THE LINUX FOUNDATION
OPEN SOURCE SUMMIT
EUROPE

Embedded Linux Conference
Europe

# Customize Real-Time Linux for Rocket Flight Control System

George Kang,
Advanced Rocket Research Center, Taiwan
Oct 29, 2019

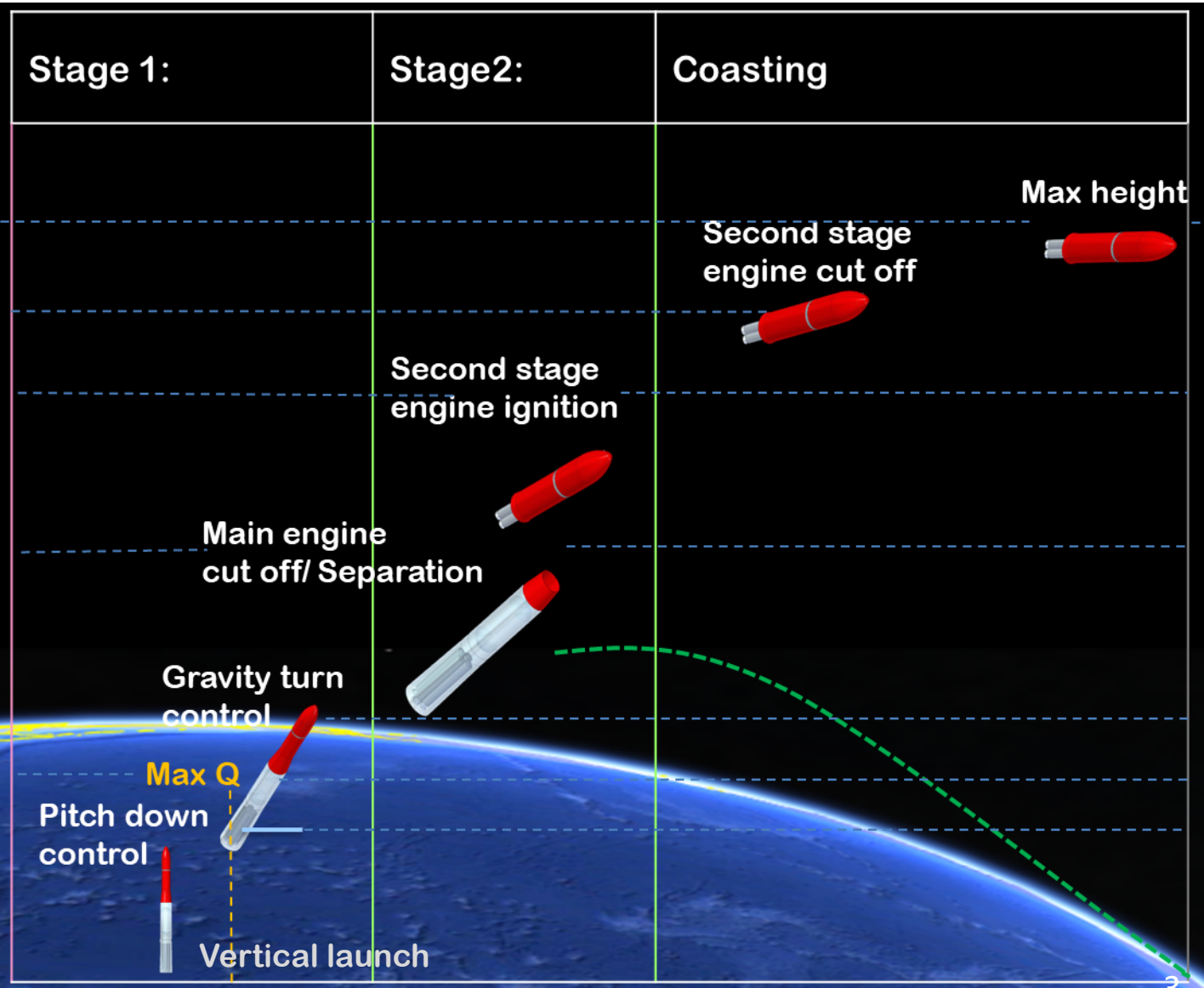
THE LINUX FOUNDATION

# About me and ARRC

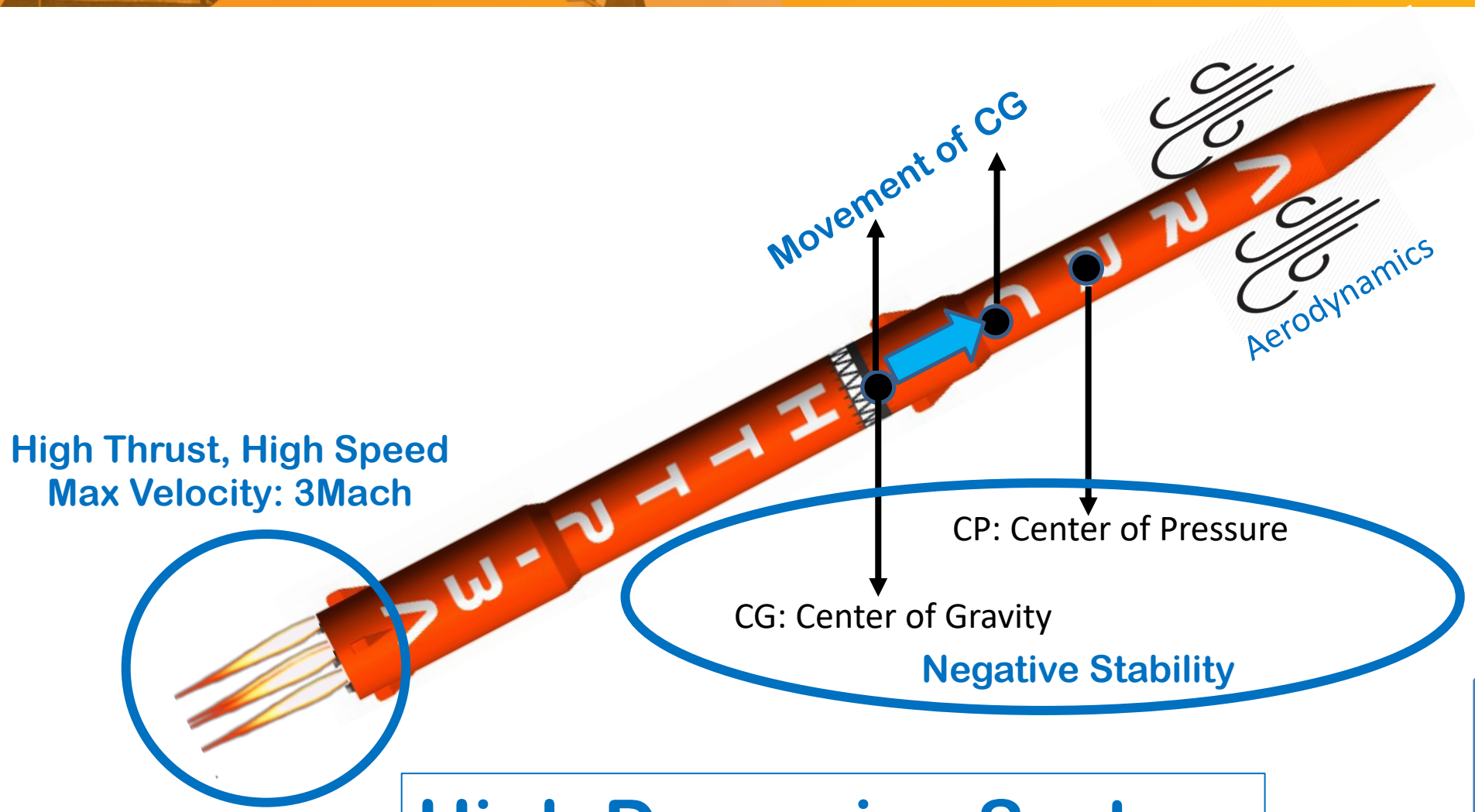
- George Kang,
  - Avionics Software Manager, ARRC, Taiwan
- **Advanced Rocket Research Center** (ARRC)
  - Taiwan space transport research organization headquartered at National Chiao Tung University in Hsinchu City

# HTTP-3a Flight Mission

- 2- stage hybrid rocket
  - Liquid Oxidant
  - Solid Fuel
- Vertical launch
- TVC control for both stages
- Liftoff weight: 800 kg
- Expected impulse:
  - ✓ Stage 1: 770,000 N-s
  - ✓ Stage 2: 310,000 N-s
- Hot staging separation
- Mission: 100 km height



# Rocket Flight Control



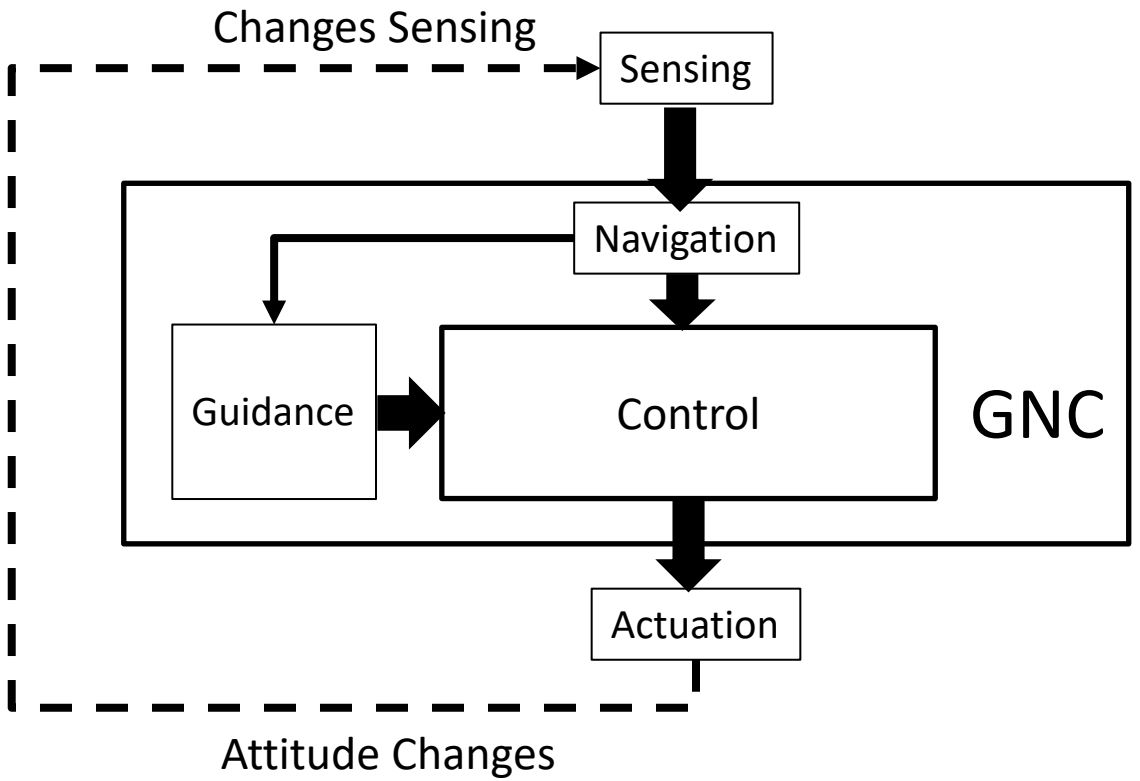

**Mission**

**High Dynamics System**

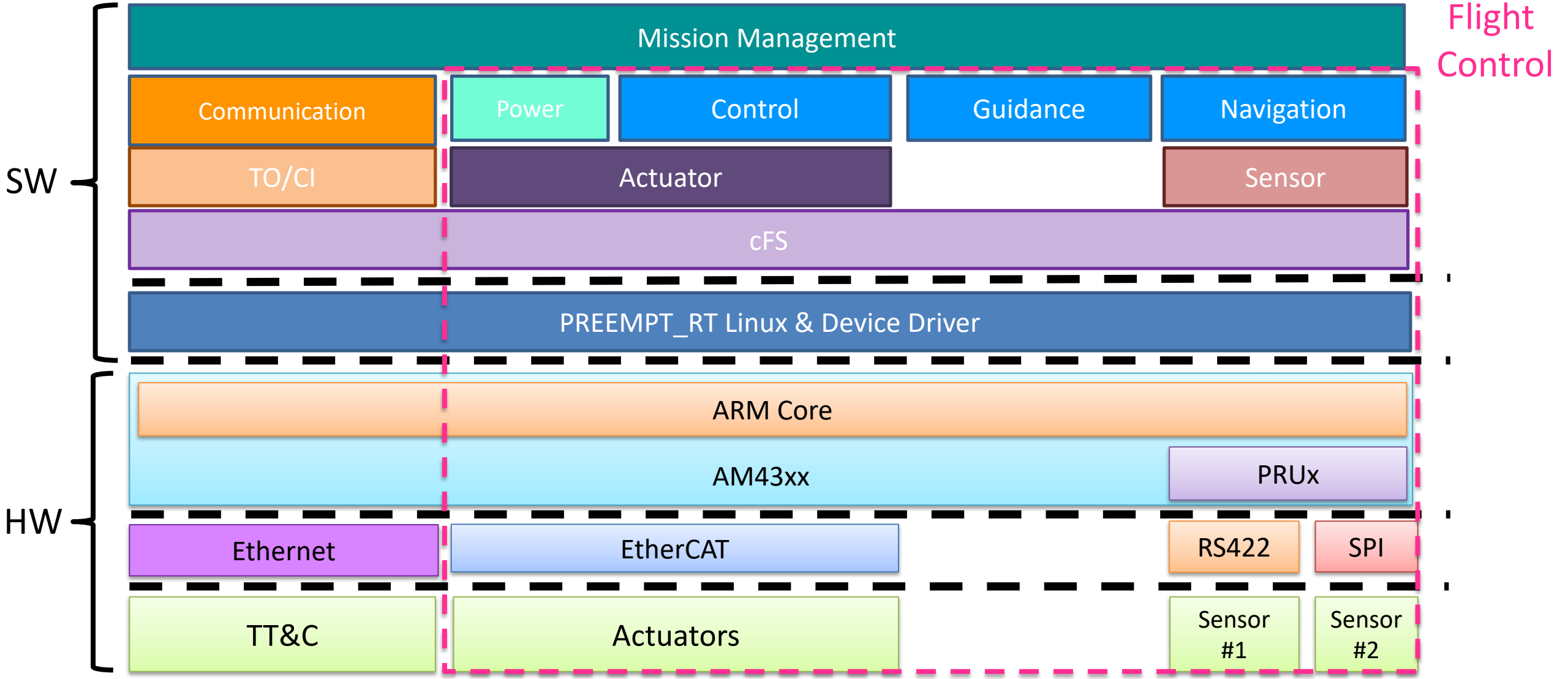
**Real Time Control System**

# Real Time Flight Control Model

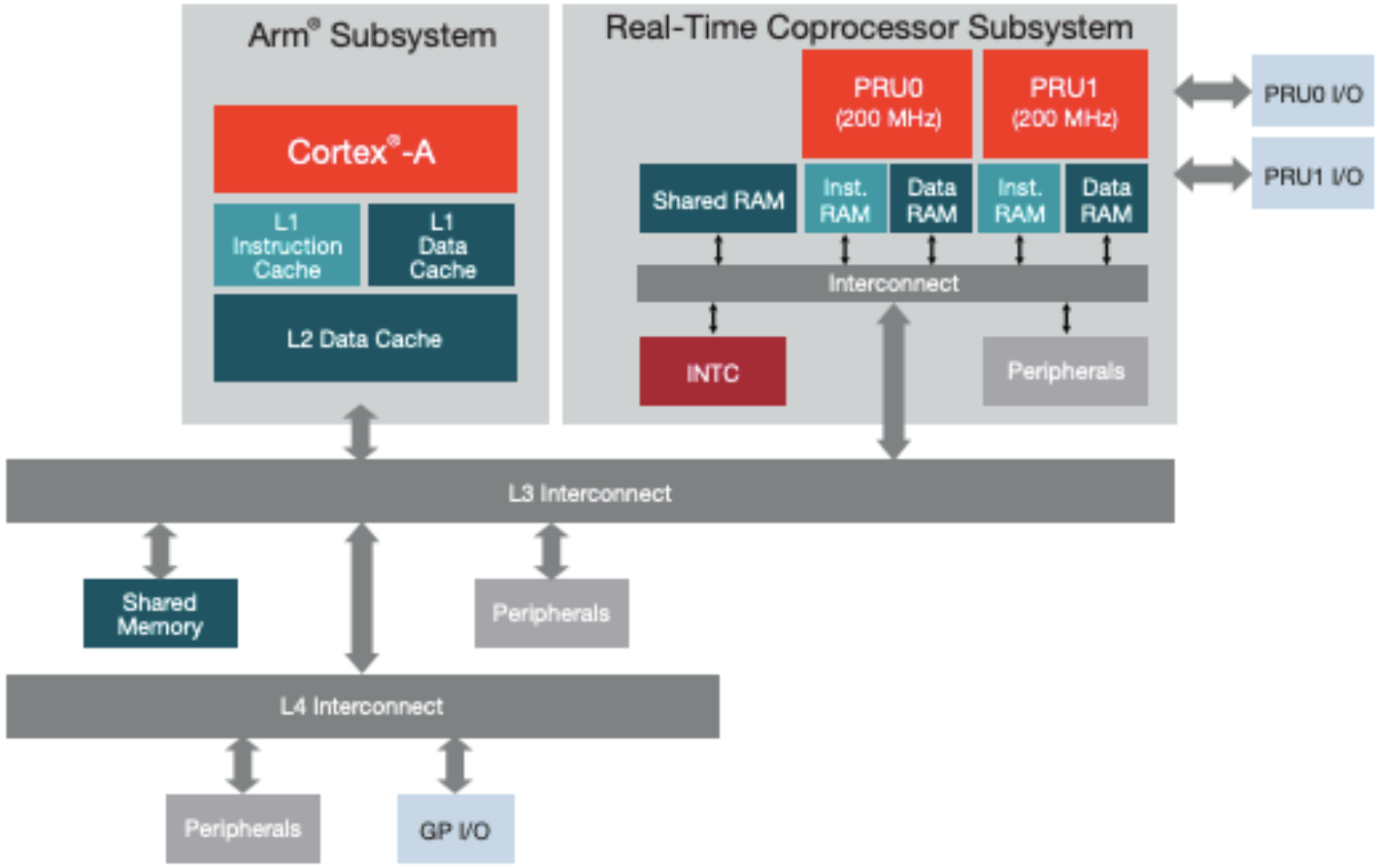
- Sensing:
  - Retrieve the rocket status from sensors
  - Moment, Rotation
- Computing:
  - Produce control commands for actuators through sensor data
  - Guidance/Navigation/Control (GNC)
- Actuation
  - Physical reaction by the control commands
- Real Time:
  - Response the rocket status within constraint
  - Deterministic timing

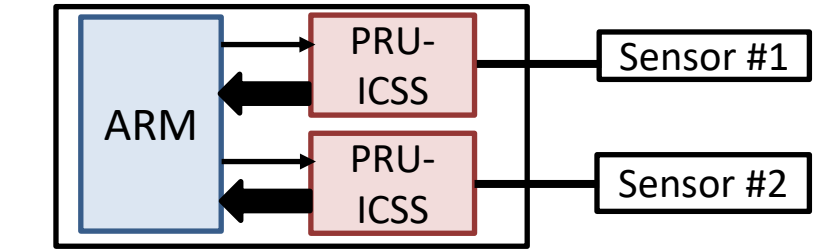


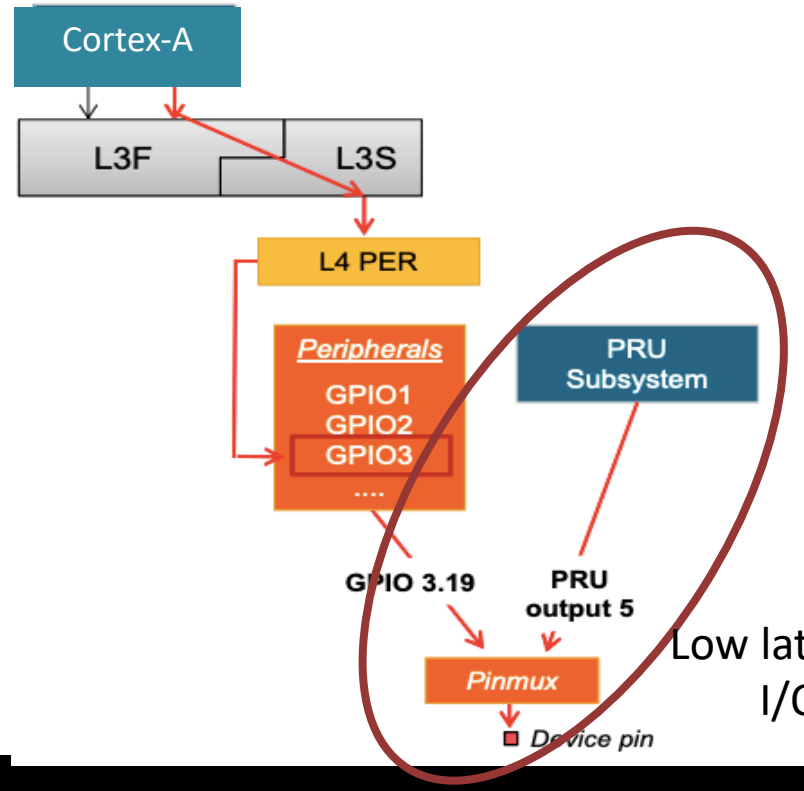
# Avionics System Architecture



# PRU-ICSS for Sensing I/O



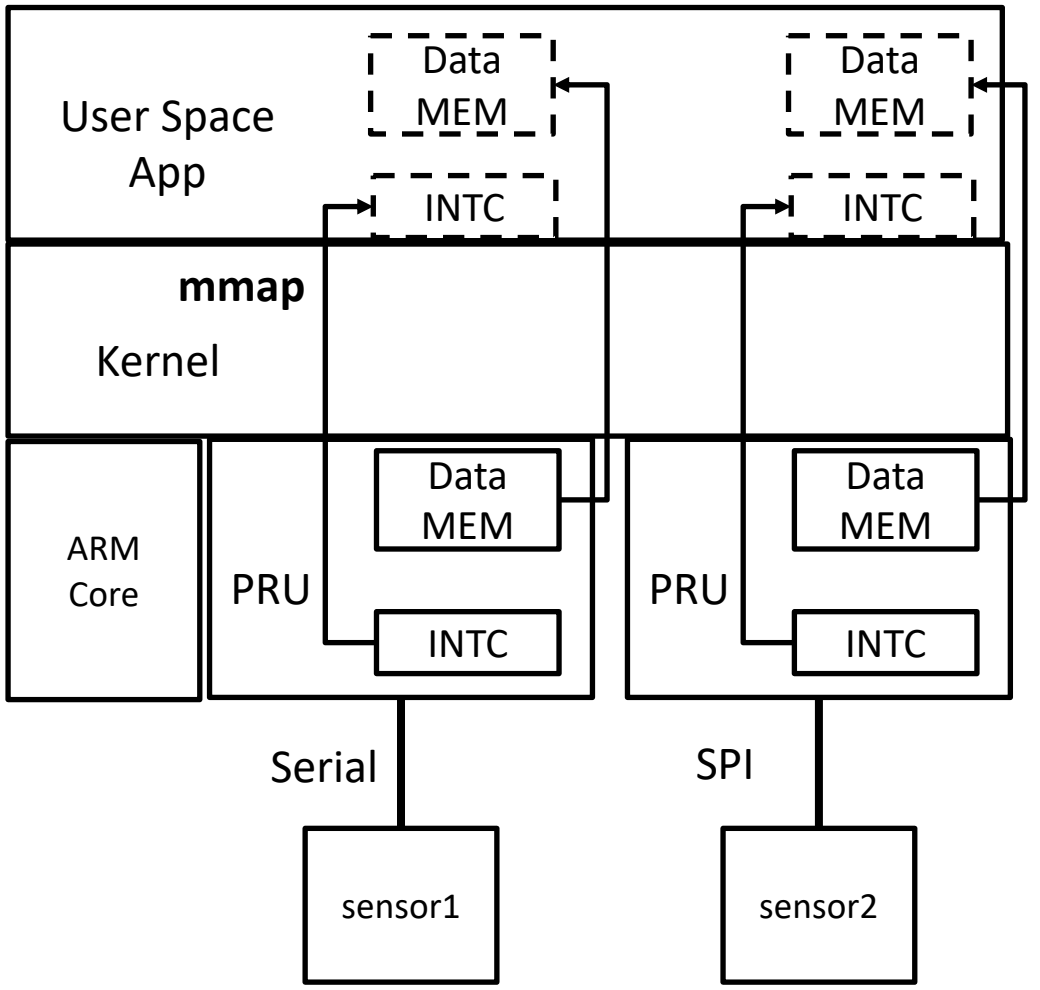




Low latency I/O

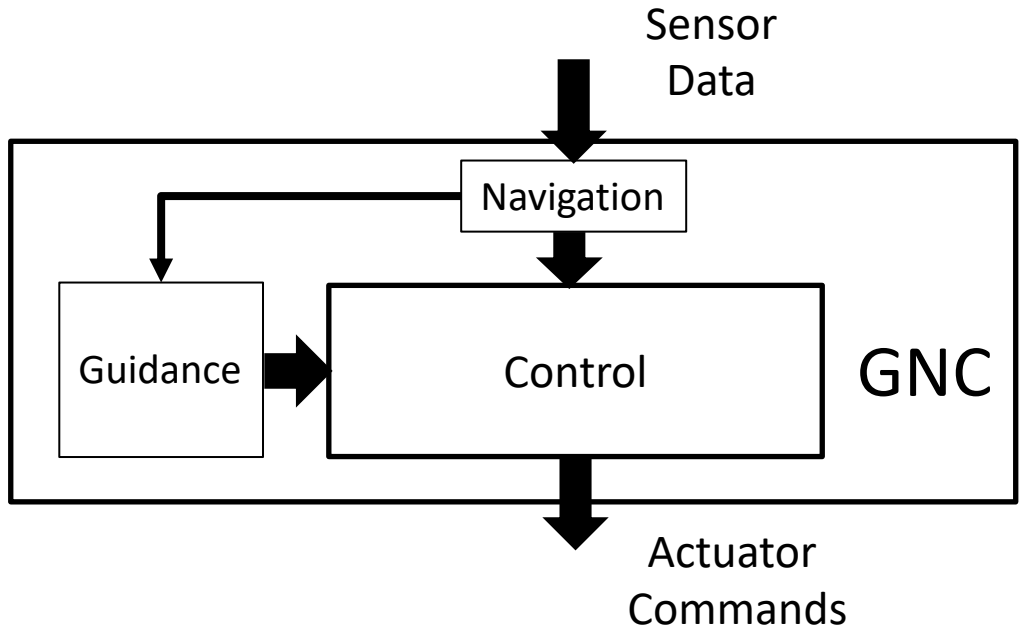
# Sensing Process

- Reduce the communication latency between user application and PRU
- mmap PRU resource
  - Data MEM: query result
  - INTC: Synchronization



# Computing Model

- Navigation
  - Reduce sensor flaws
  - Coordinate transformation
  - Sensor fusion to increase accuracy
- Guidance
  - Optimal steering by mission & current navigation data
- Control
  - Manipulate the rocket status by N&G data
  - Produce actuation commands

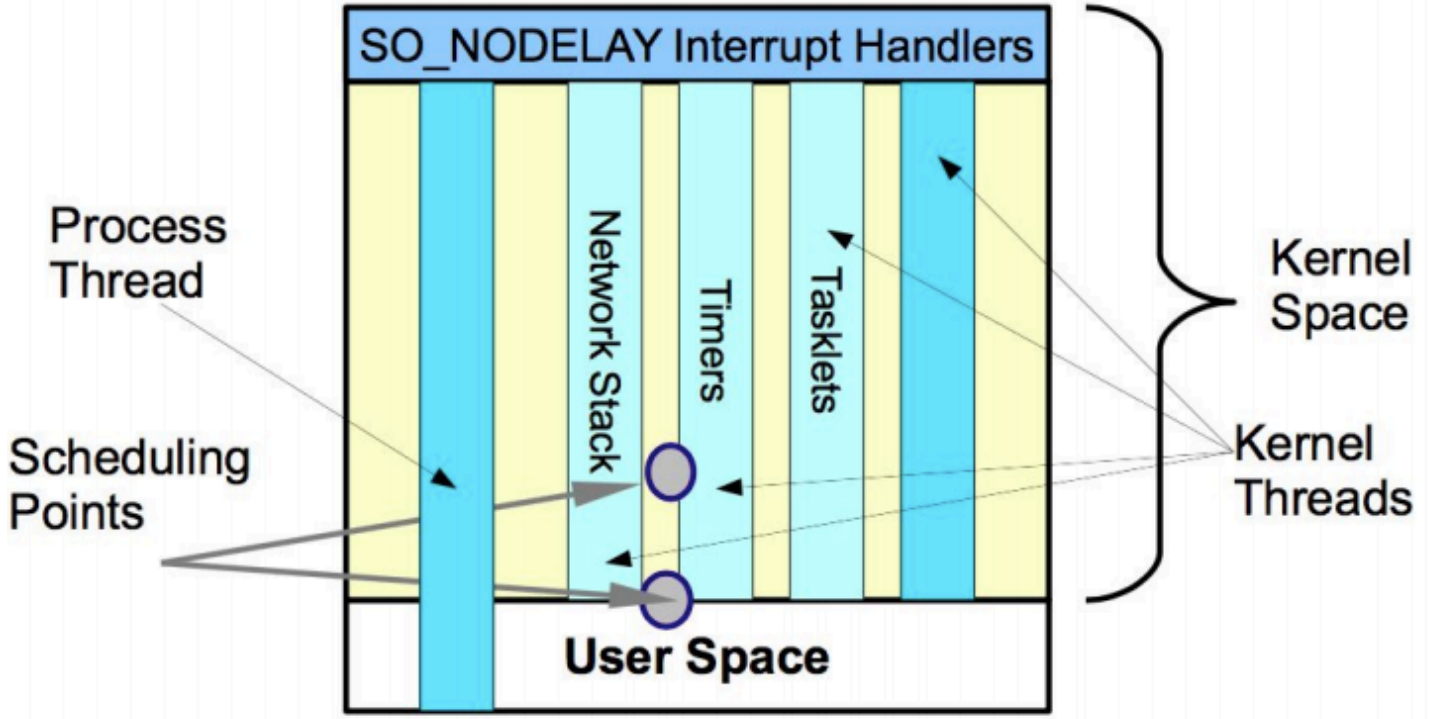


# PREEMPT_RT Linux

## PREEMPT_RT_FULL

Threaded Interrupts


Reduce non-preemptible cases in kernel: `spin_lock`, interrupt



# Flight Software Framework

- Based on NASA core flight System (cFS) v.6.5
  - Open source released
  - OSAL (OS abstraction layer) for Linux Platform
  - cFE (core Flight Executive)
    - A framework of mission independent, re-usable, core flight software services and operating environment
  - cFS Libraries/Applications

# Application Execution

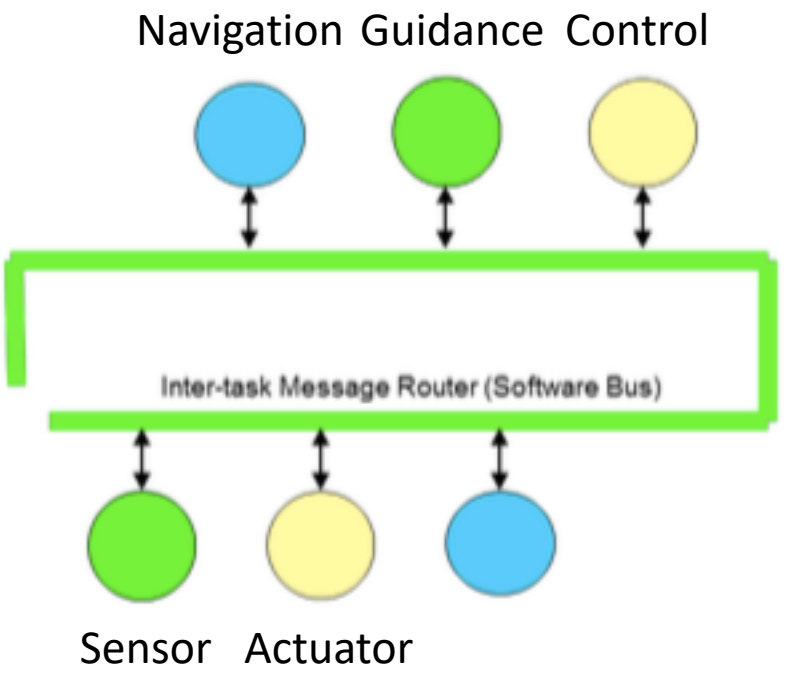
- Implemented by POSIX thread
- Managed by the cFE Executive service
  - Start, restart, and delete
  - Priority
  - Stack size

# cFE Memory Model

- Memory pool service
- Get/Put API for memory block
  - lists for returned blocks
  - allocate block from lists if found
  - create new block with requested size
- Deterministic (but restricted) allocation
  - pre-defined memory size
  - predictable but not constant execution time in multi-threading env because of lock

# Inter-process Communication

- Software bus
- Implemented by Linux Messag Queue
- Publish/Subscribe
  - Loosely coupled
  - Standard interface
  - Component independence
- Flight control applications on software bus

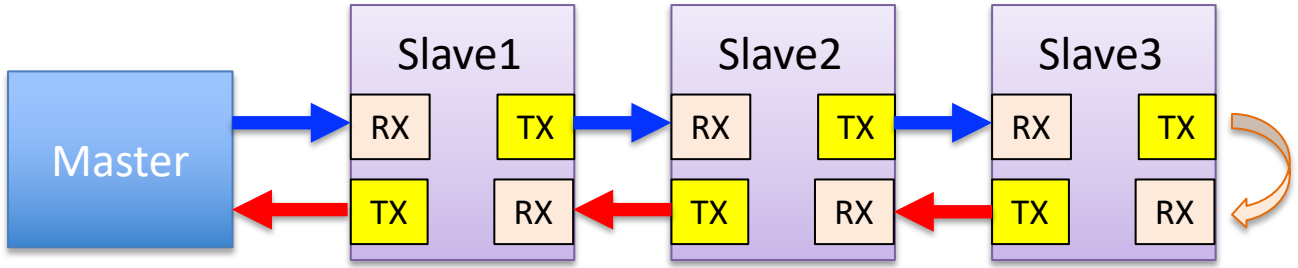


# Time Service

- Precise spacecraft time
  - MET: Mission elapsed time
  - STCF: Correlate MET to ground epoch
- Timer:
  - Local 1HZ timer
  - Tone: Accurate and trusted time signal for system time adjustment
    - 1HZ for MET second – 1PPS
    - External Tone by GPS receiver
    - Flywheeling while the Tone is invalid
- Distribute an 1HZ wakeup command
- Increase the Timer frequency in ARRC Rocket

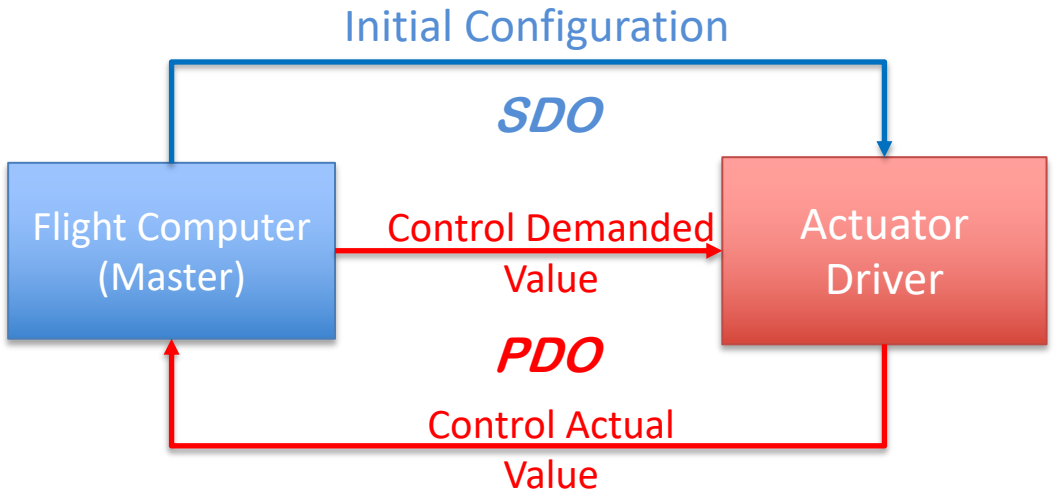
# Real Time Actuation Network

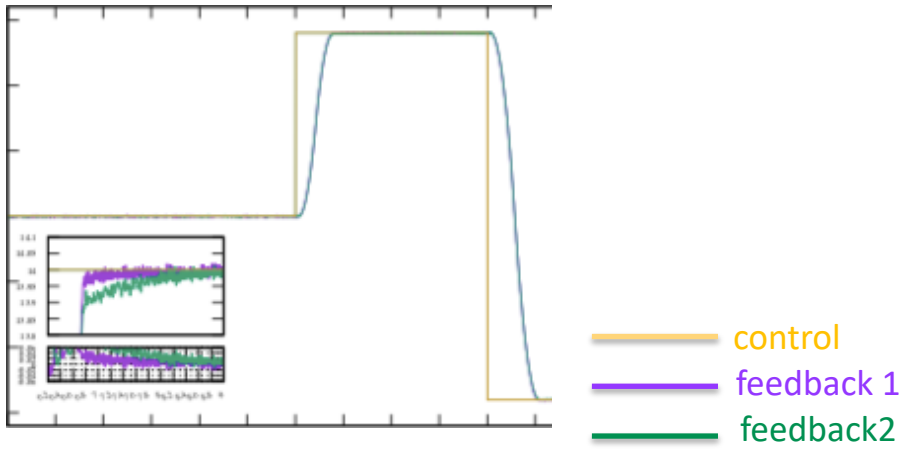
- Synchronized control
- Small jitter
- EtherCAT
  - master/salve:
  - cyclic operation
  - cycle time <= 100us
  - jitter <= 1us
  - Distributed clock (DC)for synchronization
  - flexible topology
  - cable redundancy



# Actuator Control

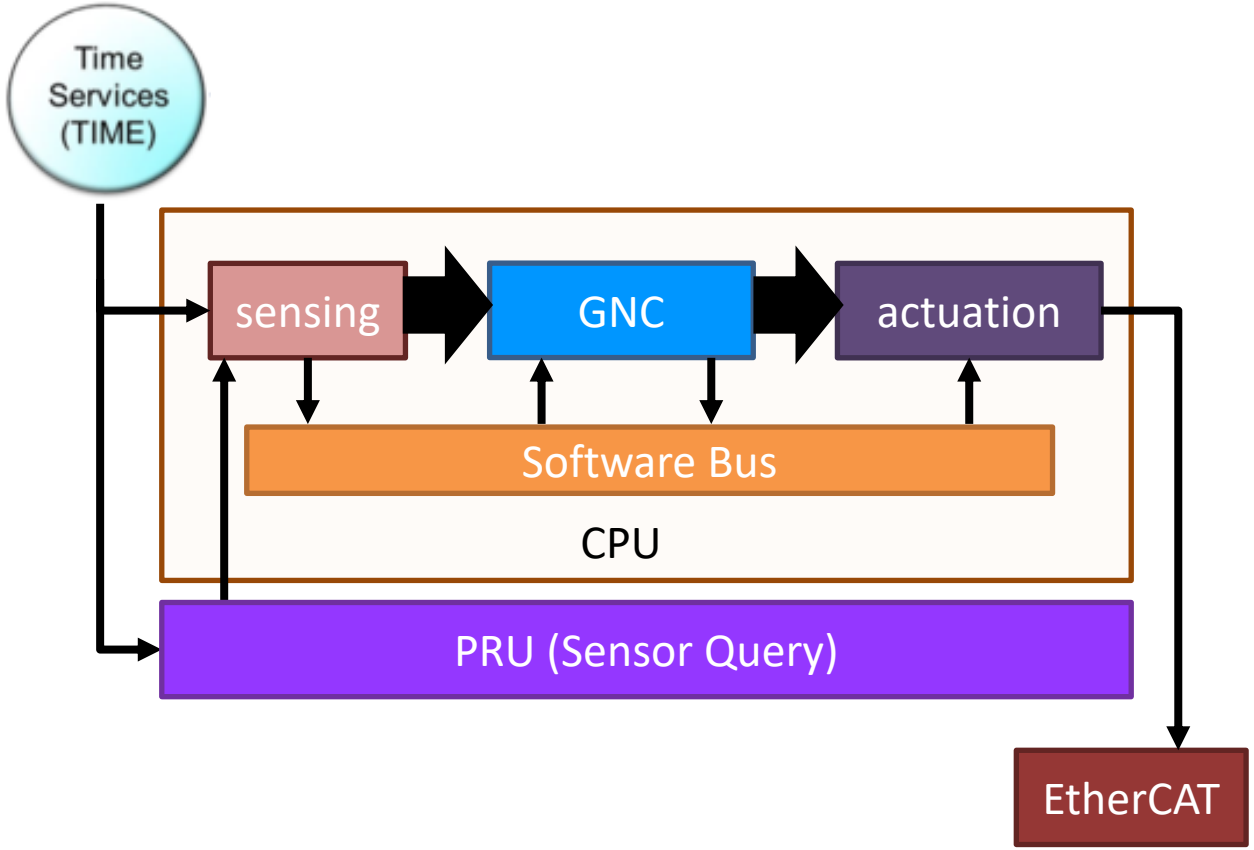
- EtherCAT Actuator App on cFS
- Integrate Etherlab IgH Master
- SDO (Service Data Object):
  - Initial configuration
  - Not real time
  - One-to-one communication
- PDO (Process Data Object):
  - Cyclic control data exchange
  - Real time
  - One-to-many communication



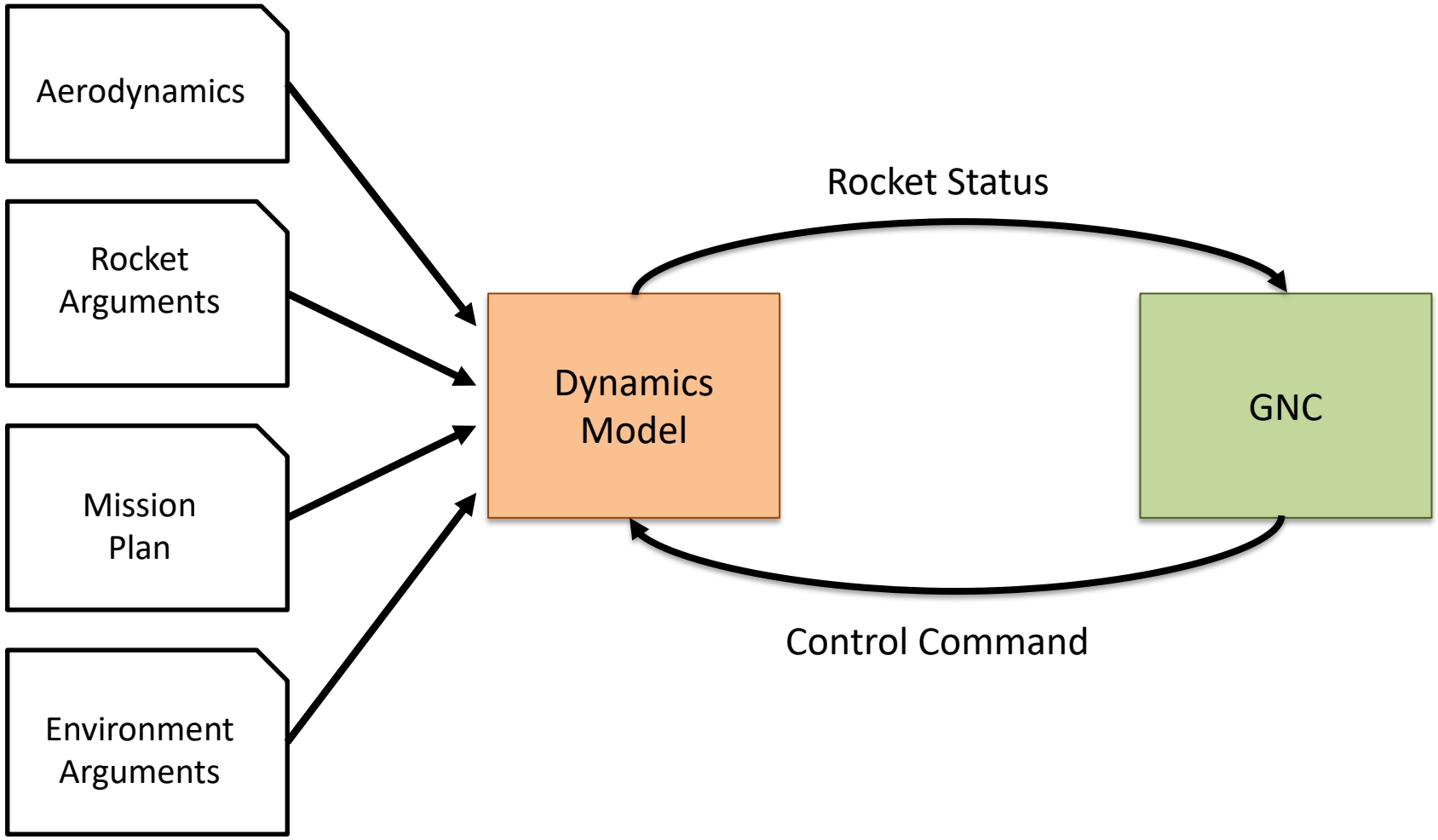



# Flight Control Software

- Sequential execution
  - Sensor => GNC => Actuator
- Triggered by cFE Time Service
- Real time Issues:
  - Accuracy & precision of time service
  - Latency of software bus
  - Synchronization between PRU & CPU
  - GNC execution time
  - EtherCAT transmission time

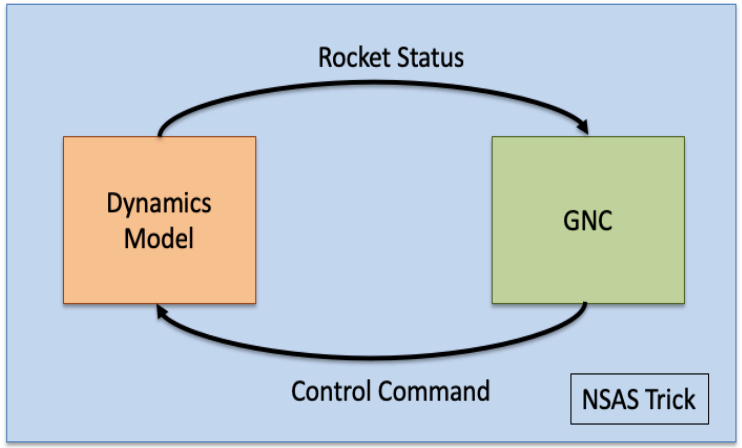


# Flight Control Evaluation



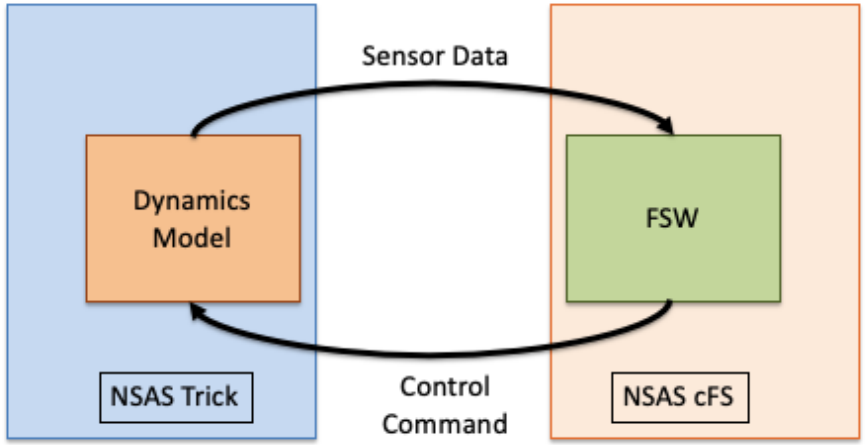
# Flight Control Evaluation Process

## SIL
(Software in loop)



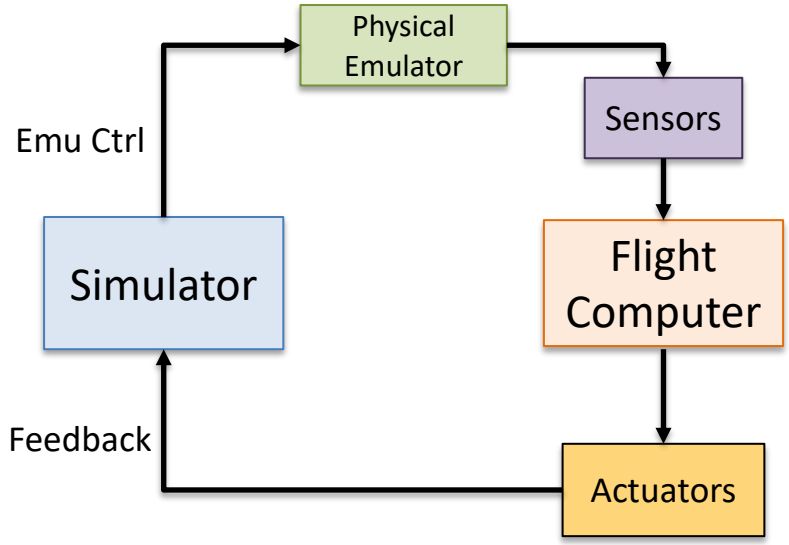

- DM & GNC in Simulator
  - Mission Planning
  - Model Development and Verification

## PIL
(Process in loop)




- GNC Flight Software (FSW)
  - ✓ Software Platform Integration
  - ✓ FSW Performance Evaluation

## HIL
(Hardware in loop)

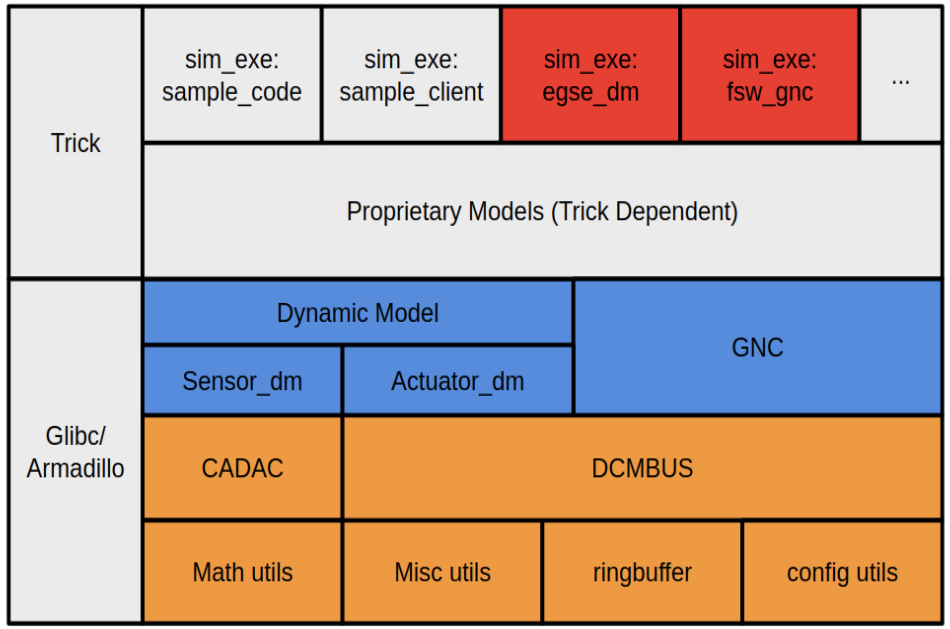



- Integrate with the physical hardware
- Similar to real flight test

# Mazu Rocket Simulation

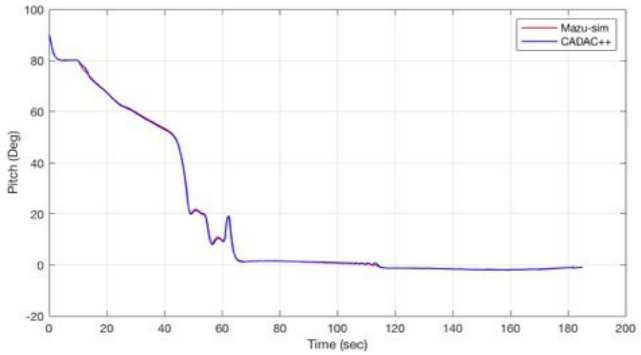
- 6DoF (Degrees of Freedom) Rocket Simulation
- Open source project
  - https://github.com/octoberskyTW/mazu-sim
- Powered by NASA Trick simulation Framework
- Re-implement CADAC++ Three-Stage Rocket Booster Simulation as basic structure
- Customized models for ARRC rocket mission

Mazu-Sim Software Stack

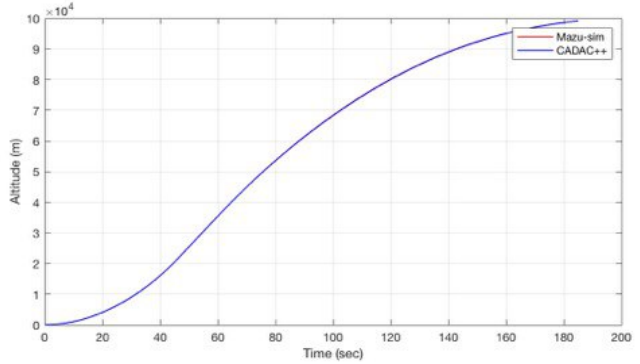


# Mazu SIL Simulation Results

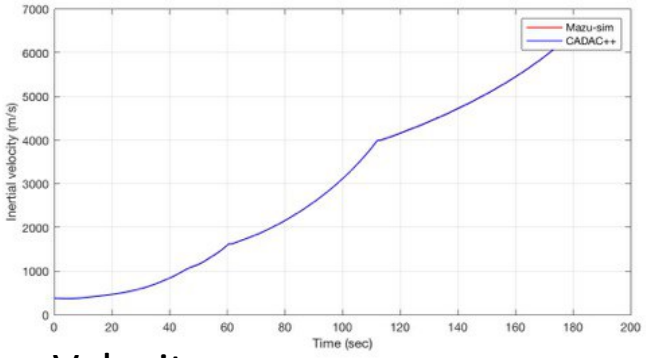
- CADAC++ 3-Stage Rocket
- Weight:
  - Stage1: 48984 kg
  - Stage2: 15490 kg
  - Stage3: 5024 kg
- Thrust
  - Stage1: 1407866.64 N
  - Stage2:  528506.6 N
  - Stage3: 124686.51 N
- longitude and latitude
  - -120.49, 34.68



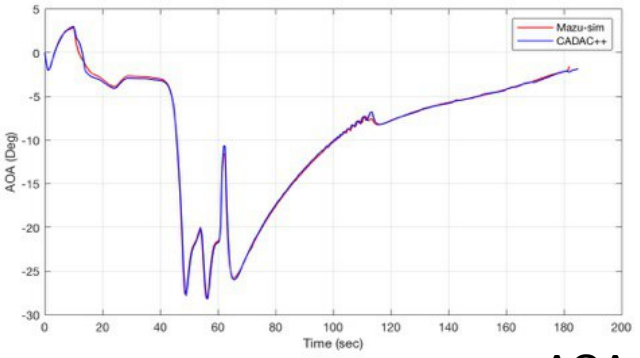
Pitch



Altitude



Velocity



AOA

# Ongoing Open Source Project

- Full integrated Rocket SIL/PIL Simulation
  - CADAC++ PIL:
    - Integration of Mazu Simulation & cFS
- Contribution to cFS
  - I/O driver
  - Performance improvement

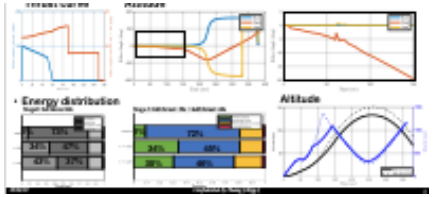
# Progress of ARRC Rocket

Sounding Rocket
(No Flight Control)

~ 2016

Simulator

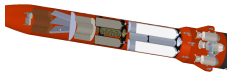
FSW



Mission Plan

Ground Station

Propulsion



structure

Valve

TVC

2018/8/1

TVC Vertical Hot Fire

Cold Flow for
Propellant
feed system
(2019/7)

Stage-2
Flight Test
2020/3

HTTP-3A
Official
Flight
2021/8

# Acknowledgements


- Financial supports of this study are highly appreciated:
  - Grant No. MOST-107-2218-E-009-054 Ministry of Science and Technology of Taiwan
  - Q-530 of Advanced Rocket Research Center of National Chiao Tung University of Taiwan

# Thank You!