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
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
ADDAM

- 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

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)
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

Outlining Areas of Work & Interest

- Dependable, Distributed, & Parallel (new)
- Management of System-Wide Resources (new)
- Plug and Play (DDS)
- Flight System Management
- Flight Computer Management

(cFE, CFS)
Example Comparison

Centralized Architecture

```
<table>
<thead>
<tr>
<th>FSM-CE</th>
<th>cFE/CFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Computer</td>
<td></td>
</tr>
</tbody>
</table>
```

Distributed Architecture

```
<table>
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<td></td>
</tr>
</tbody>
</table>
                      
| FSM-CE          | cFE/CFS       |
| Space Module    |               |
                      
| FSM-C           |               |
                      
| FSM-C           |               |
| Space Module    |               |
                      
| FSM-CE          | cFE/CFS       |
| Space Computer  |               |
                      
```

U = unit (sensor, NAS, comm, power, thruster, et al.)

FSM-C = core services of FSM

FSM-CE = core & extended services of FSM

Intra- and Inter-Spacecraft Networks

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

Distributed Task Layer
- Task Manager
- Health Reactor
- Process Discovery
- Process Announcement

Application Support Layer
- Command and Data Acquisition
- Message Transfer
- Device Enumeration
- Synchronization

Transfer Layer
- Transport Protocol
- Network Protocol

Subnet Layer
- Device Discovery
- Packet Service
- Datalink Convergence
- Device Security

Flight System Management

Flight Computer Management
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

Ground Station (COSMOS)
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?