criticality Tasks
$T_i(L_{sys} = \text{LO}) \leq T_i(L_{sys} = \text{HI})$	$T_i(L_{sys} = \text{LO}) > T_i(L_{sys} = \text{HI})$

LO ⟷ HI LO ⟷ HI

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Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

smARTflight : System Mode Changes

- System mode changes are asynchronous events
  - Triggers: attitude change with respect to Euler angle thresholds

Threshold $\triangleq$ Maximum tolerable transient deflection from the target attitude

LO Criticality Tasks	HI Criticality Tasks
$T_i(L_{sys} = \text{LO}) \leq T_i(L_{sys} = \text{HI})$	$T_i(L_{sys} = \text{LO}) > T_i(L_{sys} = \text{HI})$

LO ⟷ HI LO ⟷ HI

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smARTflight : System Mode Changes

- System mode changes are asynchronous events
  - Triggers: attitude change with respect to Euler angle thresholds
  - Attitude task registers the change and propagates the mode change flag to the scheduler
  - smARTflight scheduler:

LO Criticality Tasks	HI Criticality Tasks
$T_i(L_{sys} = \text{LO}) \leq T_i(L_{sys} = \text{HI})$	$T_i(L_{sys} = \text{LO}) > T_i(L_{sys} = \text{HI})$

LO ⟷ HI LO ⟷ HI

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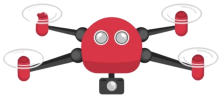

smARTflight: Schedulability Framework

- RMS CF: no criticality semantics (standard RMS)

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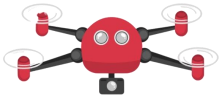

smARTflight: Schedulability Framework

- RMS CF: no criticality semantics (standard RMS)
- **smARTflight**: extended and modified Liu & Layland's RMS algorithm
  - Task rates and priorities adapt
  - Ready queue updated @ runtime
  - Scheduler quantum reprogramming
  - Transient system overload checks to avoid failure

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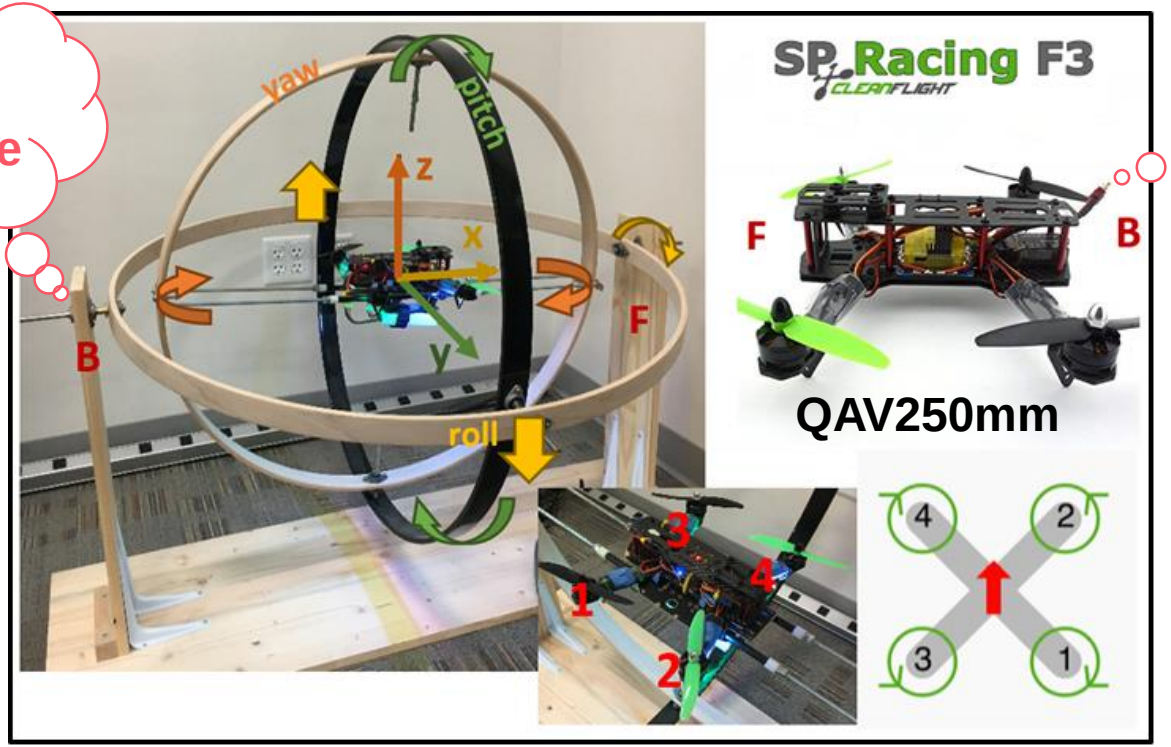
smARTflight : Experimental Setup

The BirdCage

The Bird



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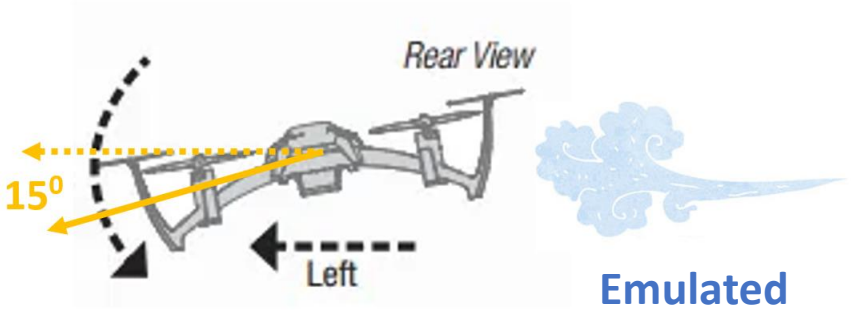
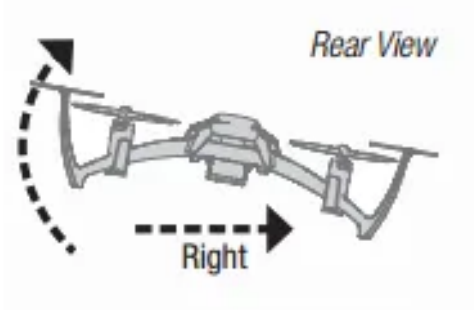
smARTflight : Experiment Type





HI ⟷ LO
smARTflight

Step Attitude Disturbance

Attitude Correction

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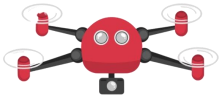

smARTflight : Experimental Phases

CLEANFLIGHT

I	II	III
Vanilla CF	RMS CF	smARTflight
Static Rate Response Times	Real-Time Scheduler	Adaptive Real-Time + Criticality

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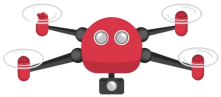

smARTflight : Experimental Phases

CLEANFLIGHT

I Vanilla CF

Static Rate
Response Times

II RMS CF

Real-Time Scheduler

III smARTflight

Adaptive Real-Time
+ Criticality

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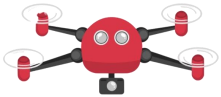

Vanilla Result : 15^0 Roll-Left Response Times

Critical Tasks	Default Rates (Hz)			Custom Execution Rates (Hz)									
GYROPID/Looptime	1000	500	250	1000			500			250			
ACCEL	1000			1000			500			250			
ATTITUDE	100			200	100	50	200	100	50	25	200	100	50
Roll: Avg. Response Times (s)	13.5	18.5	21.5	14	13.5	21.5	33	16.5	20	33	33	32.5	26.5

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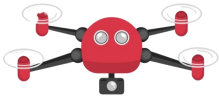
smARTflight : Experimental Phases



I
Vanilla CF

Static Rate
Response Times

II
RMS CF

Real-Time
Scheduler

III
smARTflight

Adaptive Real-Time
+ Criticality

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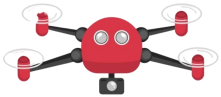
smARTflight : Experimental Phases



I Vanilla CF

Static Rate Response Times

II RMS CF

Real-Time Scheduler

III smARTflight

Adaptive Real-Time + Criticality

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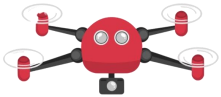
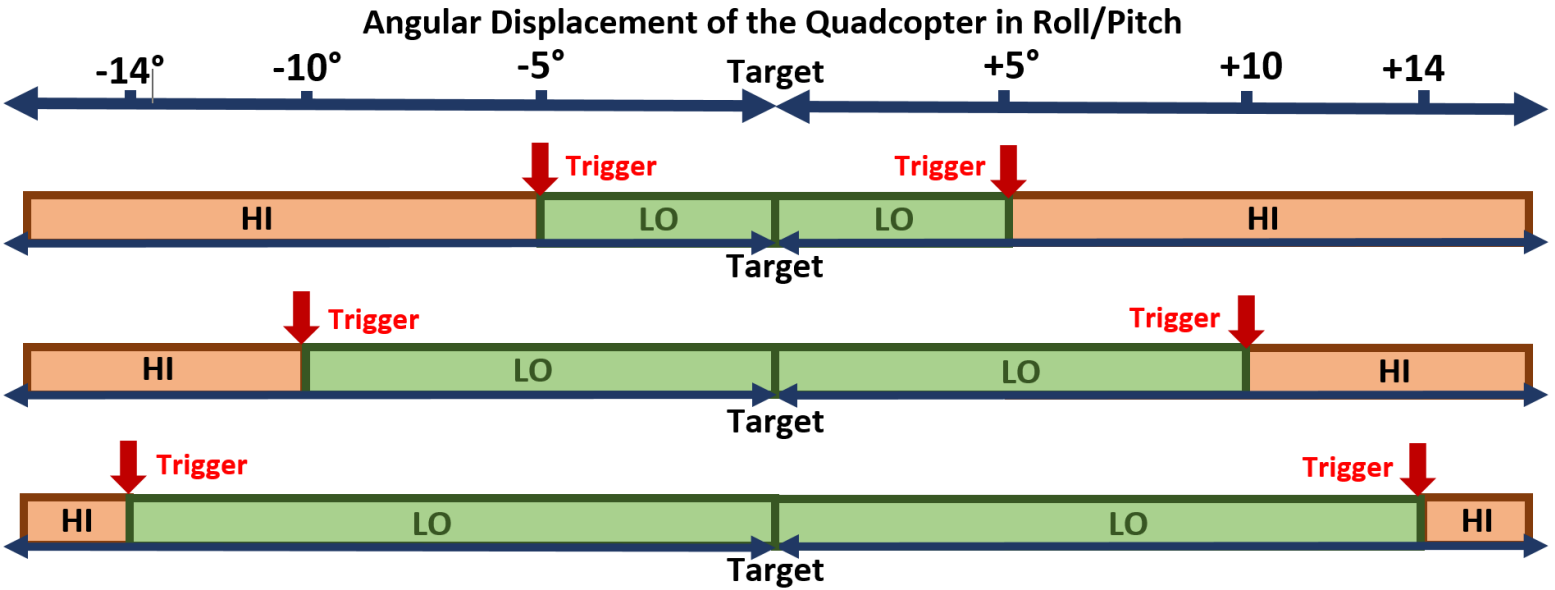
smARTflight : Roll Thresholds





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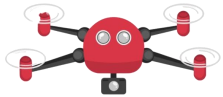
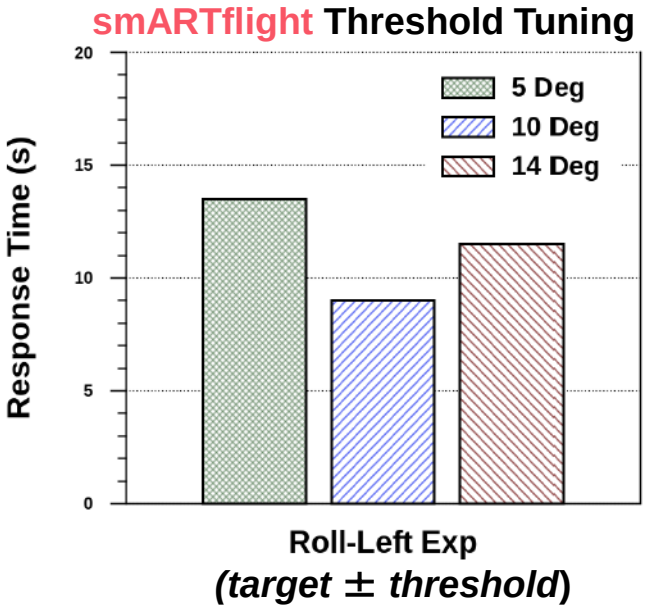
Comparison : 15^0 Roll-Left Response Time





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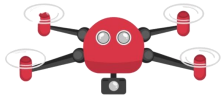
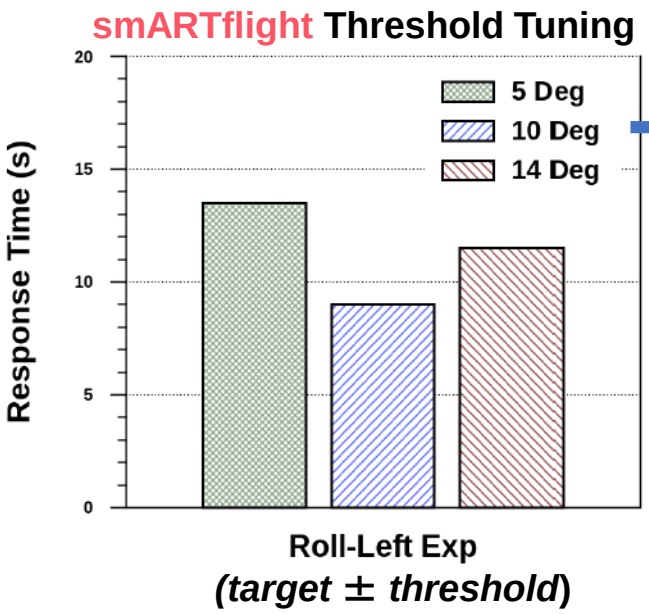
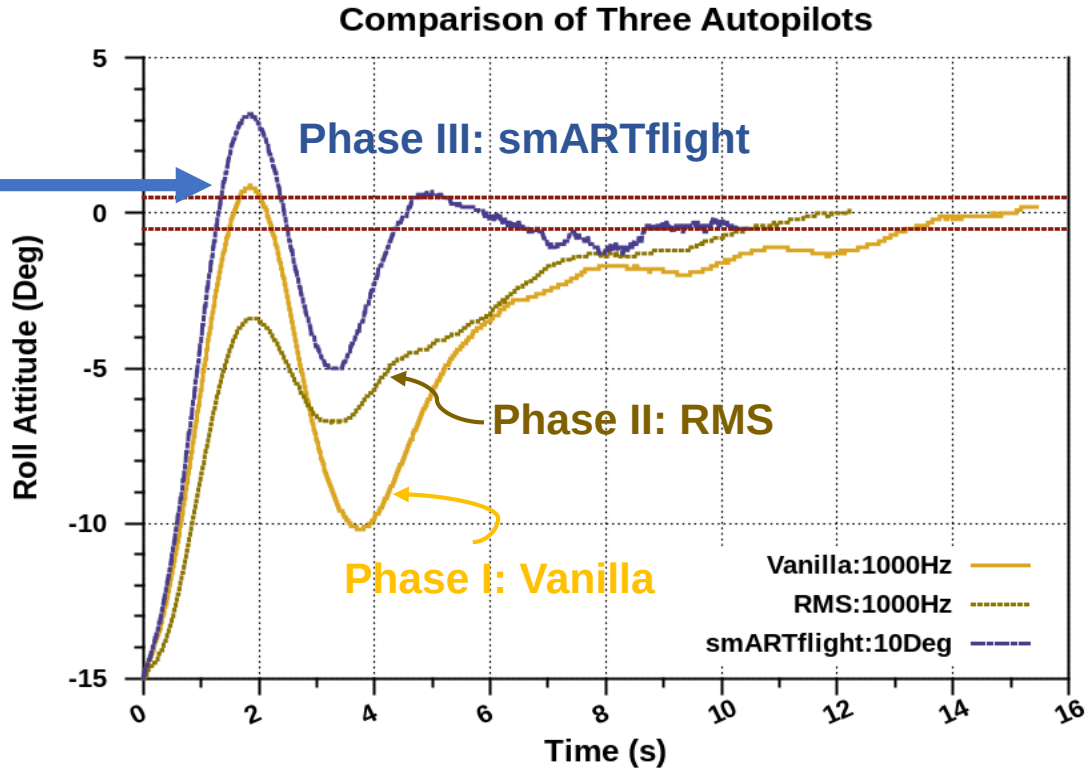
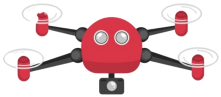
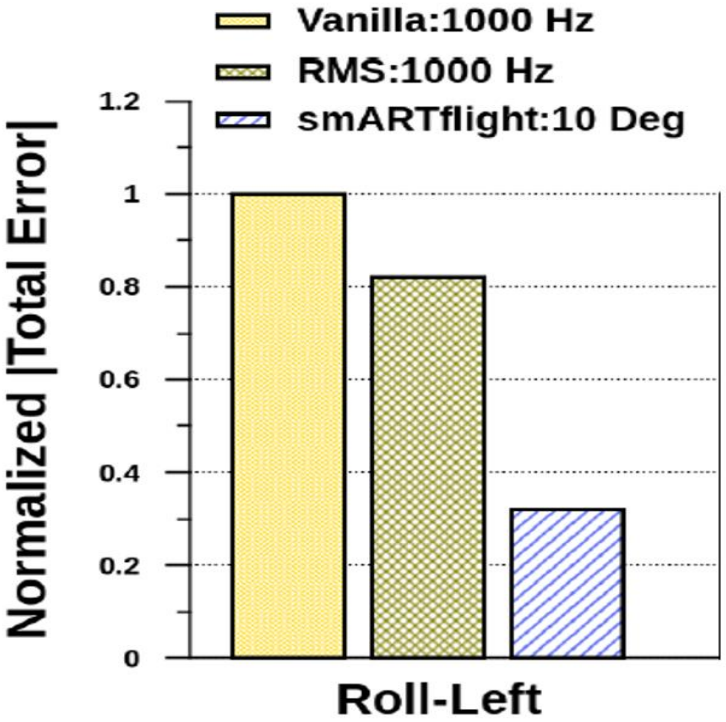






Autopilot Comparison Results





Cumulative Absolute Error

Image courtesy: https://www.slideteam.net/flying-drone-robot-with-two-propellers.html

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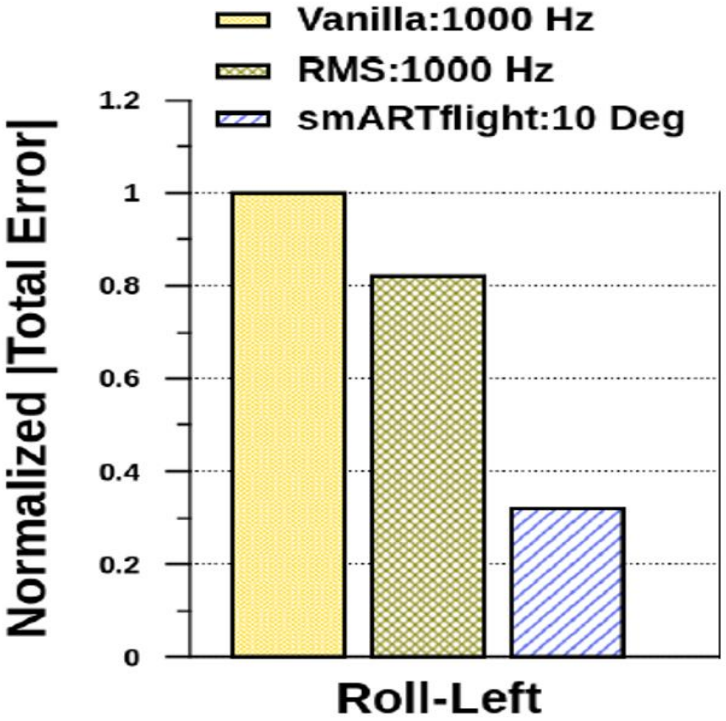

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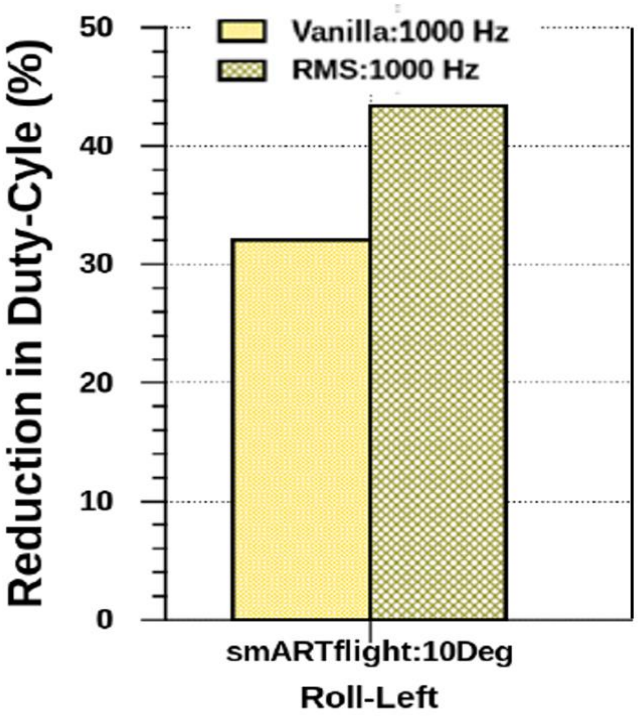

Avg. Duty-Cycle : Motor

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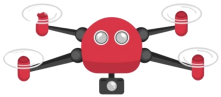
Conclusions



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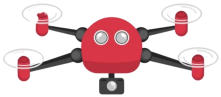

- **smARTflight**: an environmentally aware, criticality based Adaptive, Real-Time flight management system for multi-copters
  - Task and system criticality
    - Environmental triggers for system modes
    - Dynamic reconfiguration of task execution frequencies

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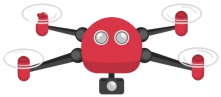

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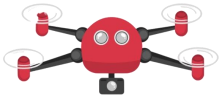
Conclusions



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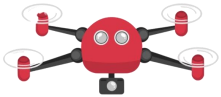
Conclusions



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  - Improved flight performance : {response, energy & absolute error}
  - Extends legacy autopilots with smart resource management

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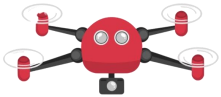

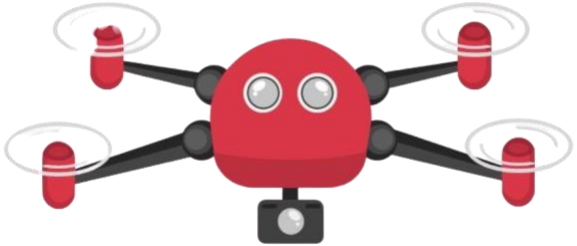

Thank You

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