Customize Real-Time Linux for Rocket Flight Control System

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Oct 29, 2019
About me and ARRC

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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

High Dynamics System

High Thrust, High Speed
Max Velocity: 3Mach

Movement of CG

CP: Center of Pressure

CG: Center of Gravity

Negative Stability

Aerodynamics

Real Time Control System

Mission
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

Mission Management

Communication

Power

Control

Guidance

Navigation

Actuator

Sensor

cFS

PREEMPT_RT Linux & Device Driver

ARM Core

AM43xx

PRUx

Ethernet

EtherCAT

TT&C

Actuators

RS422

SPI

Sensor #1

Sensor #2
PRU-ICSS for Sensing I/O

Arm® Subsystem
- Cortex®-A
  - L1 Instruction Cache
  - L1 Data Cache
  - L2 Data Cache

Real-Time Coprocessor Subsystem
- PRU0 (200 MHz)
  - Inst. RAM
  - Data RAM
- PRU1 (200 MHz)
  - Inst. RAM
  - Data RAM

Interconnect
- Shared RAM
- IntC
- Peripherals

ARM

Low latency I/O

Sensor #1

Sensor #2

Cortex-A

L3F

L3S

L4 PER

PRU Subsystem
- GPIO1
- GPIO2
- GPIO3
- GPIO 3.19
- PRU output 5

Pinmux

B Device pin
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 FULL
Threaded Interrupts

Reduce non-preemptible cases in kernel: spin_lock, interrupt

Process
Thread

Scheduling
Points

SO_NODELAY Interrupt Handlers

Network Stack
Timers
Tasklets

Kernel Space
Kernel Threads

User Space
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
• 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 Message 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

- Aerodynamics
- Rocket Arguments
- Mission Plan
- Environment Arguments

Dynamics Model

Rocket Status

GNC

Control Command
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

Legend:
- Rocket Status
- Dynamics Model
- Control Command
- NSAS Trick
- Sensor Data
- FSW
- FSW cFS
- Emu Ctrl
- Physical Emulator
- Sensors
- Flight Computer
- Actuators
- Simulator
- Feedback
Mazu Rocket Simulation

- 6DoF (Degrees of Freedom) Rocket Simulation
- Open source project
  - [https://github.com/octoberskyTW/mazu-sim](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 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
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

Mission Plan

Propulsion
- Valve
- TVC

Structure

FSW

Ground Station

Simulator

Cold Flow for Propellant feed system (2019/7)

TVC Vertical Hot Fire

Stage-2 Flight Test 2020/3

HTTP-3A Official Flight 2021/8
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!