An End-to-End FSW Development Cycle

for an Interplanetary Spacecraft Mission

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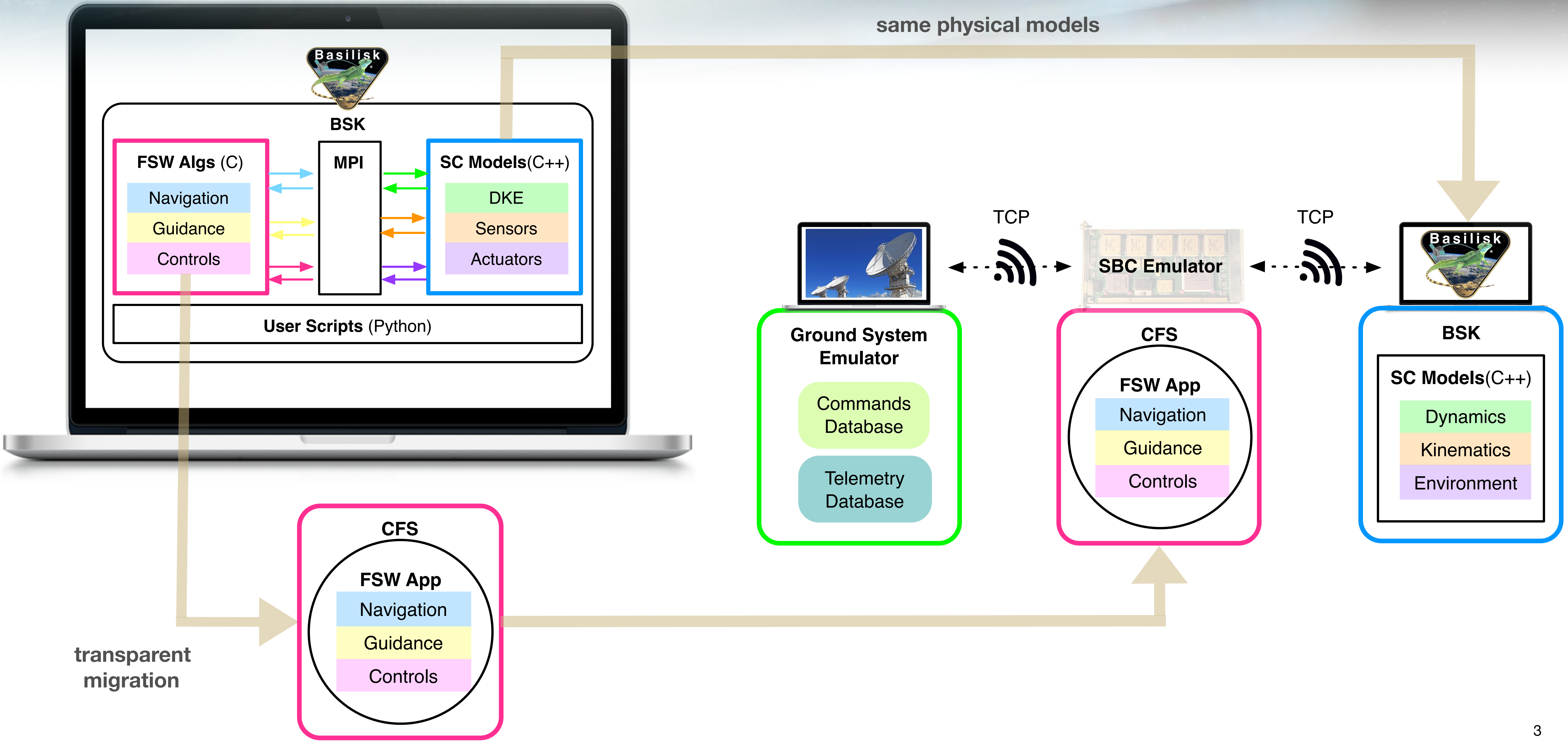
Outline

- **Complete FSW cycle for an interplanetary spacecraft mission**
- **Desktop algorithm design:** the Basilisk software testbed
- **Migration into the Core Flight System**
- **Embedded testing** of CFS-FSW in an emulated flat-sat

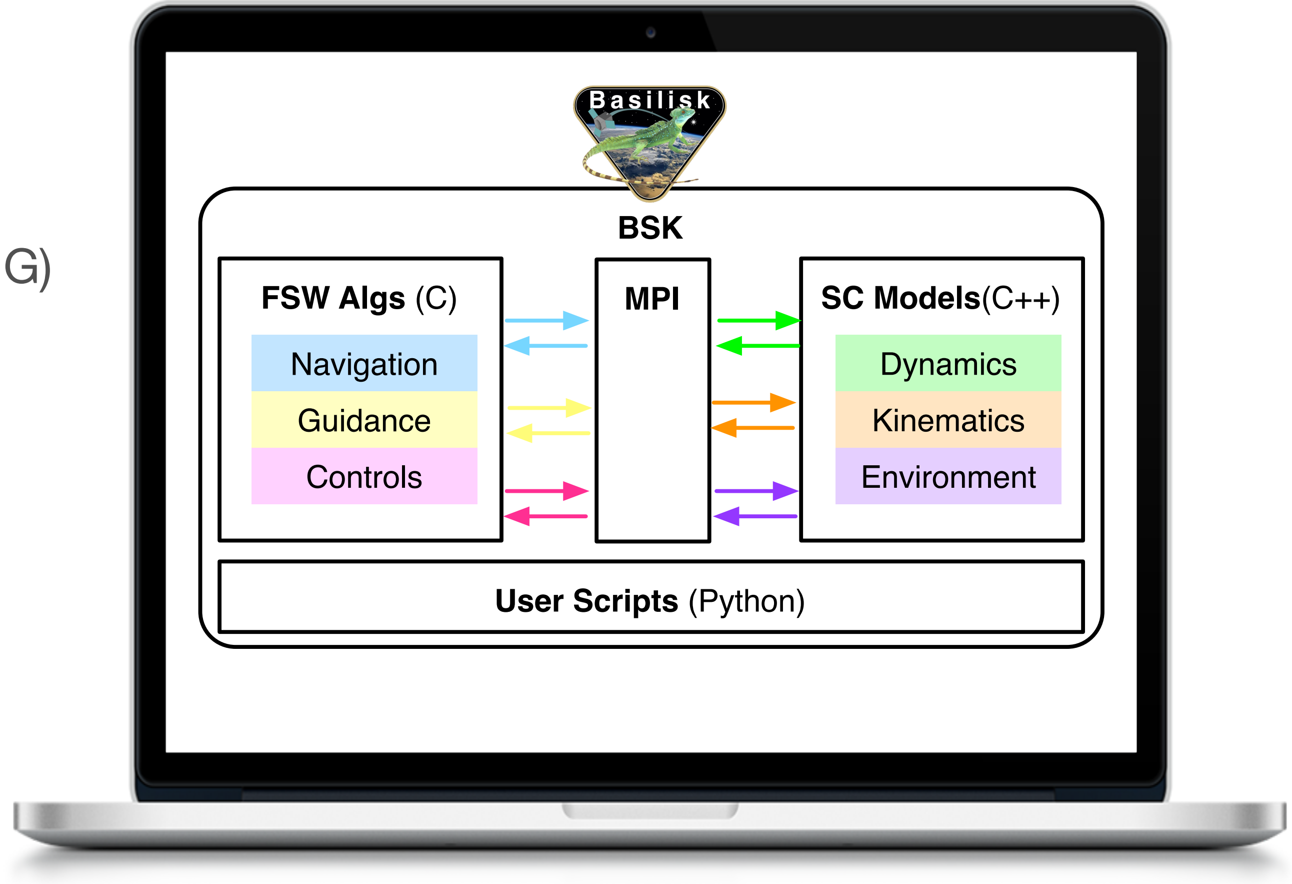
- **Interesting aspects:**
    1. **Automated yet transparent migration into CFS**
    2. **Consistent testing throughout testbeds**

Development Cycle



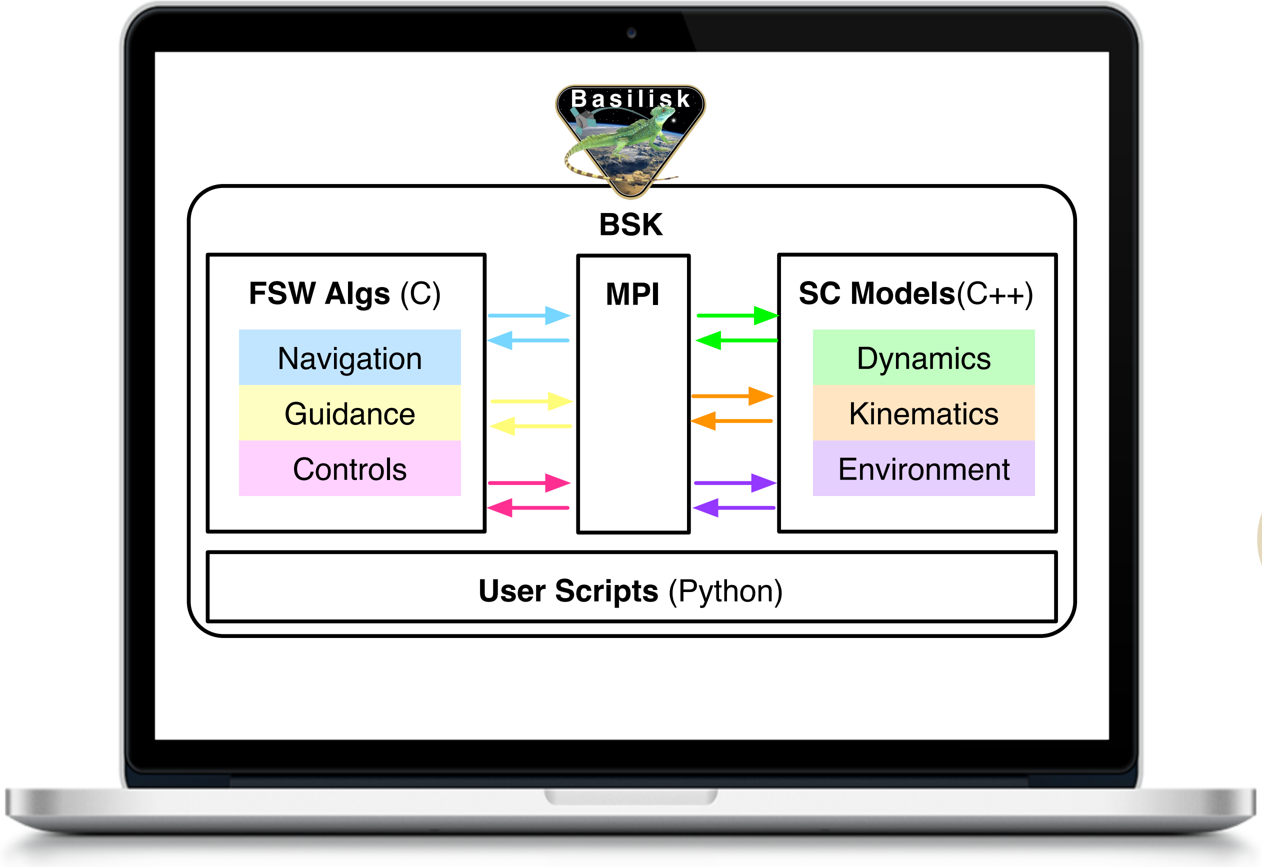
Basilisk Desktop Testbed: Overview

- **Basilisk:** open-source, cross-platform, desktop testbed
  - Designing flight algorithms
  - Testing in closed-loop dynamics
- **Language:** C/C++ source code wrapped in Python (through SWIG)
  - **Python** for: **(1)** setup, **(2)** desktop execution, **(3)** post-proc
- **Nominal configuration**:
  - **Dynamics Process**: spacecraft physical models (C++)
  - **FSW Process**: mission-specific GN&C algorithms (C)
- **Features:** modular arch. & pub-sub message passing

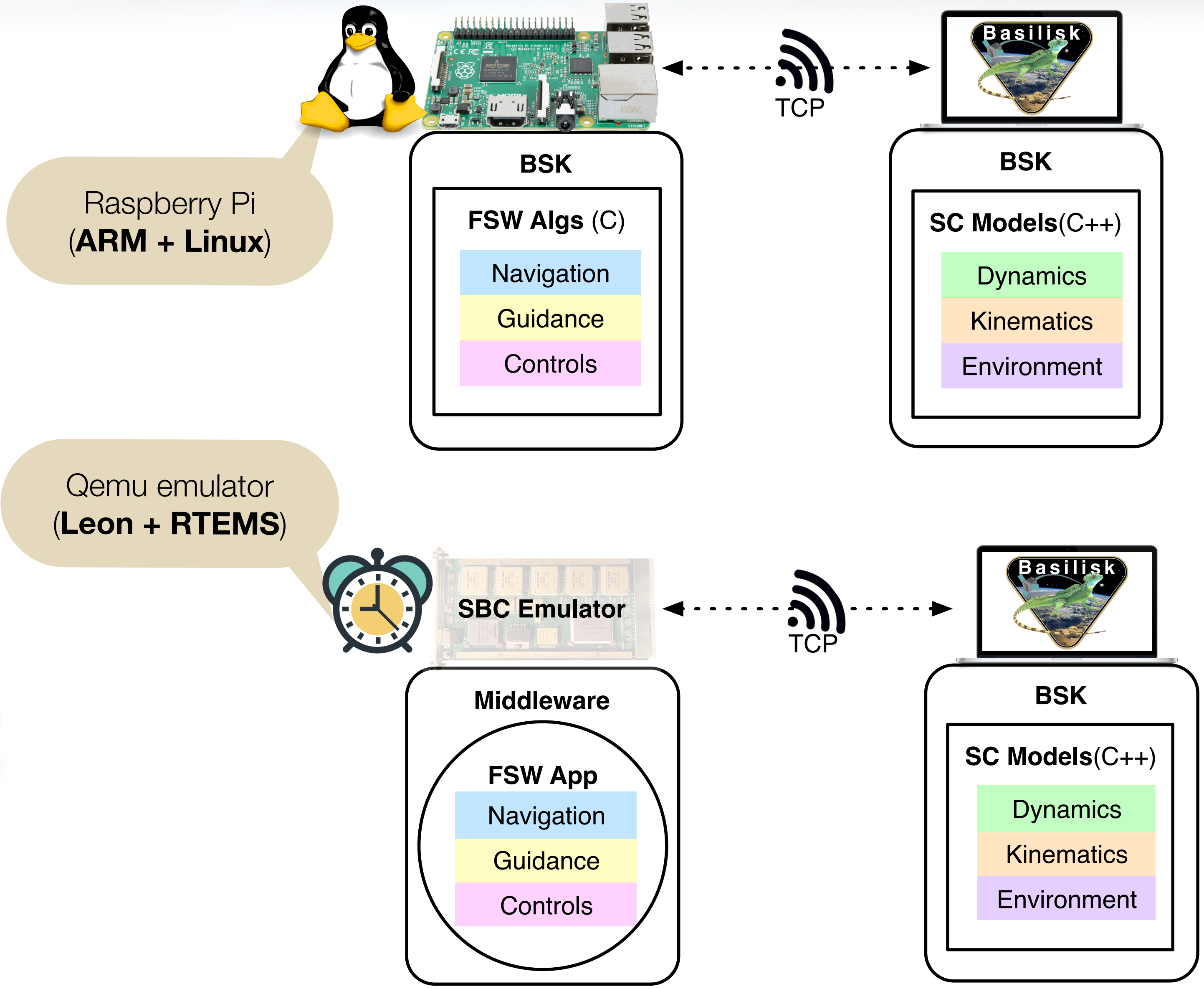


Migration of the Basilisk Flight Application

- **Single processor environment:**

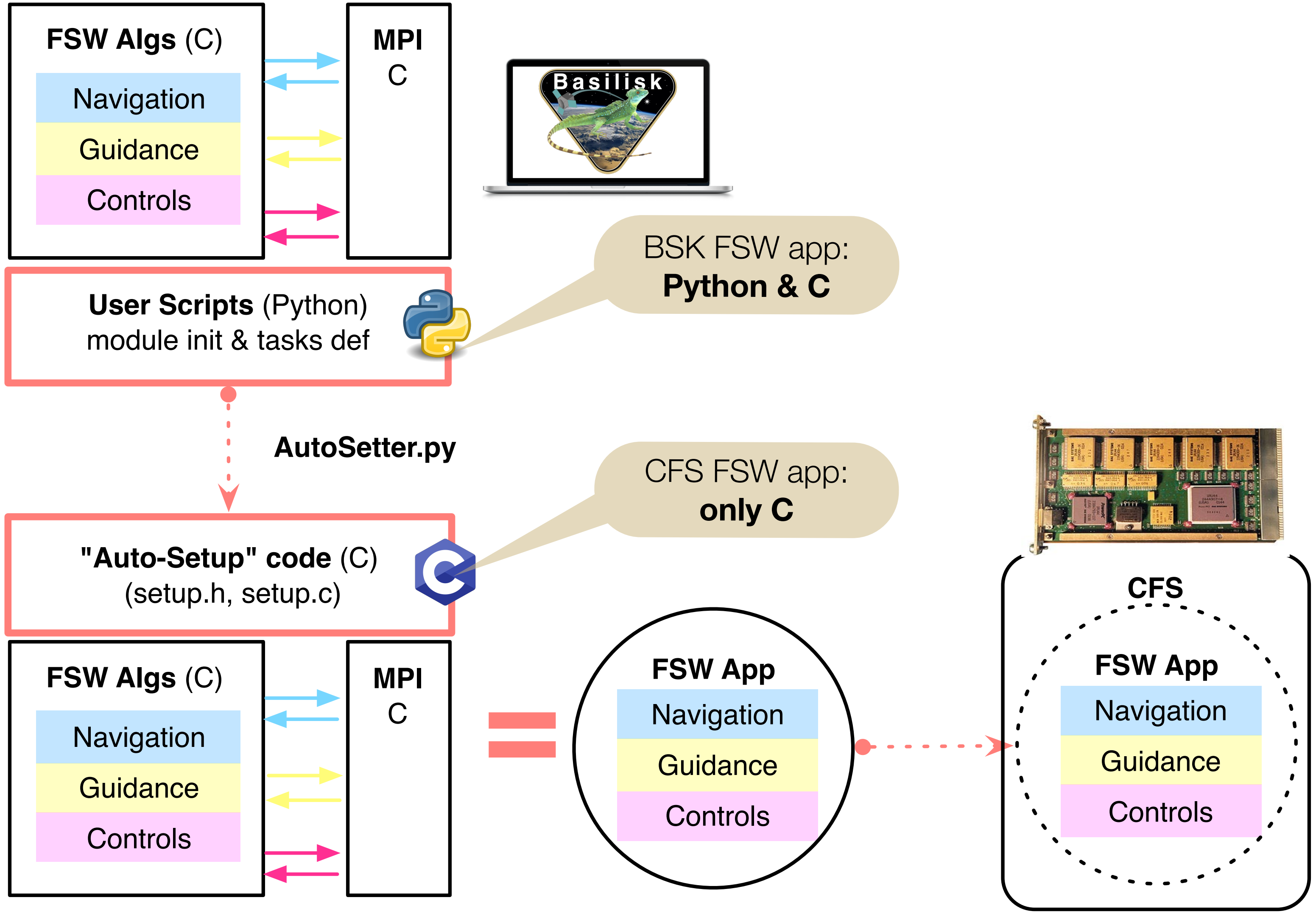


- **Multi processor environment:** realistic testing



FSW Migration: from Basilisk to CFS

- **What does it take to migrate FSW algs?**
- **Recall:** Basilisk leverages Python for FSW
  1. **Setup**
  2. Desktop execution
  3. Post-processing
- **Setup code**: translated from Python to C
  - Modules' variable initialization
  - Tasks definition (modules groups)



Python setup: C module initialization

- **Basilisk C module**: a stand-alone model or self-contained logic.
  - **Config struct**
  - **Generic algorithm calls**: self-init, cross-init, update & reset

```c
// Configuration struct
typedef struct{
    double ISCPntB_B[9]; // Inertia
    double CoM_B[3]; // Center of mass
    char outputMsgName[MAX_LENGHT]
}VehicleConfig;

// Generic algorithms
void SelfInit_vehConfigData(...);
void CrossInit_vehConfigData(...);
void Update_vehConfigData(...);
void Reset_vehConfigData(...);
```

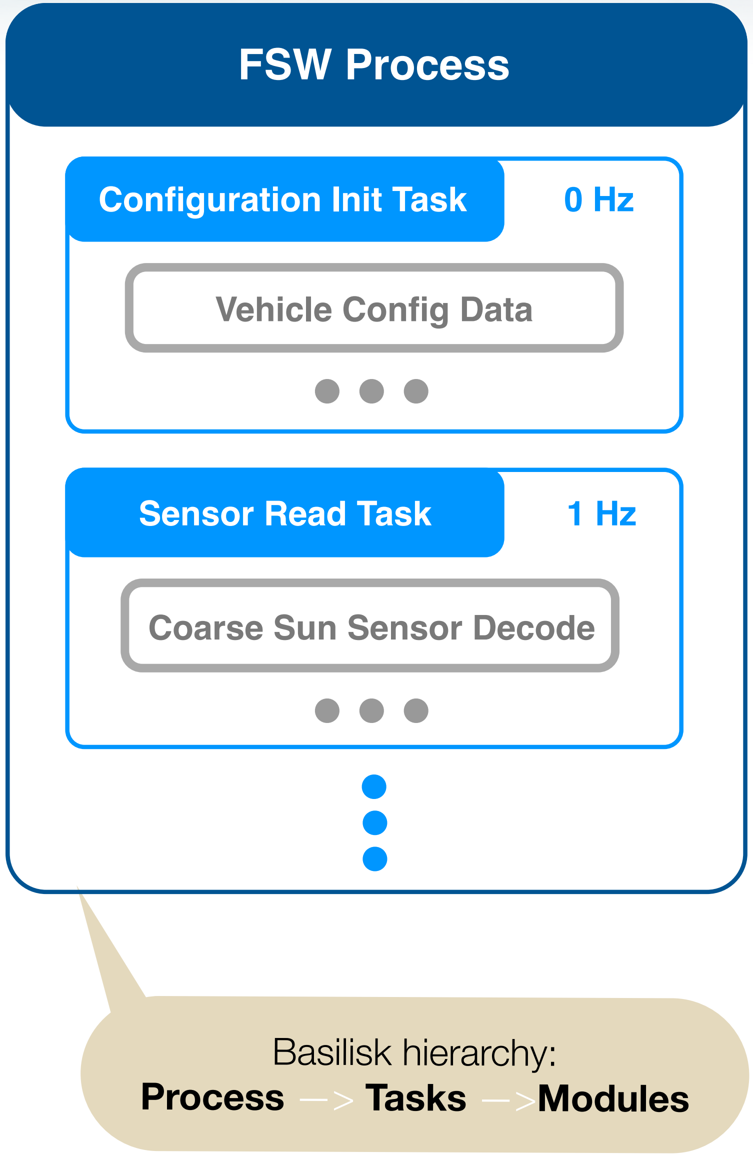
called from Python for desktop execution

SWIG

- **Python module initialization**

```python
# Instantiate C modules
self.veh_config = VehicleConfig()

def SetVehicleConfigData(self):
    # Initialize vehicle data C module
    self.veh_config.ISCPntB_B = [600.0, 0.0, 0.0, 0.0, 600.0, 0.0, 0.0, 0.0, 600]
    self.veh_config.CoM_B = [0.0, 1.0, 0.0]
    self.veh_config.outputPropsName = "adcs_config_data"
```

Python setup: task groups & rates



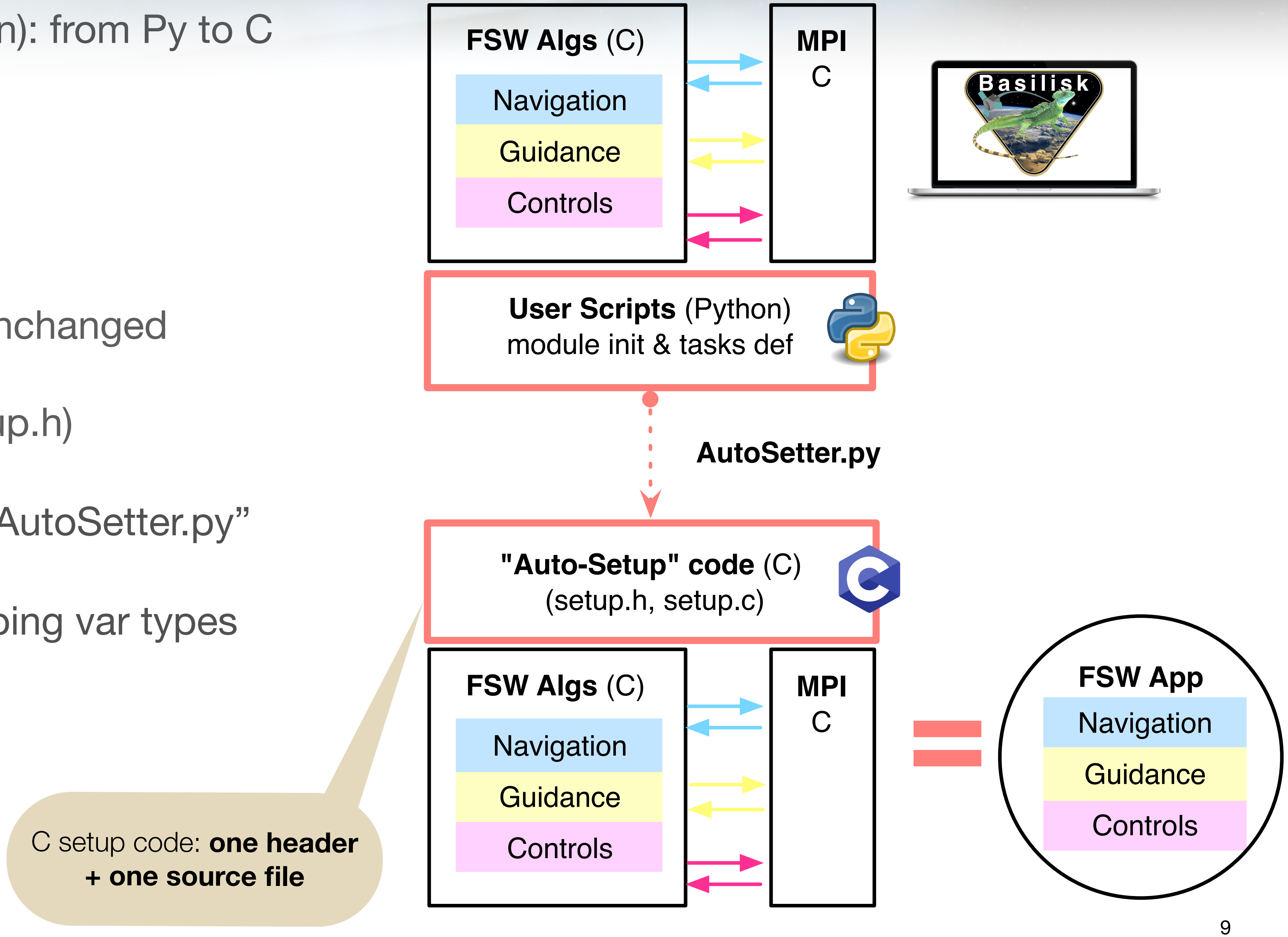
- **Define tasks** at certain rates
- **Modules added into each to task**
- **Example:** init-only task contains vehicle config data module

```python
# Instantiate C modules
self.veh_config = VehicleConfig()

def SetVehicleConfigData(self):
    # Initialize vehicle data C module
    self.veh_config.ISCPntB_B = [600.0, 0.0, 0.0, 0.0, 600.0, 0.0, 0.0, 0.0, 600]
    self.veh_config.CoM_B = [0.0, 1.0, 0.0]
    self.veh_config.outputPropsName = "adcs_config_data"
```

```python
# Create FSW process
self.fswProc = self.CreateNewProcess("FSWProcess", 100)

def populateFSWTasks(self):
    # Create tasks and add modules
    self.fswProc.addTask(self.CreateNewTask("initOnlyTask", int(0)), 200000)
    self.AddModelToTask("initOnlyTask", self.veh_config, 1)
```

Pure-C FSW Application

- **Setup code** (module init & tasks definition): from Py to C
- **Key remark**:
    - Only setup code is translated
    - FSW algs. source code: remains unchanged
- **Pure-C FSW**: FSW Algs + (setup.c + setup.h)
- **Automatic translation of setup code**: “AutoSetter.py”
    - Transparent & open template mapping var types
    - Resulting C setup code: minimal
- **Trick**: Python introspection



Python Introspection: AutoSetter

User Scripts
module init & tasks def

AutoSetter.py

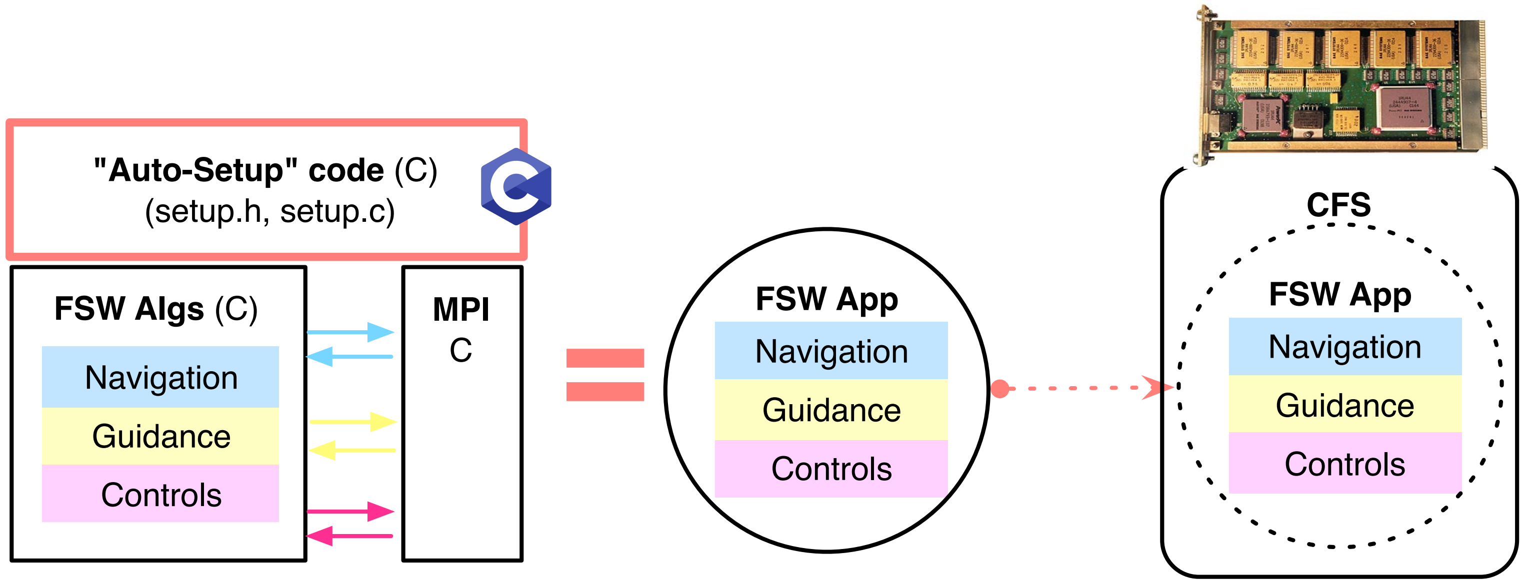
Setup Code
(setup.h, setup.c)

I am a model.
I've these **variables**
and **algorithm** names.

```python
# Instantiate C modules
self.veh_config = VehicleConfig()

def SetVehicleConfigData(self):
    # Initialize vehicle data C module
    self.veh_config.ISCPntB_B = [600.0, 0.0, 0.0, 0.0, 600.0, 0.0, 0.0, 0.0, 600]
    self.veh_config.CoM_B = [0.0, 1.0, 0.0]
    self.veh_config.outputPropsName = "adcs_config_data"
```

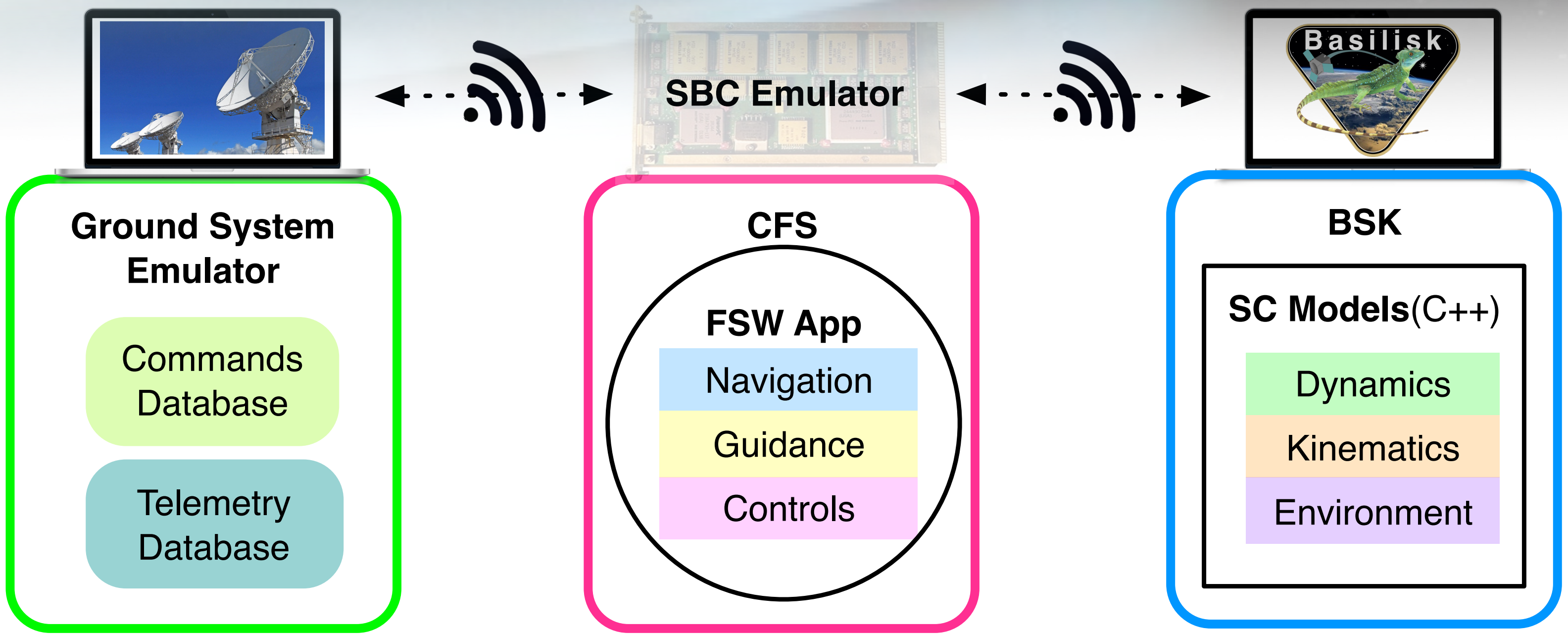
```c
typedef struct{ // Struct with all FSW modules
        VehicleConfig veh_config;
        // [...] More modules below
} AllConfig;
void AllConfig_DataInit(AllConfig *data){ // Modules initialization
        memset(data, 0x0, sizeof(AllConfig));
        // VehicleConfig module init
        data->veh_config.ISCPntB_B[0] = 600.0;
        data->veh_config.ISCPntB_B[4] = 600.0;
        data->veh_config.ISCPntB_B[8] = 600.0;
        strcpy(data->veh_config.outputMsgName, "adcs_config_data");
        // [...] More modules below
}
```

Embedded FSW Dev & Testing

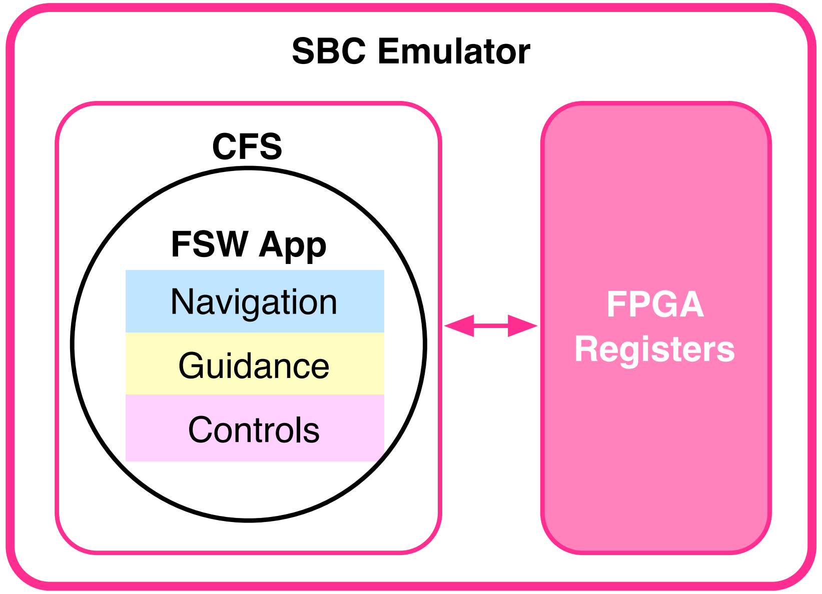


Embedded Testing: CFS

- CFS-FSW testing in **emulated flat-sat**

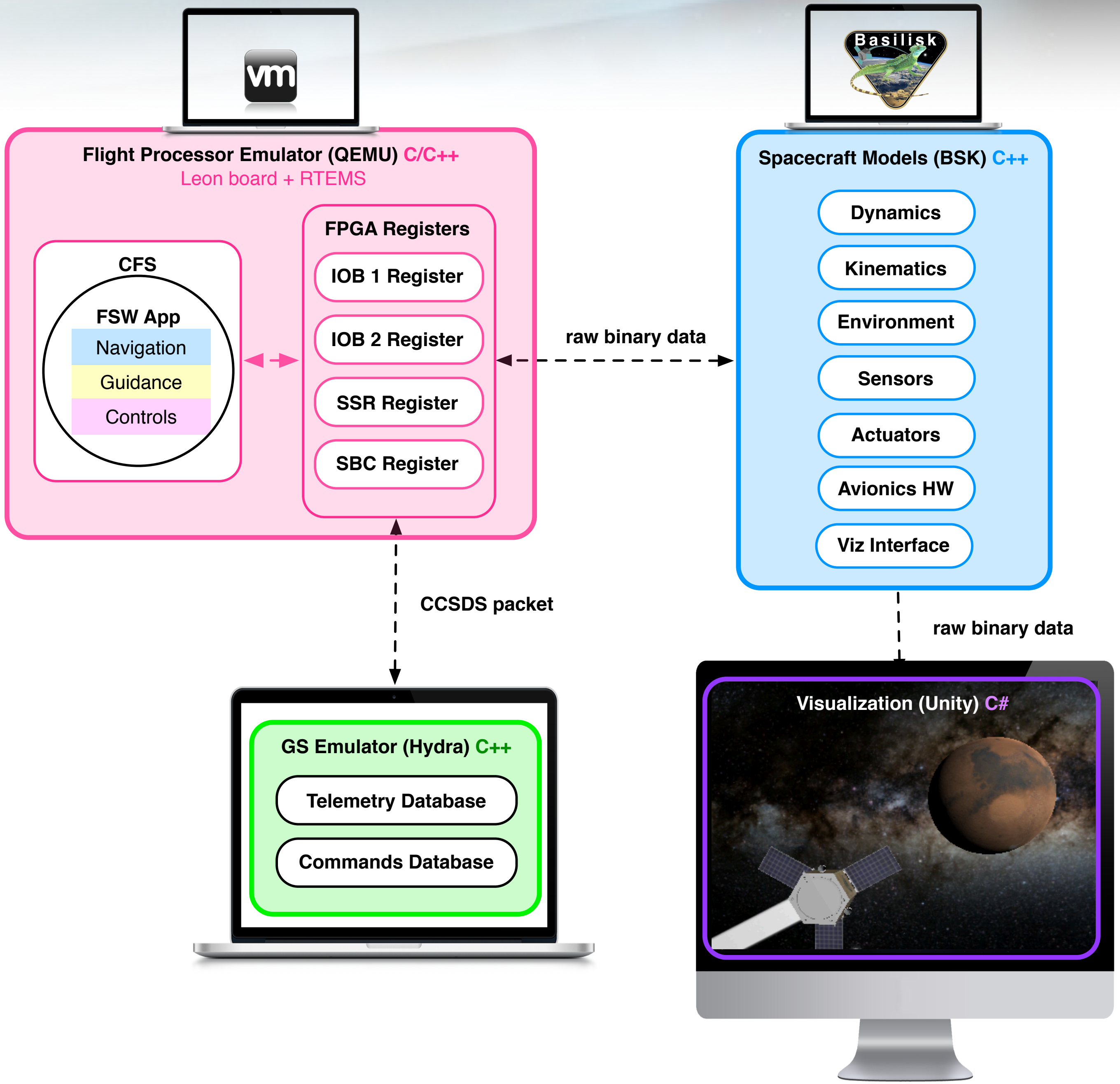


- **Interaction** with embedded FSW **becomes tricky**
- **FPGA registers**: memory map for I/O of bin data

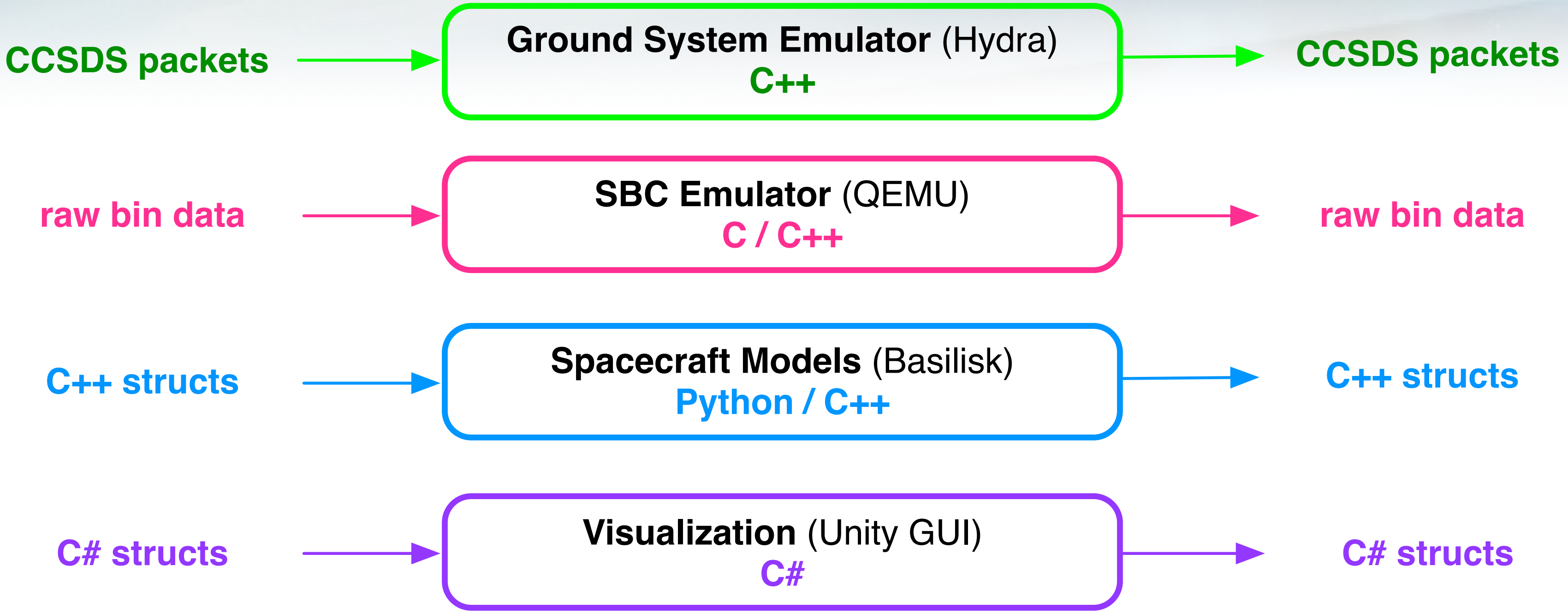


Emulated Flat-Sat Models

- **Flight Processor Emulator**: **QEMU**
  - Virtual Leon3 + RTEMS
  - CFS-FSW app + FPGA registers
- **Spacecraft Models**: **Basilisk**
  - Dynamics, Kinematics, Environment
  - Sensors, Actuators, Avionics HW
- **Ground System Emulator**: **Hydra**
  - Command & Telemetry
- **Visualization**: **Vizard**
  - Unity-based GUI



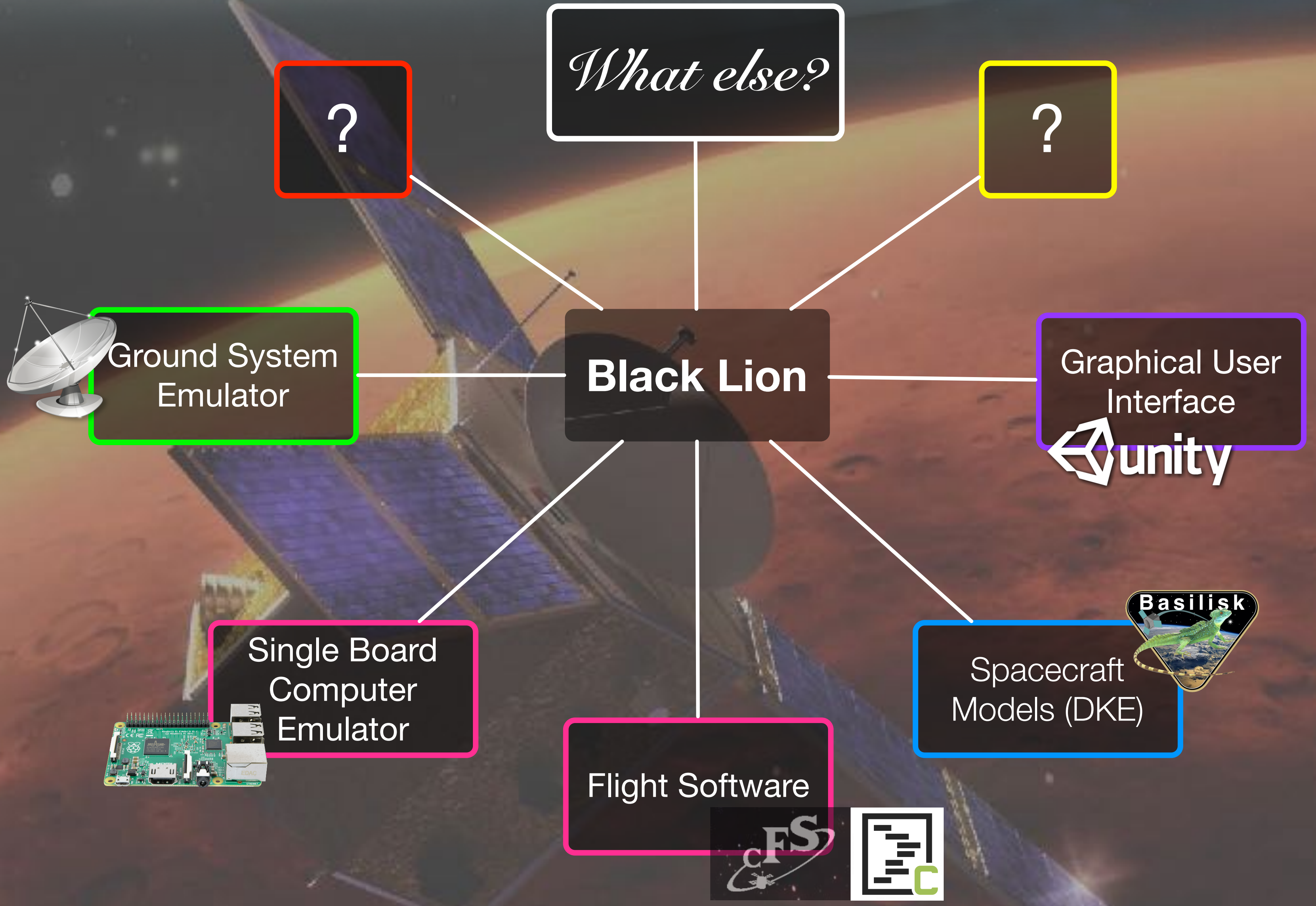
Models heterogeneity



stand-alone apps never designed to work together…

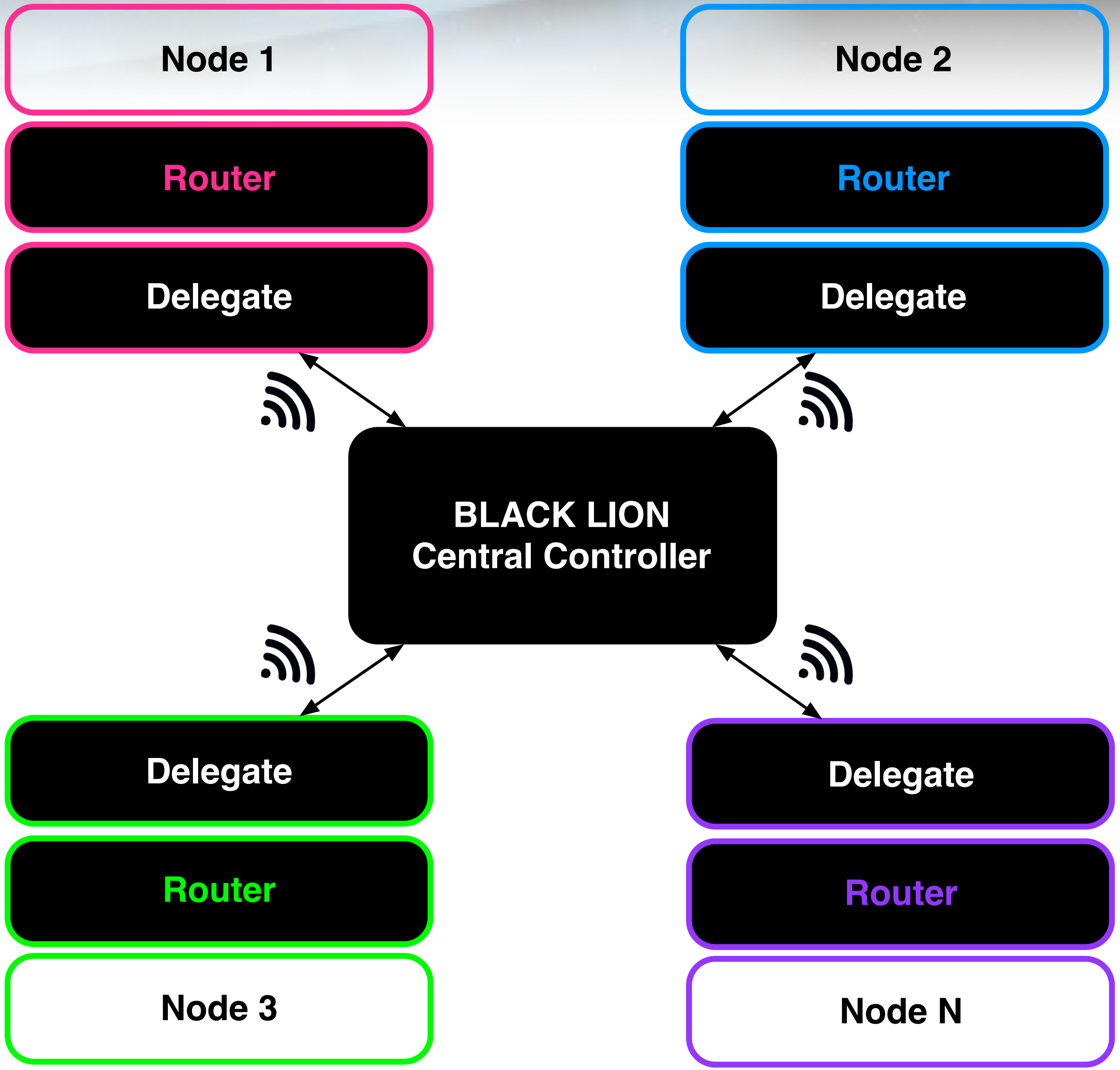
- Written in **different programming languages**
- **Different execution speeds** (asynchronous vs. synch, faster vs. slower than RT)
- **Multi-threaded** vs. **single-threaded** (important for sockets)
- **Different endianness** (specially tricky)

The Black Lion Communication Architecture



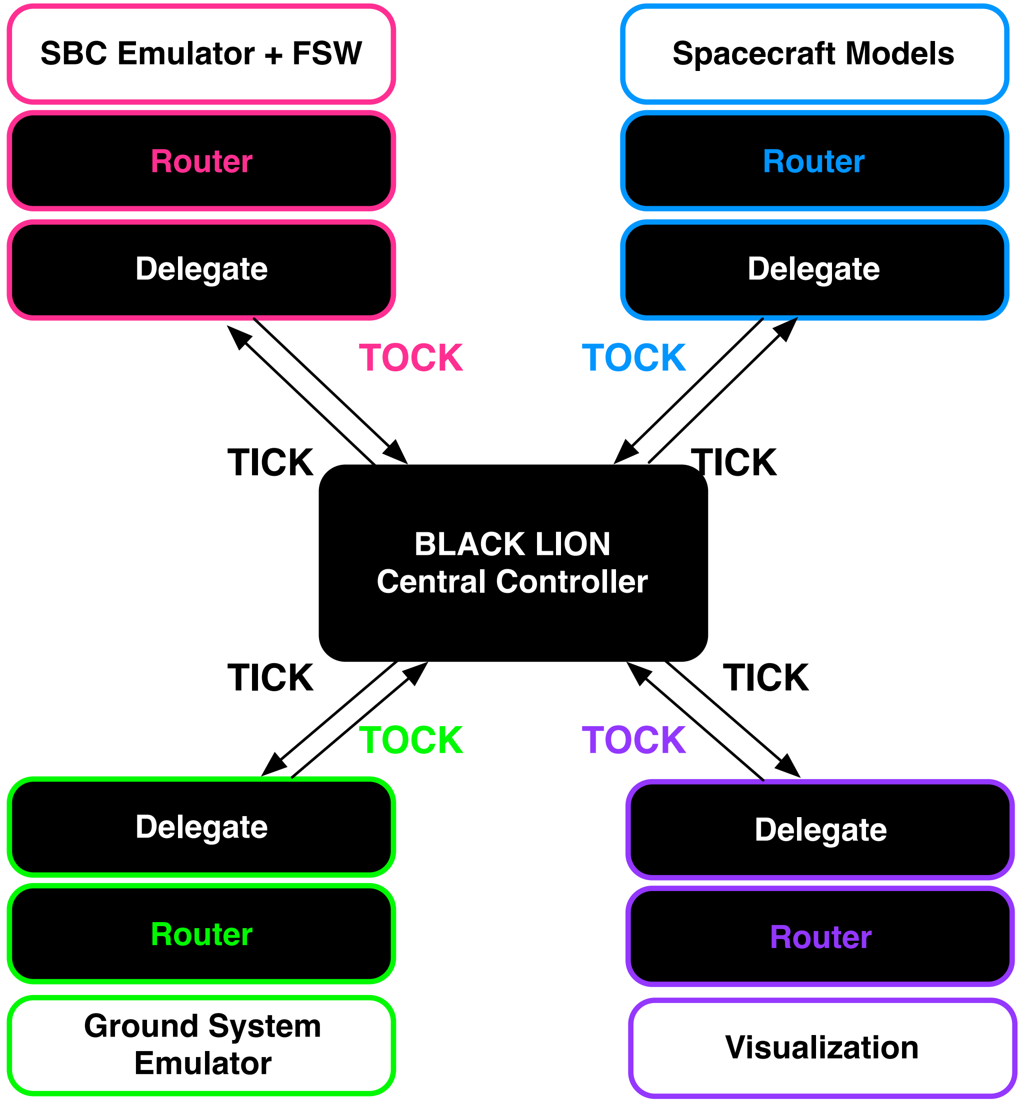
Black Lion: Architecture Overview

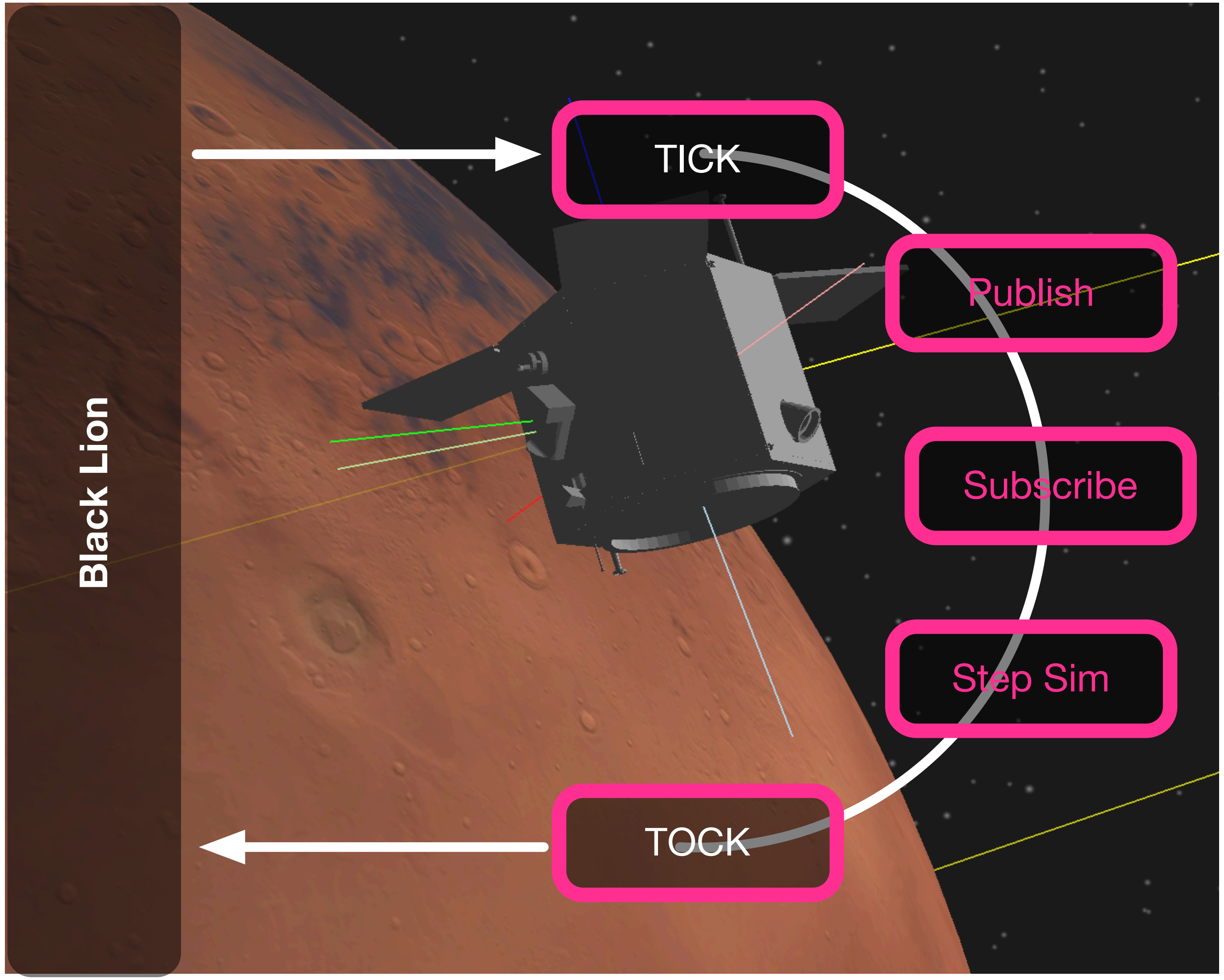
- **Communication Goals**
  1. **Transport** of binary data
  2. **Serialization** of binary data
  3. **Synchronization** of nodes/components
  4. **Dynamicity** in the connections map
- **While** remaining abstracted from each node
  - **Central Controller:** msg broker & synch master
  - **Delegate API:** sockets & connections
  - **Router API:** route data in & out of node



Black Lion: Synchronization

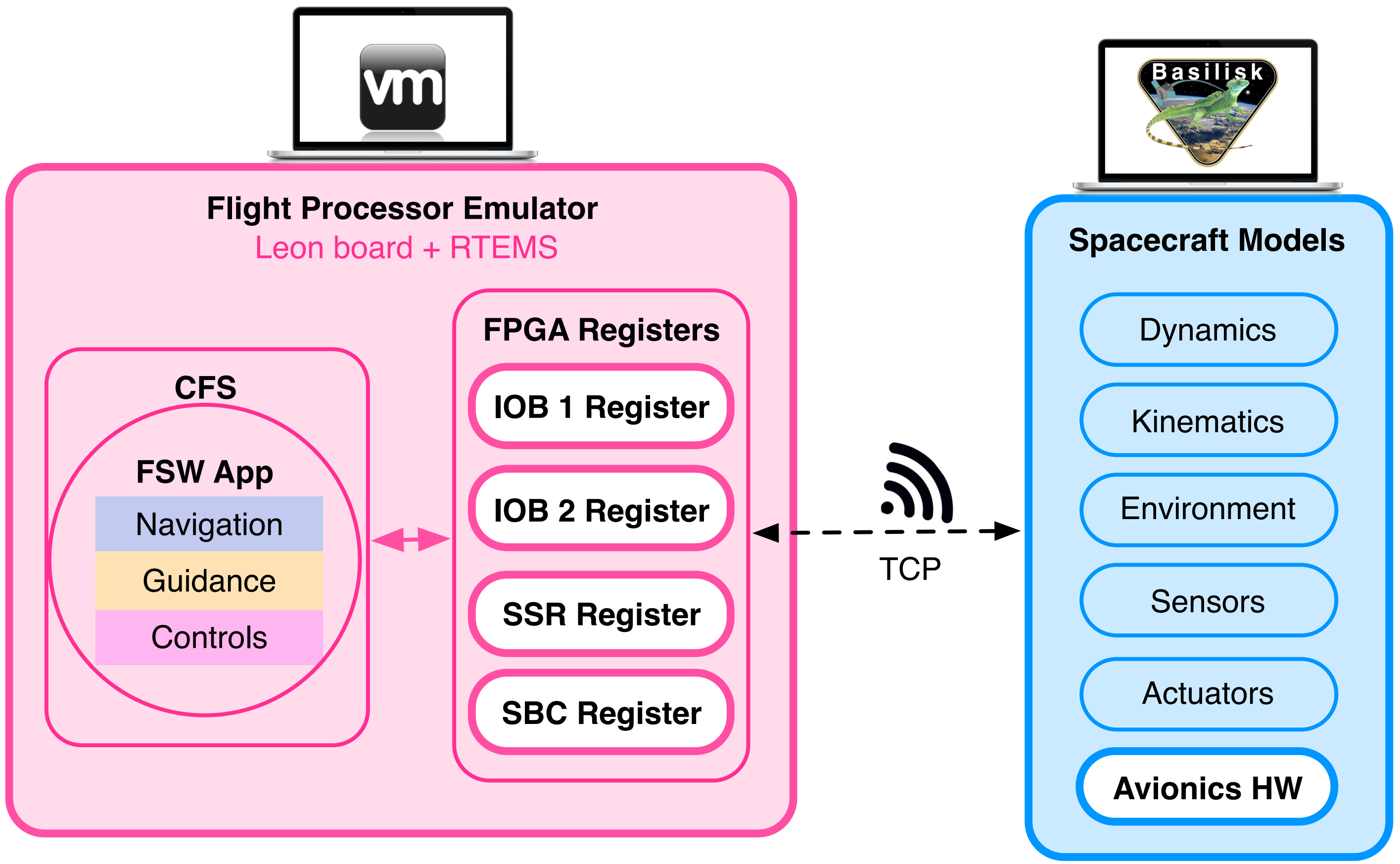
- **"Tick-Tock":** maintain all the nodes in lock-step



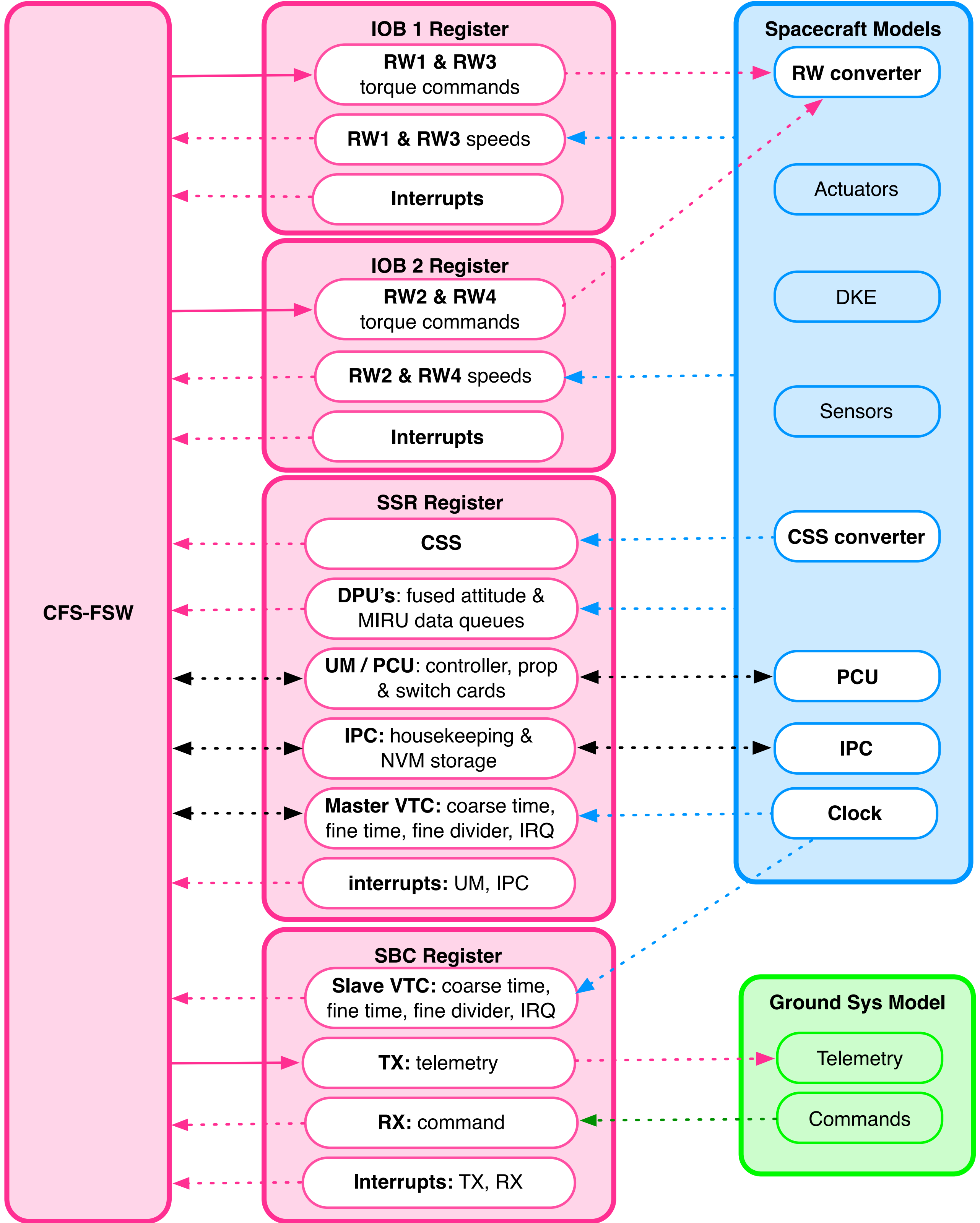


CFS-FSW Interaction: FPGA + Avionics HW

- **FPGA**: 4 different register boards
  - Each register has a memory buffer
  - Shared FSW states are mapped (snorkels)
- **FSW reads/writes in HW-like fashion**
  - Board interrupts are also replicated
- **Avionics HW models**:
  - Leverage complex functionality
  - **PCU**: avionics cards (ctrl, switch, prop)
  - **IPC**: NVM commands & HK packets

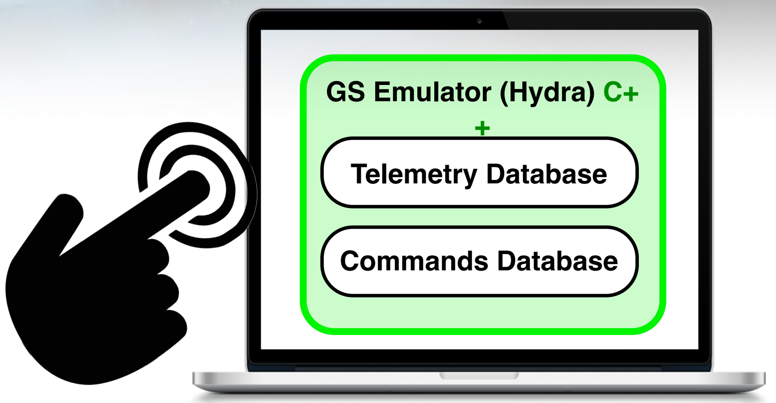


- **Register snorkels**:
  - **Actuators**: RW cmd & speeds
  - **Sensors**: CSS, ST
  - **Avionics**: PCU, IPC
  - **Clocks**
  - **Command** & **telemetry**
- **Heterogeneity challenges**
  - Unidirectional vs. bidirectional
  - Packet &/ descriptor addresses
  - Single word packets vs. queues
  - Fixed-sized vs. variable-sized
  - Add/remove byte headers
  - Endianness handling

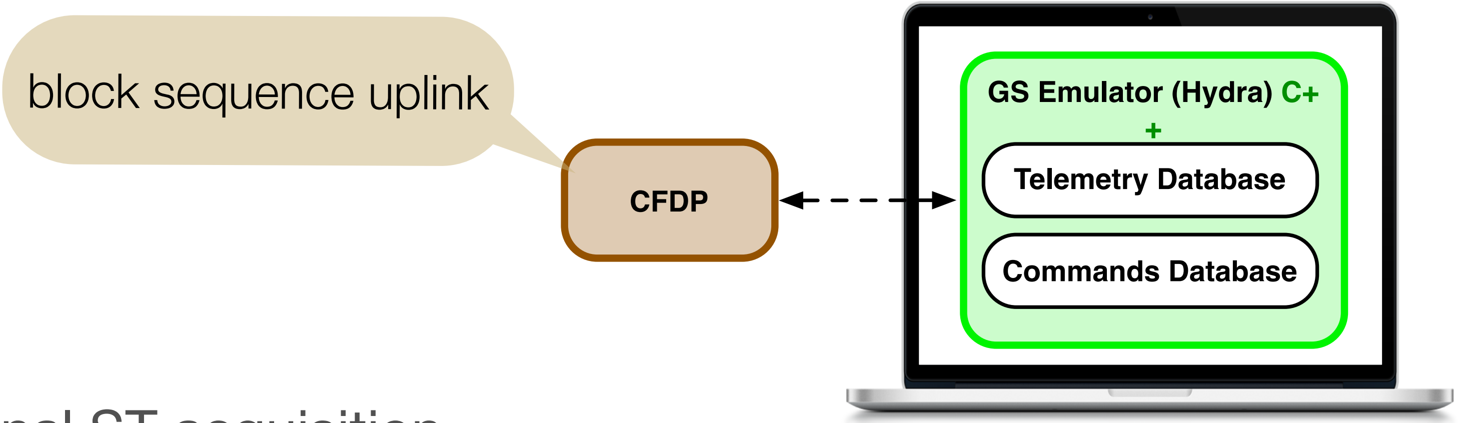


Numerical Closed-Loop Simulations

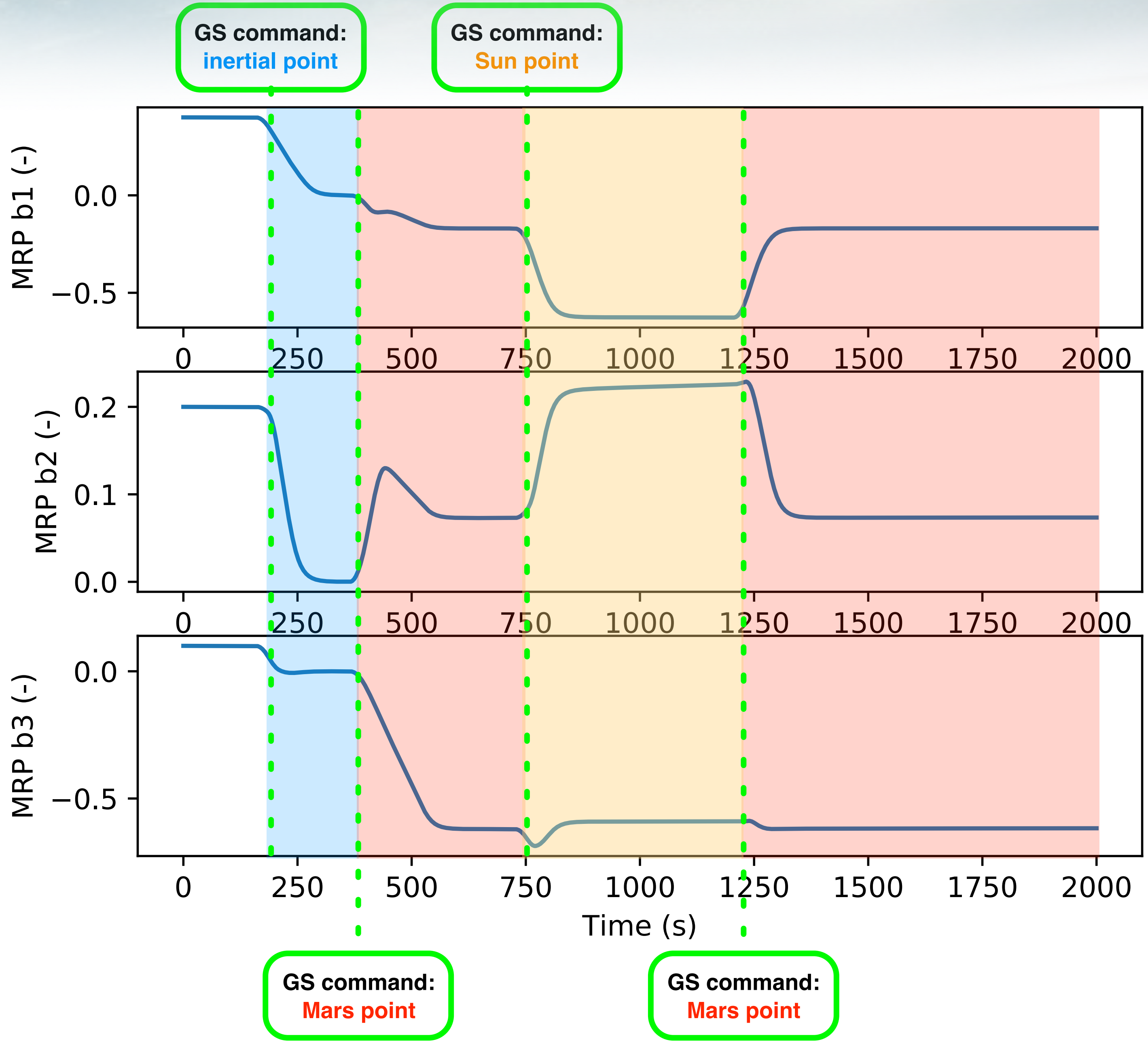
1. **Spacecraft pointing manoeuvres** manually triggered by the user
    - **Monitoring** Command + **Inertial Pointing** Command
    - **Ephemeris Correlation** Command + **Mars Pointing** Command
    - **Sun Pointing** Command
    - **Mars Pointing** Command

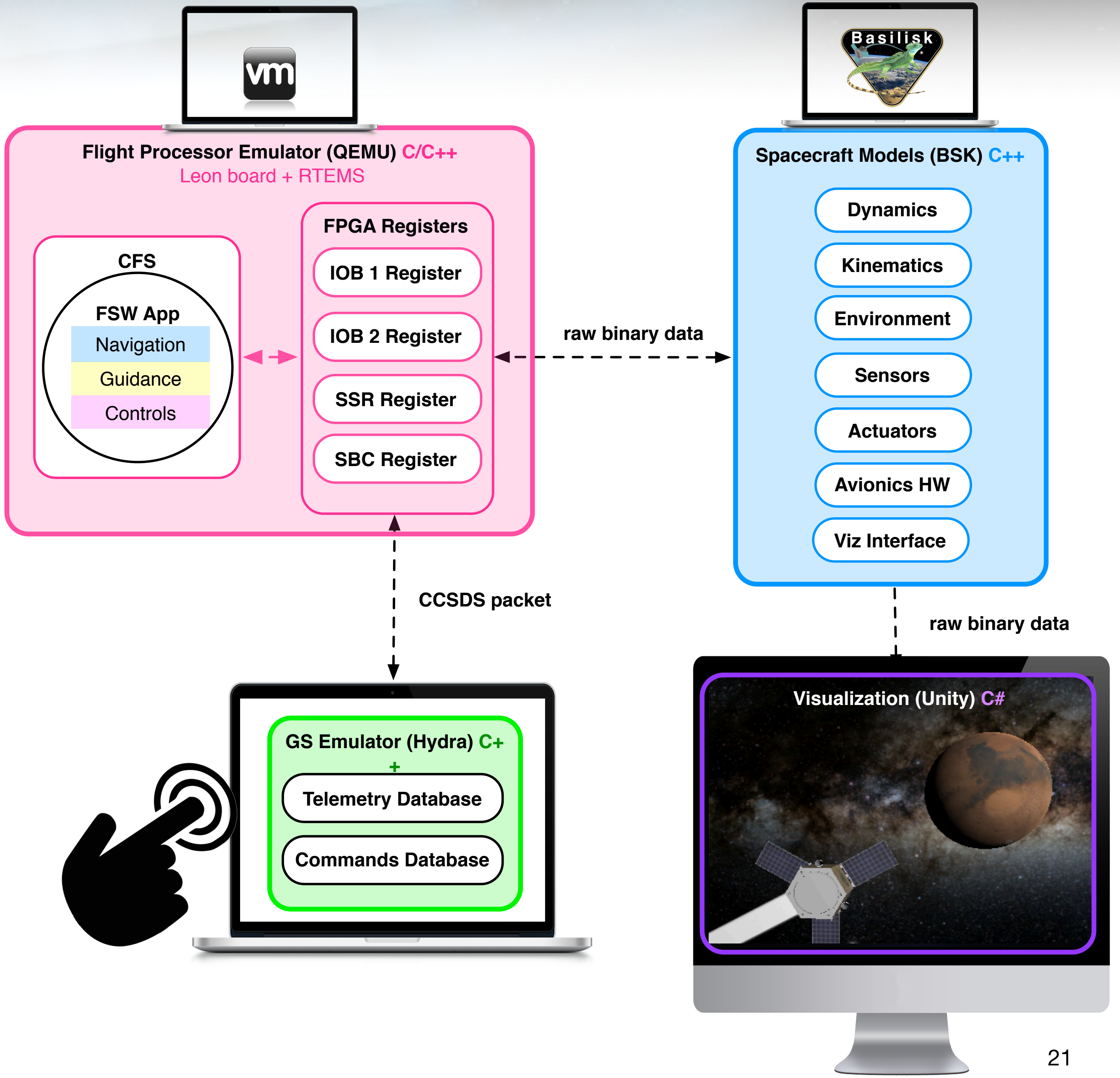


2. **Mars orbit insertion**
    - **Time jam**: bring SC right before MOI
    - **DV burn**: propulsion cards within the PCU
    - **Off-nominal testing**: FSW resets + off-nominal ST acquisition

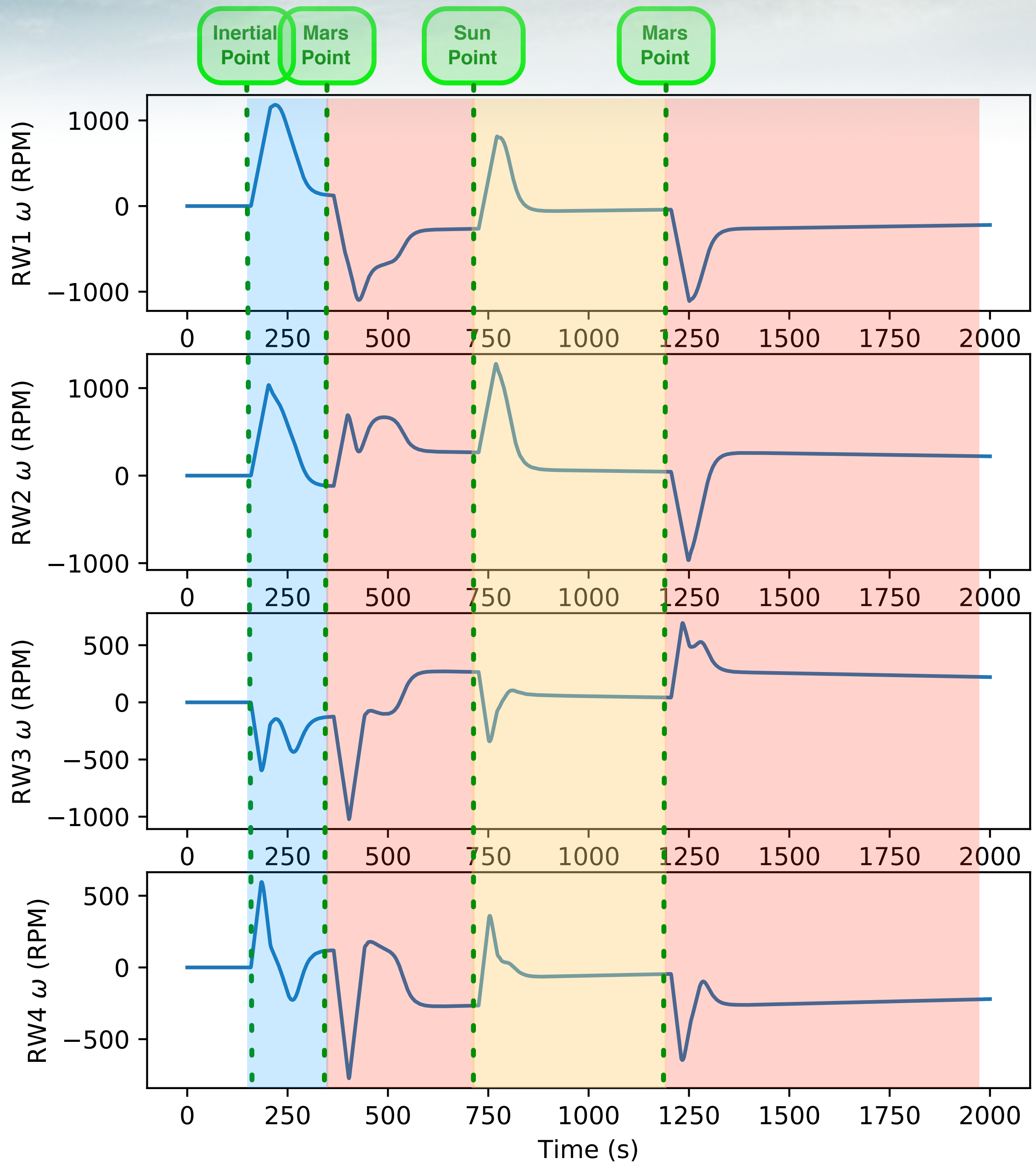


1. Spacecraft Pointing Manoeuvres

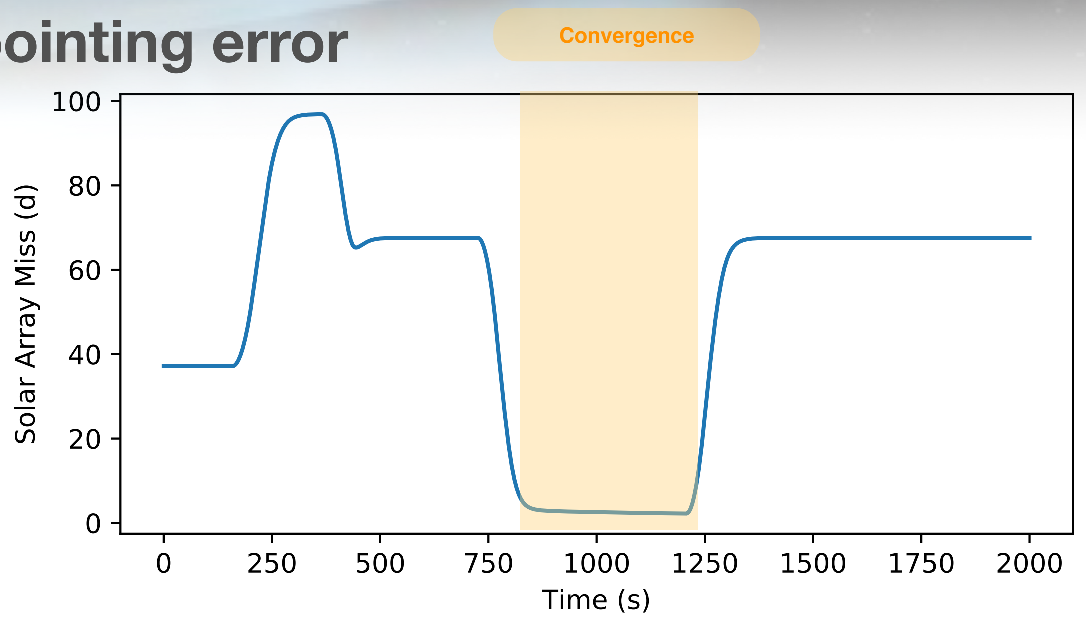




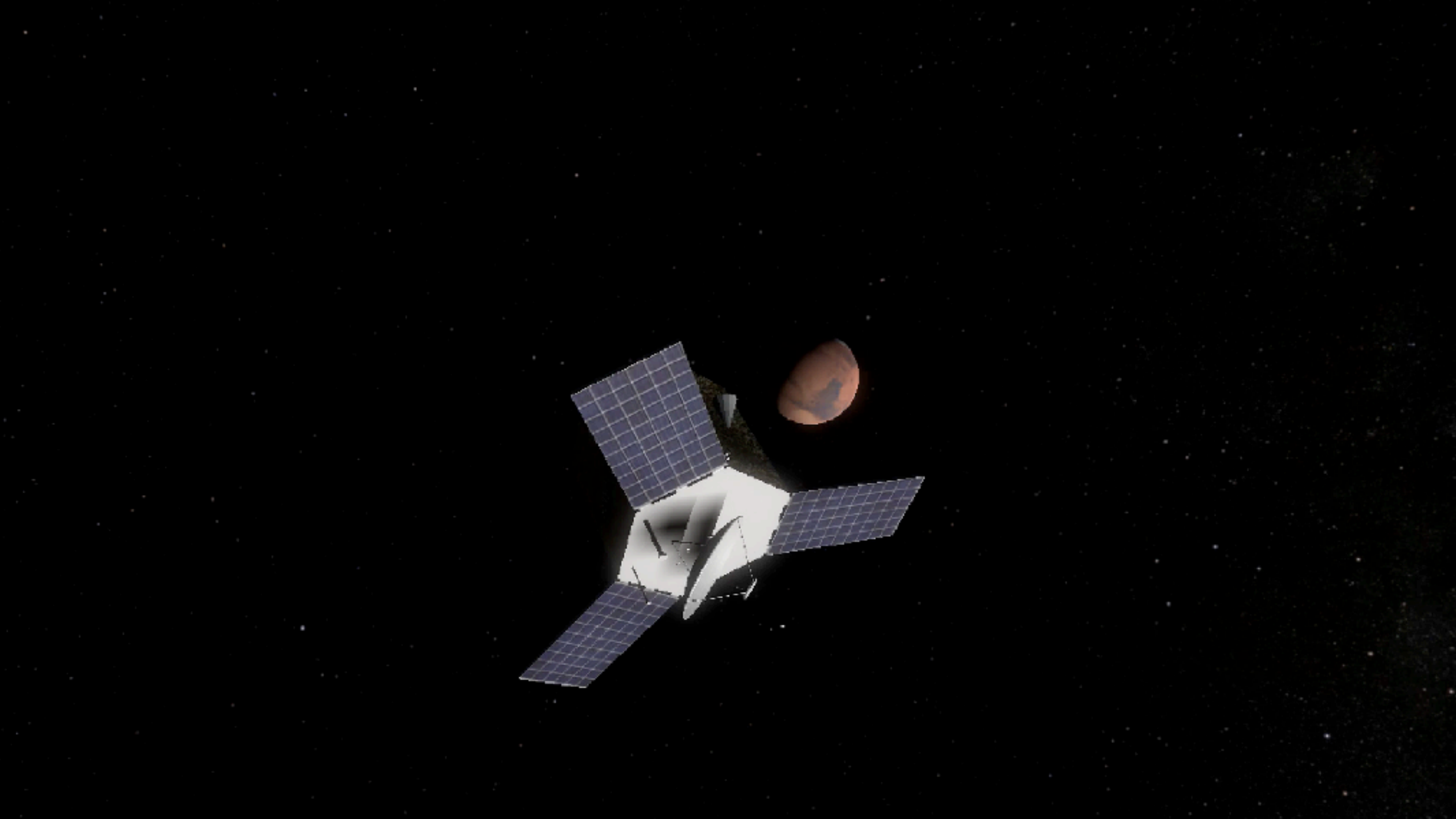
1. Spacecraft Pointing Manoeuvres



- **Sun pointing error**



- **Mars pointing error**



Conclusions

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- **Desktop algorithm design**: the Basilisk software testbed
- **Migration into the Core Flight System**
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Thanks for listening!