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Toward a Suite of Middleware Services for Enhanced Spacecraft Configuration and Capability

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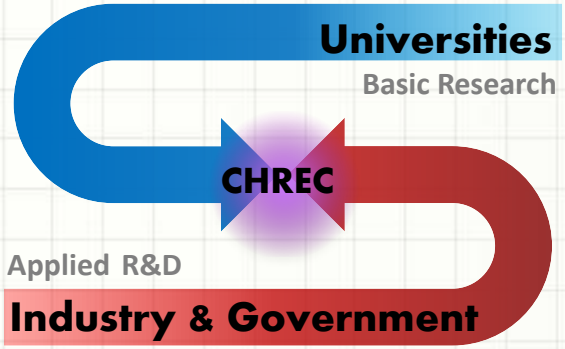
Outline

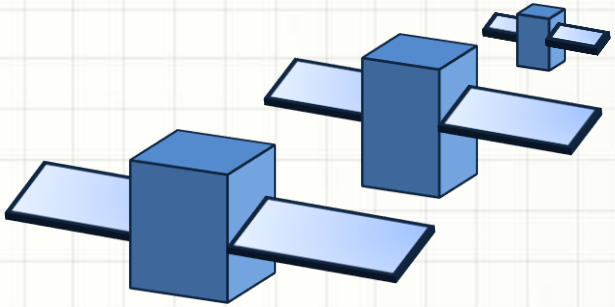
- Acknowledgements
- Key Technologies
- Motivations and Goals
- Architectural Overview
- Prototype
- Conclusions

Acknowledgements

- Space Middleware is a research project at CHREC
  - NSF Center for High-Performance Reconfigurable Computing (**CHREC**)
    - Top national research center founded in 2007
    - Comprises 3 university sites (UF, BYU, VT) and **over 30 industry and government** partners



- Space Middleware investigation is a collaborative CHREC effort
  - Key Partners
    - NASA KSC, GSFC, JSC, LRC, ARC
    - Honeywell
    - Lockheed-Martin SVIL

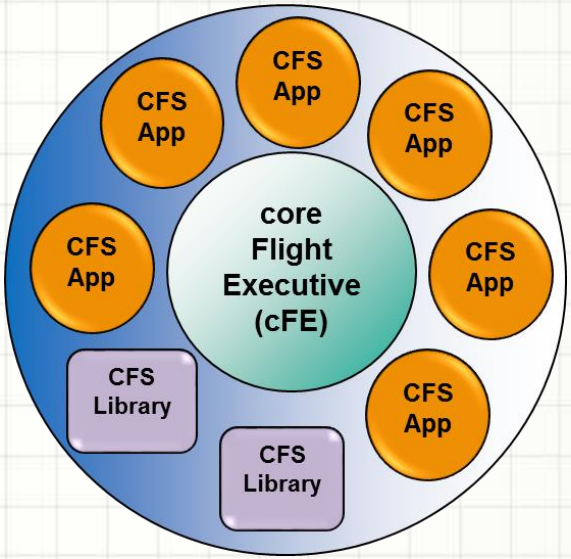


See **www.chrec.org** for more info

KEY TECHNOLOGIES

Core Flight Executive

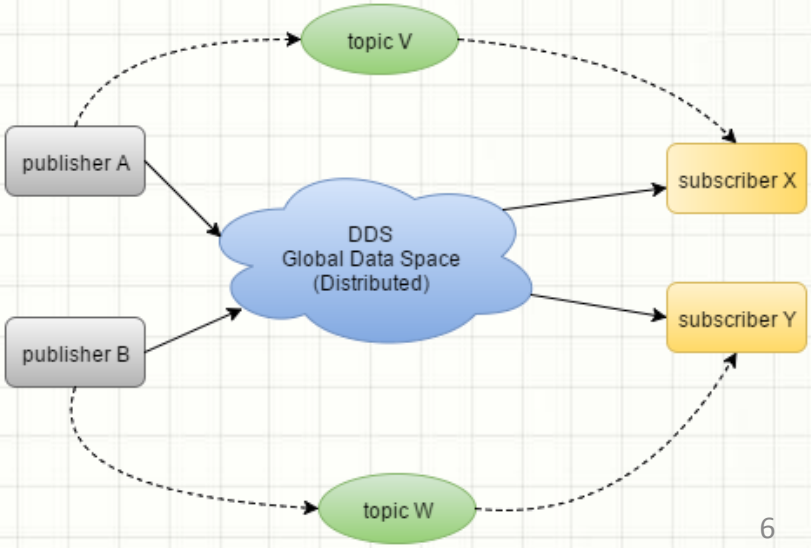
- Integrates with NASA Goddard's reusable flight software framework
  - Open source version of cFE/CFS **available at SourceForge**
  - Perform local device management, software messaging, & event generation
- Core Components
  - Core Flight Executive (cFE)
    - Mission-independent software services
  - Core Flight System (CFS)
    - Applications and libraries running on cFE



Developed by Object Management Group (OMG)

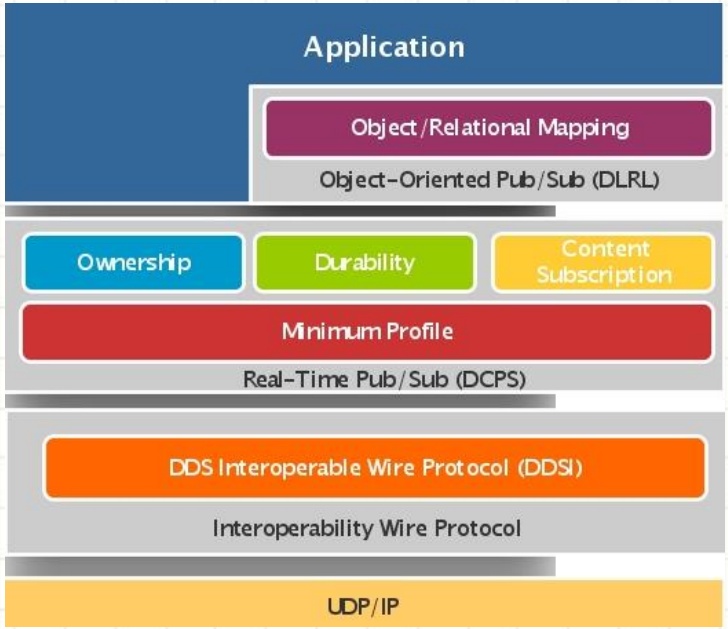
Data Distribution Service (DDS)

- Uses publish-subscribe model for data, events, and command exchange
  - Eliminates complex network programming for distributed applications
- Multiple DDS implementation vendors exist
  - OpenDDS (OMG)
  - OpenSplice (PrismTech)
  - ConnextDDS (RTI)

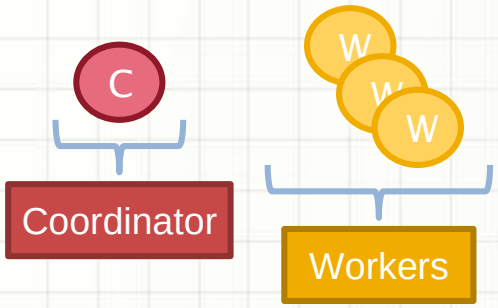


Data Distribution Service (DDS)

- Main DDS entities
  - Domain
    - Conceptual container: Entities communicate with each other only if they belong to same domain
  - Topic
    - Data object exchanged by subscribers/publishers
  - Publishers
    - Data producers
    - Creates “topics” and publishes data samples
  - Subscribers
    - Data consumers
    - DDS delivers data samples to them
- Interoperability
  - DDSI-RTPS specification
    - Interoperability protocol to allow multi-vendor DDS implementations communicate

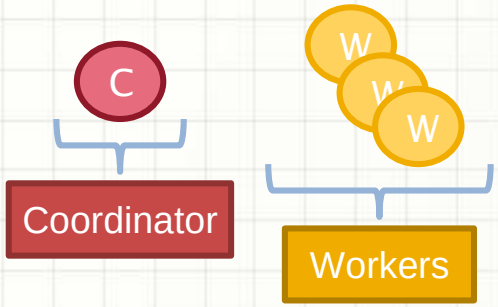


ADDAM

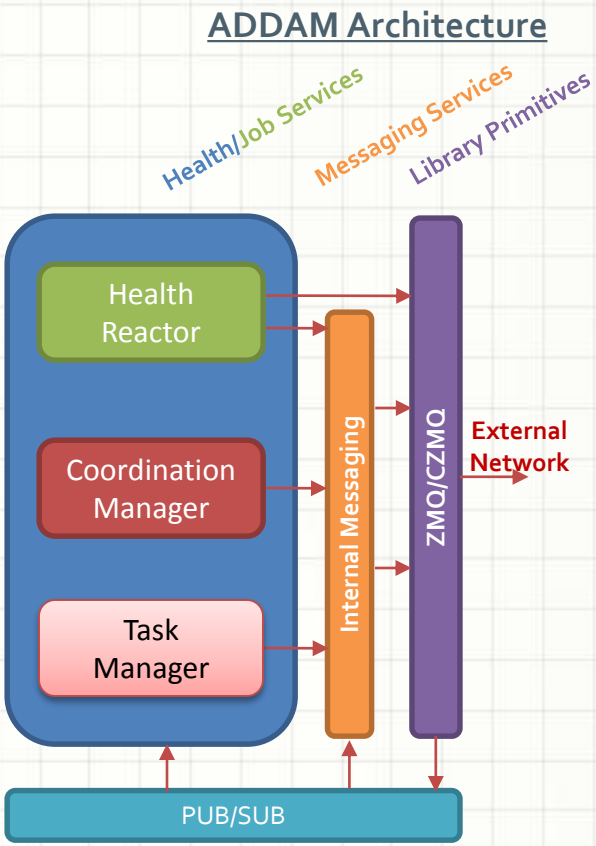


- Adaptive Dependable Distributed Aerospace Middleware (**ADDAM**)
  - System for dependable, distributed, and parallel computation
  - Self-recovering distributed system consisting of worker and coordinator agents
- Aims to provide a platform for dependable processing on parallel and distributed space computers
  - Assists in design and execution of fault-tolerant applications (serial and parallel)

ADDAM



- Uses heartbeats from agents to interpret system events
  - Newly joined agents
  - Disconnected agents
  - Reconnected agents
- Peer discovery
  - Broadcast and receive availability beacons; doubles as heartbeats
- Health reactor
  - Track changes in peer availability
- Task manager
  - Handle task dispatching and re-issue
- Coordination manager
  - Perform coordinator election



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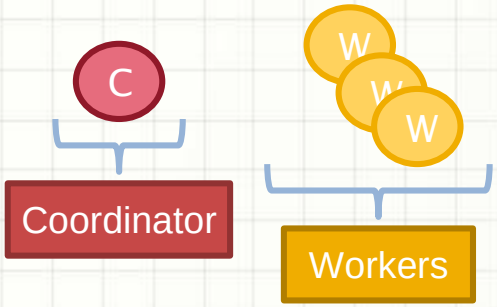
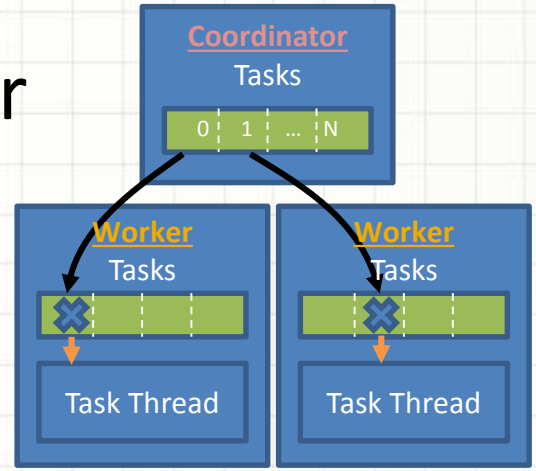
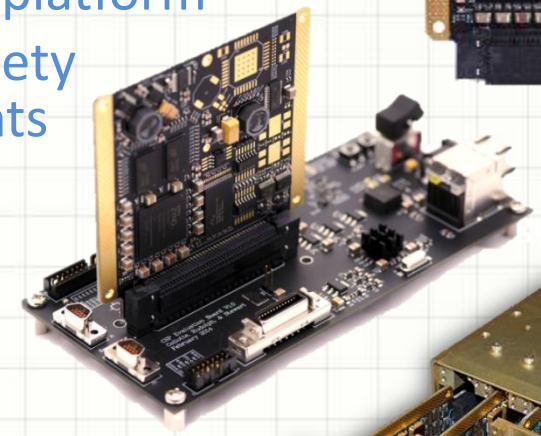


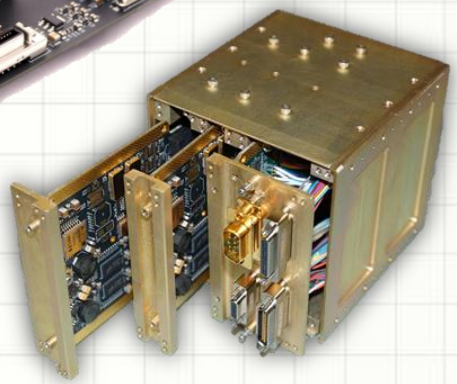
- Task redundancy
- Task reassignment on worker failure
- Coordinator failover
  - Using RAFT[1] consensus algorithm
- Per-device/node process failover
  - By use of an external daemon to monitor ADDAM processes and respawn them upon failure



[1] D. Ongaro and J. Ousterhout, "In search of an understandable consensus algorithm," in Proc. USENIX Annual Technical Conference, 2014, pp. 305–320.

CHREC Space Processor (CSP)



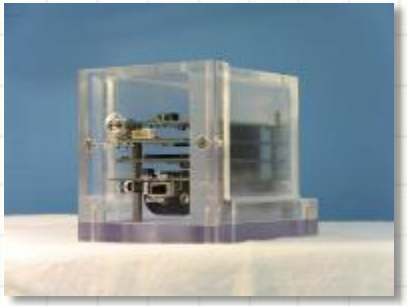


- Goal
  - High-performance, energy-efficient, low-cost, and dependable space-computing platform
  - Scalable and flexible to fulfill a variety of demands in mission requirements
  - Low power, high performance, and high reliability/availability
- Concept
  - **Multifaceted** hybrid computer
    - Hybrid system (commercial + rad-hard)
    - Hybrid processor (multicore CPU + FPGA subsystem) via Xilinx Zynq
  - Selective population scheme
    - **Pick-and-choose** commercial or rad-hard components
  - Flexible architecture (mission interfaces, algorithm acceleration)

Modular Integrated Stackable Layers

- Goals
  - Controller and processor "rack and stack" instrumentation technology with flexible design
  - Features reusable modules to meet varying mission requirements

- Objectives
  - Microcontroller systems and apps
  - Modular, scalable, reconfigurable
  - Quick to reconfigure for new apps
  - Industrial temperature environments
  - LEO environments



Related Work

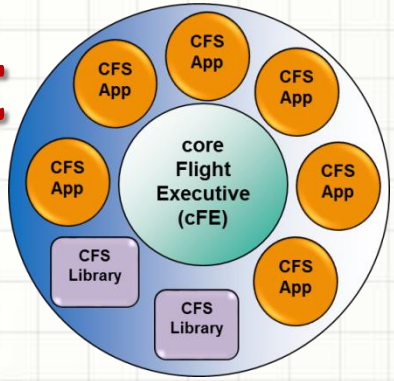
- In pursuit of this research, several other software solutions and middleware objects were studied
- **BioNET** – BioServe Space Tech., UC, NASA JSC
  - BioNet: A developer-centric middleware architecture for heterogeneous devices and protocols
- **CCSDS SOIS** – NASA / ESA
  - Spacecraft Onboard Interface Services
- **DMM** – Honeywell, UF, NASA
  - Dependable Multiprocessor Middleware
- **EDS** – CCSDS SOIS WG, ESA TRP
  - Electronic Data Sheets for Onboard Devices
- **Zero Configuration Networking (Zeroconf)**
  - Universal Plug and Play (UPnP)
  - Apple Bonjour
  - Avahi
- **Common Avionics Enabler (CAE)** – NASA JSC
  - Electronic endpoint capable of providing and/or utilizing the services of CCSDS SOIS

MOTIVATIONS AND GOALS

Why Middleware?

- **Middleware for Space**
  - Software services for reliable, interoperable, portable, reusable, efficient, and scalable discovery, management, and use of flight hardware and software resources
- **Example Use Cases**
  - Smart spacecraft, space supercomputing
- **Strategic Questions**
  - What future needs are well met by existing tools?
    - **Flight Computer Management (cFE/CFS toolset)**
  - What future needs are beyond existing tools?
    - **Flight System Management**
    - *Operating atop cFE/CFS, spanning multiple computers & modules*
    - *Leveraging of Spacecraft Onboard Interface Services (SOIS)*

Flight System Management



- **Flight Computer Management (existing)**
  - Focus upon space computer with its attached units
  - Core (cFE) and extended (CFS) services, API, apps
- **Flight System Management (notional)**
  - **Focus upon system-wide resources and management**
    - Broader scope for higher reliability, performance, configurability, adaptability, and scalability w/ space computers and smart modules
    - Variety of interfacing specifications, as defined in SOIS of CCSDS
  - **Multiple space processors and computers**
    - Spanning multiple devices, boards, chassis, and even spacecraft
    - To enable ***dependable computing*** (redundancy), ***distributed computing*** (cooperation), and ***parallel computing*** (collaboration)
  - **Assortment of smart modules**
    - Each capable of computing and networking, however modest
    - SBCs (e.g., CSP, SpaceCube) for C&DH and/or data processing, smart thrusters, smart comm, smart power, smart instruments, et al.
    - Each running some form of flight management core (cFE, cFE-lite)

SBC = single-board computer

Ex: Smart Modules on SmallSats?

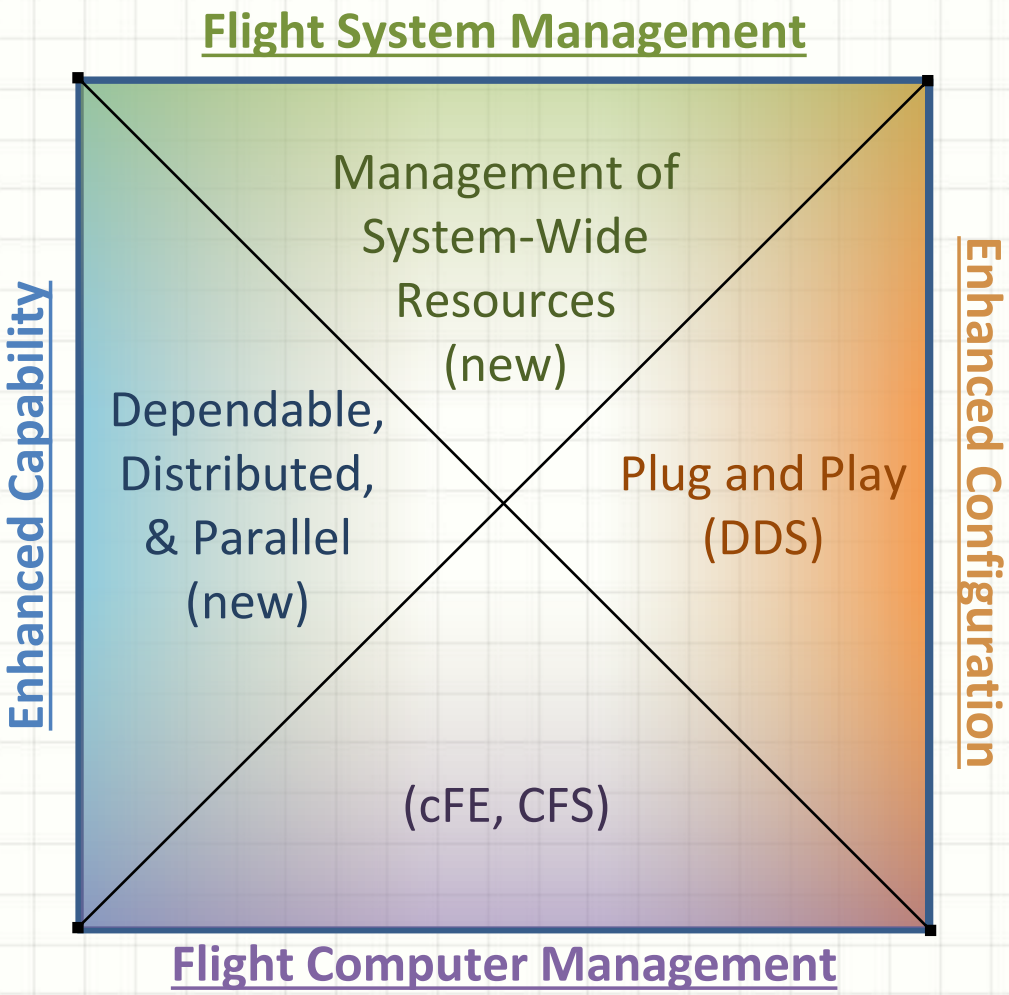
- Which devices are potential candidates as smart modules?
- Could a device type represent multiple network resources?
- Could multiple resources represent a single service?

- **Power**
  - Solar cells
  - Batteries
  - Power generator
- **Propulsion**
  - Thruster
  - Solar sail
  - Attitude determination and control
- **Communication**
  - Transmitters
    - Data rate, duplex
  - Flight terminal
    - Camera, fast-steering mirror
- **Instruments**
  - Photography camera
  - Gamma ray detector
  - Photometer
  - Optical spectrometer

- **Attitude determination and control**
  - Reaction wheels
    - Angular momentum
    - Maximum torque
    - Power
    - Microvibrations
  - Magnetorquer
  - Control moment gyros
  - Aerodynamic wing
  - Star tracker
    - Accuracy
    - Output rate
    - First tracking time
    - Maximum allowable slew rate (attitude maneuver rate)
  - Sun sensors
  - Earth sensors
  - Angular rate sensors
    - Precision: bias instability, angle random walk
  - GPS receiver and antennas
  - Active thermal control systems

Source: "Small Spacecraft Technology State of the Art" (NASA/TP–2014–216648/REV1)

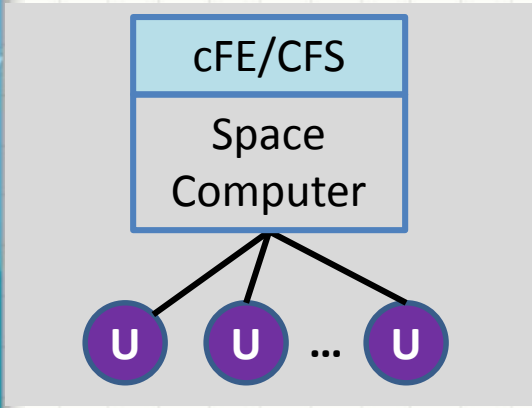
Outlining Areas of Work & Interest



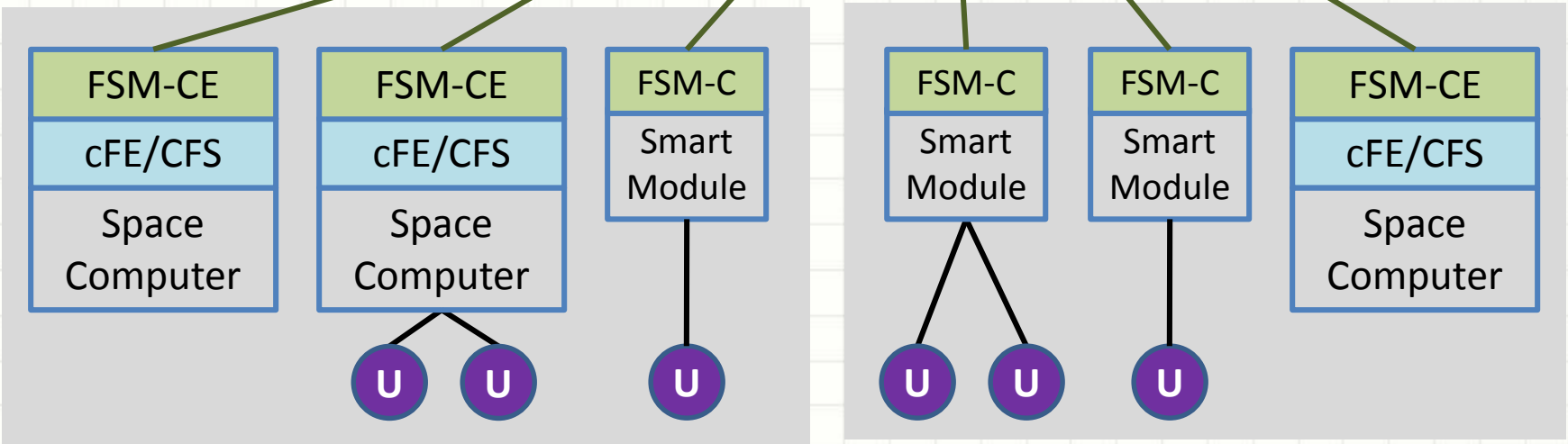
Example Comparison

U = unit (sensor, NAS, comm, power, thruster, et al.)
FSM-C = core services of FSM
FSM-CE = core & extended services of FSM

Centralized Architecture

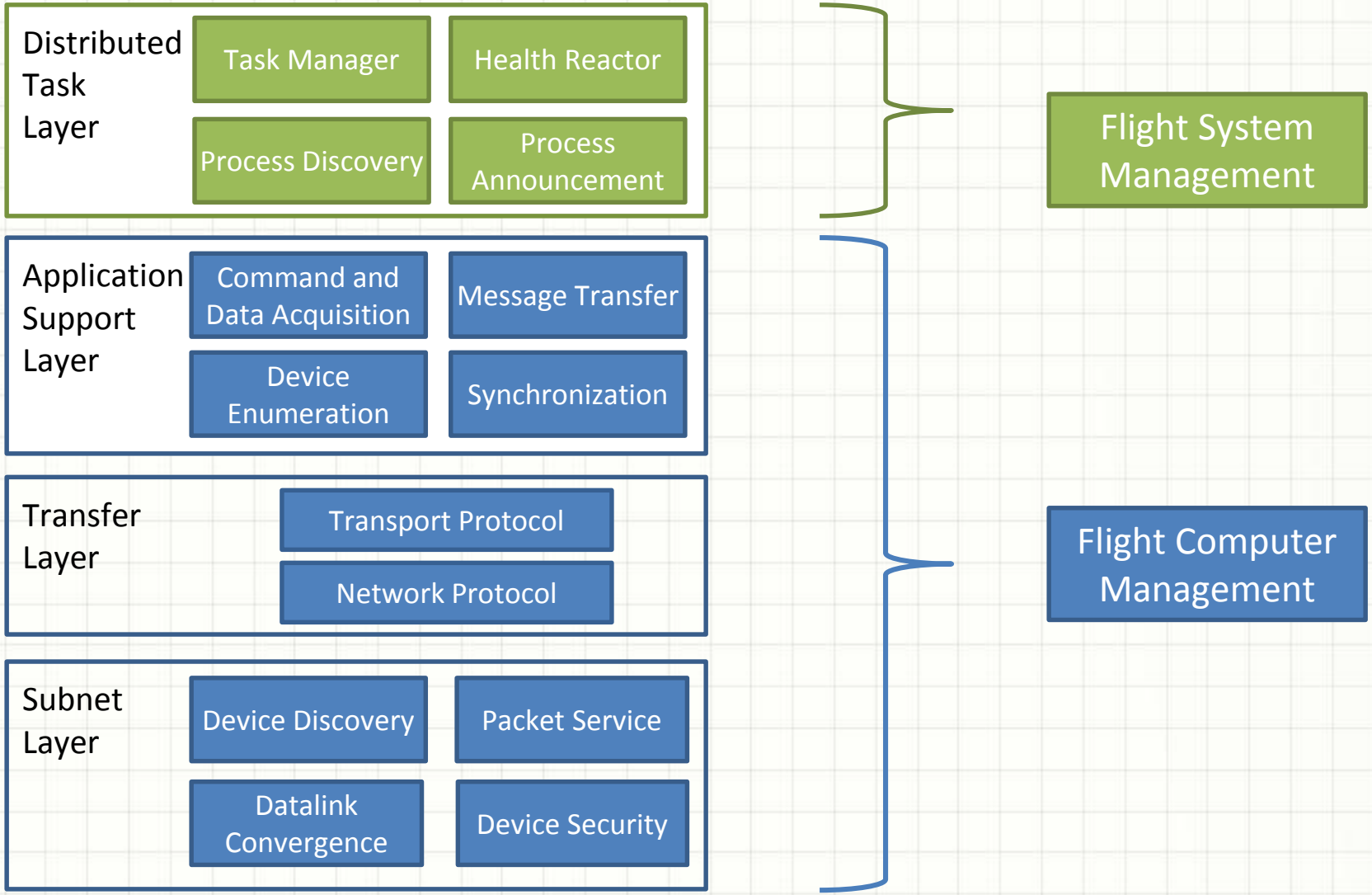


Distributed Architecture



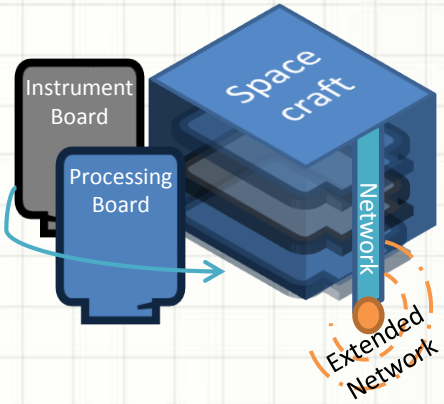
Middleware spanning multiple devices, boards, chassis, or even spacecraft

Enhanced Services

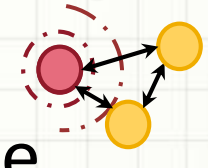


Goal: Enhanced Spacecraft Configuration

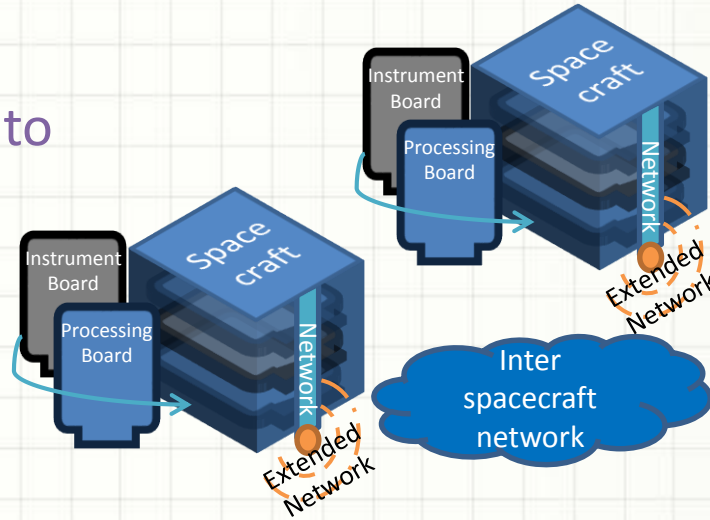
- Aims to be reliable, interoperable, portable and reusable
  - Expedite spacecraft development
    - Facilitate quick prototyping, integration (plug-and-play) and testing
  - Enable in-flight reconfiguration
    - Generalizing device usage to resource provider
- Technologies employed
  - DDS
    - For automatic device discovery and plug and play capability
  - cFE/CFS



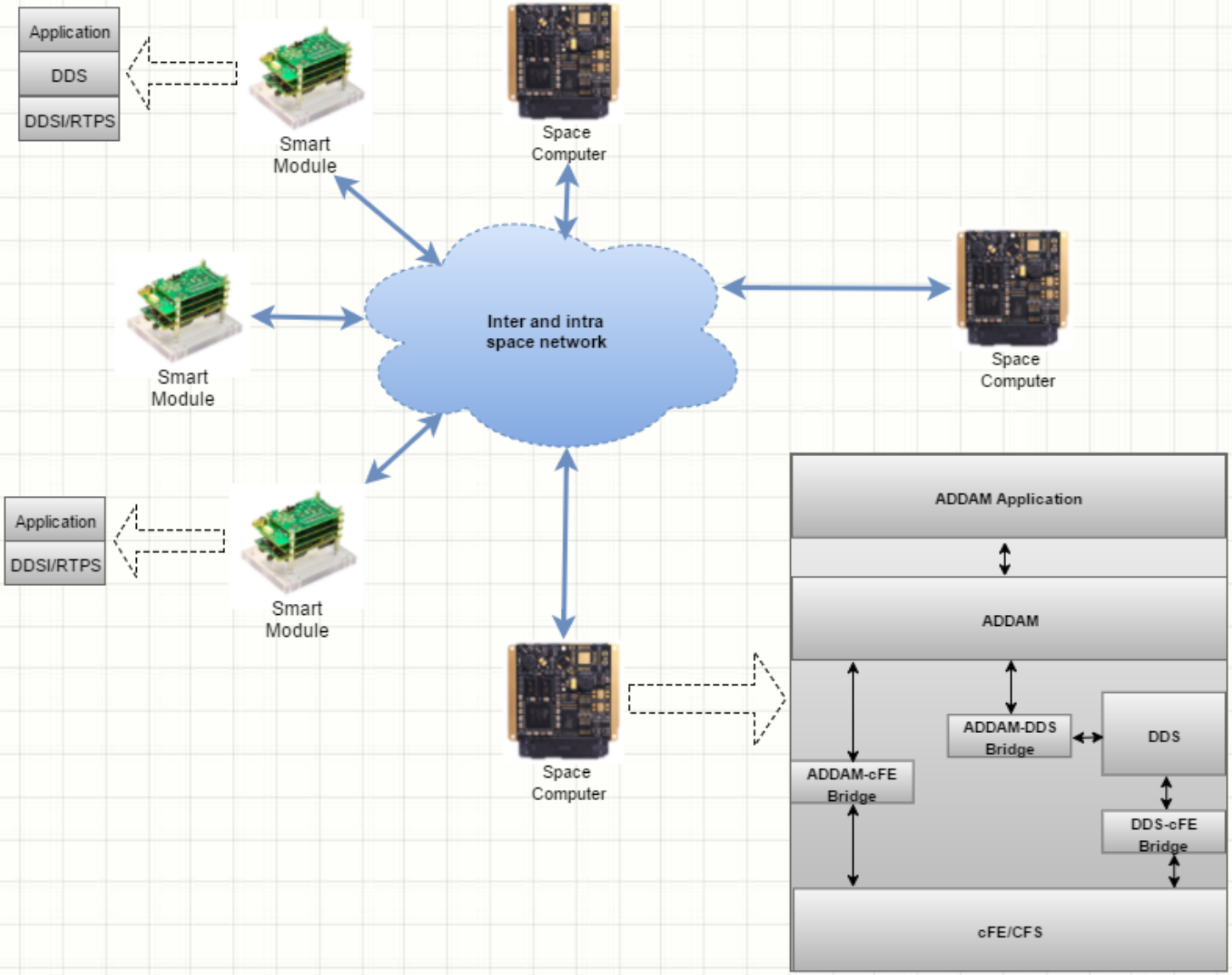
Goal: Enhanced Spacecraft Capability



- Aims to be fast, efficient, reliable, and scalable
  - Enhanced dependability
    - Make use of redundant resources to improve reliability and availability
  - Distributed resources
    - Producer-consumer relationships for advanced functionality
  - Parallel computing
    - Coordinated resources improving performance, scalability
- Technologies employed
  - ADDAM
    - For enhanced dependability and parallel computing

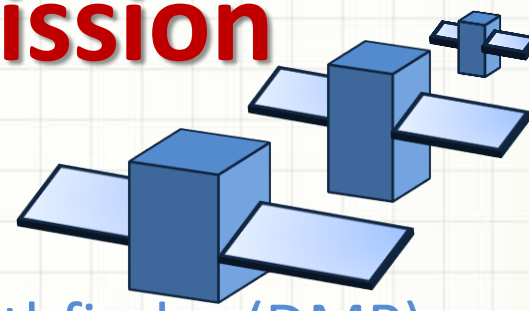


Architectural Overview



PROTOTYPE: NETWORKED STEREOSCOPIC IMAGING

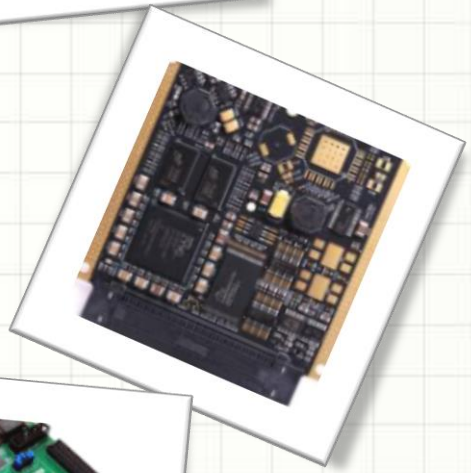
Prototype: Motivating Mission

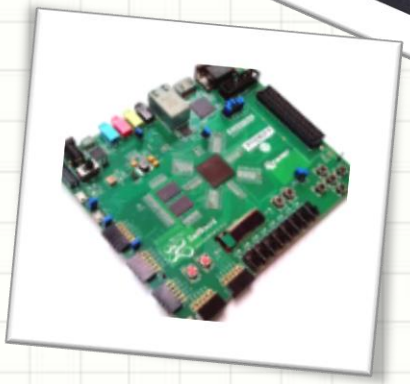


- Platform
  - Emulate Distributed Measurement Pathfinder (DMP)
    - 3 small satellites in formation, each with 1 camera and 2 space processors (DMP is a proposed mission by GSFC)
  - Intra-satellite network unified with inter-satellite network for simplicity
    - Network bridge is assumed for communications across satellites
    - Testing performed with Ethernet switch
- Test bed components mimicking target platform
  - Featuring smart modules (processors, sensors)

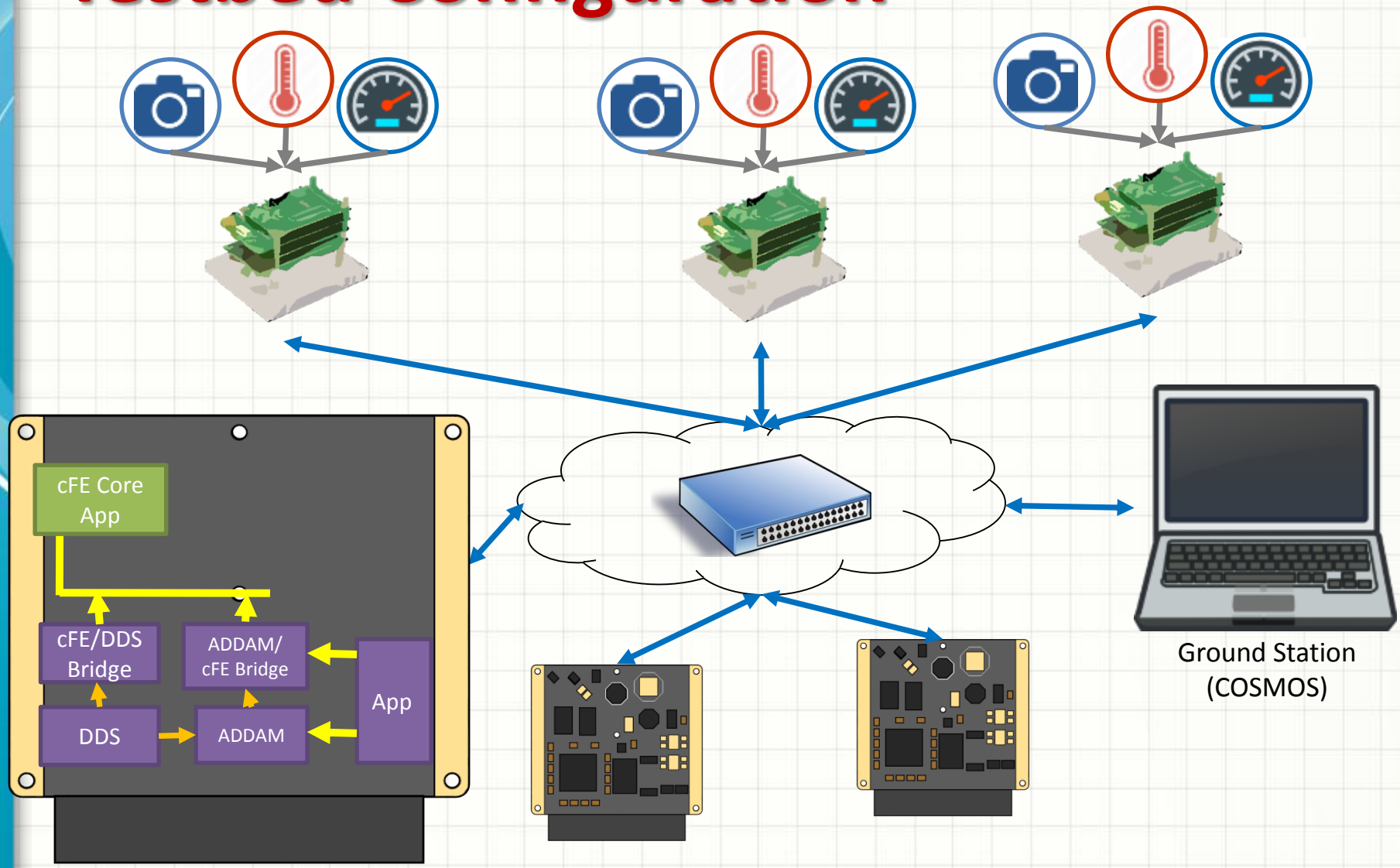
Prototype Hardware Components

- CSPv1 computers
- MISL RM48 modules
- Sensors
  - OV7670 imaging sensor
  - Thermocouple
  - Accelerometer
- Ethernet switch
- Ground station computer





Testbed Configuration



Planned Prototype Use Cases

- Communication between CSPs and smart modules
  - Verify communication between CSPs and smart modules
  - Performed by reading telemetry data sent to ground station computer
- Plug-and-play functionality
  - Add and remove smart modules and CSPs arbitrarily to verify plug-and-play capability
- Image stereoscopy
  - Perform image stereoscopy on a single node and on distributed nodes using ADDAM
  - Observe performance improvements when using ADDAM on distributed nodes

Prototype Use Cases (continued)

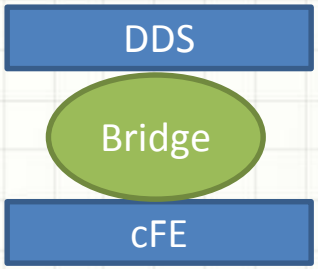
- Parallel processing
  - Demo multinode, multicore, & SIMD processing of images
  - Between and within CSPs (MPI, OpenMP, NEON)
- Coordinator failover
  - Verify election of new coordinator on failure of coordinator node
  - Performed by unplugging coordinator node and observing telemetry data on ground station
- Process failover
  - Verify ADDAM processes are respawned when they are killed
  - Performed by sending kill command from ground station and observing telemetry data on ground station to confirm election of new coordinator

Project Progress

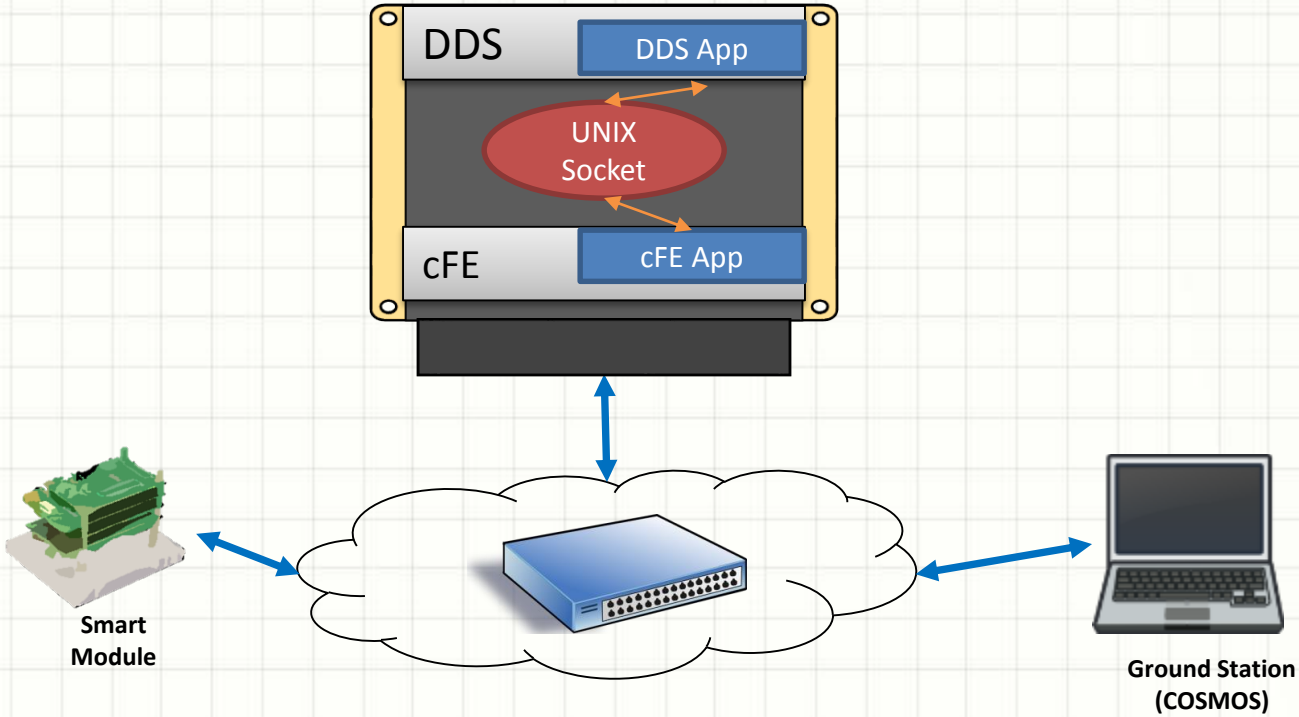
- Data Distribution Service
  - Chose OpenDDS[1] for use in space computer
  - Chose FreeRTPS[2] implementation for use in smart modules
  - Defined IDL[3] message types to be exchanged between space computers and smart modules
- cFE
  - Built cFE-DDS bridge
  - Built ADDAM-DDS bridge

[1] Open source DDS implementation by Object Management Group (OMG)
[2] Open source RTPS implementation by Open Source Robotics Foundation (OSRF)
[3] Interface Description Language

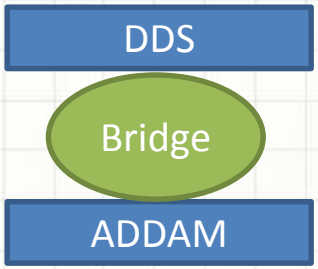
cFE-DDS Bridge



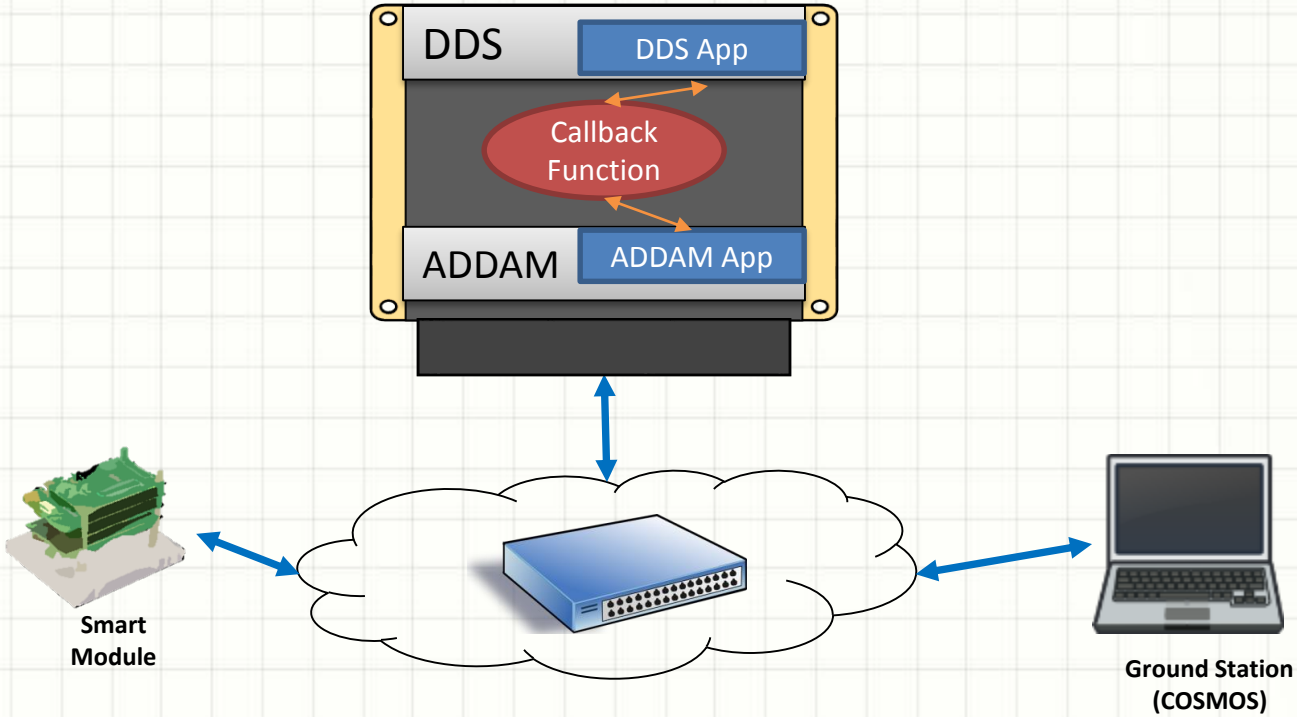
- Forwards ground station commands to smart modules
- How it works
  - cFE app sends data(commands) received from ground station to UNIX socket
  - DDS application listens on UNIX socket and interprets commands and forwards them to relevant smart modules



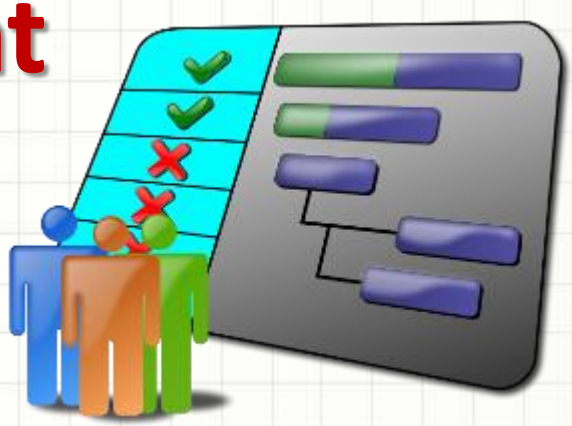
ADDAM-DDS Bridge



- Forwards DDS data from smart modules to applications running on ADDAM
- Application running on ADDAM specifies:
  - Topic name it wishes to receive data from
  - Callback function to be called whenever data samples for topic are available



Upcoming Development

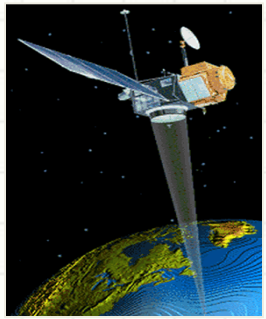


- Data Distribution Service
  - Port FreeRTPS to RM48 (MISL)
- ADDAM
  - Finish coordinator failover implementation
  - Add per-device process failover capability
    - By use of an external daemon
  - Add MPI-like API
    - addam_send, addam_receive, addam_barrier
  - Add logging framework with log replication capability across nodes

MPI = Message Passing Interface
API = Application Programming Interface

Conclusions

- R&D underway on CHREC Space Middleware (CSM)
  - Goals defined by group of CHREC members & sites
  - Focus: **Enhanced spacecraft configuration**
    - Smart modules, plug-and-play, smart spacecraft
  - Focus: **Enhanced spacecraft capability**
    - Dependable, distributed, & parallel computing



- Initial CSM prototype in development
  - Novel mix of existing & emerging technologies
    - cFE/CFS, DDS, CSP, MISL, ADDAM, et al.
  - Initial prototype: CubeSats (3) formation mockup
    - Space computers & smart sensor modules, stereoscopic imaging
  - Initial demo @ CHREC Annual Workshop (CAW15)
    - December 2-3, hosted by NASA Kennedy Space Center

QUESTIONS?