National Aeronautics and Space Administration

NASA's Core Flight Software - a Reusable Real-Time Framework

Topics:

- Core Flight Software (CFS) Overview
- Case Study: Morpheus Lander
- JSC CFS Development Efforts
- CFS Training Slides

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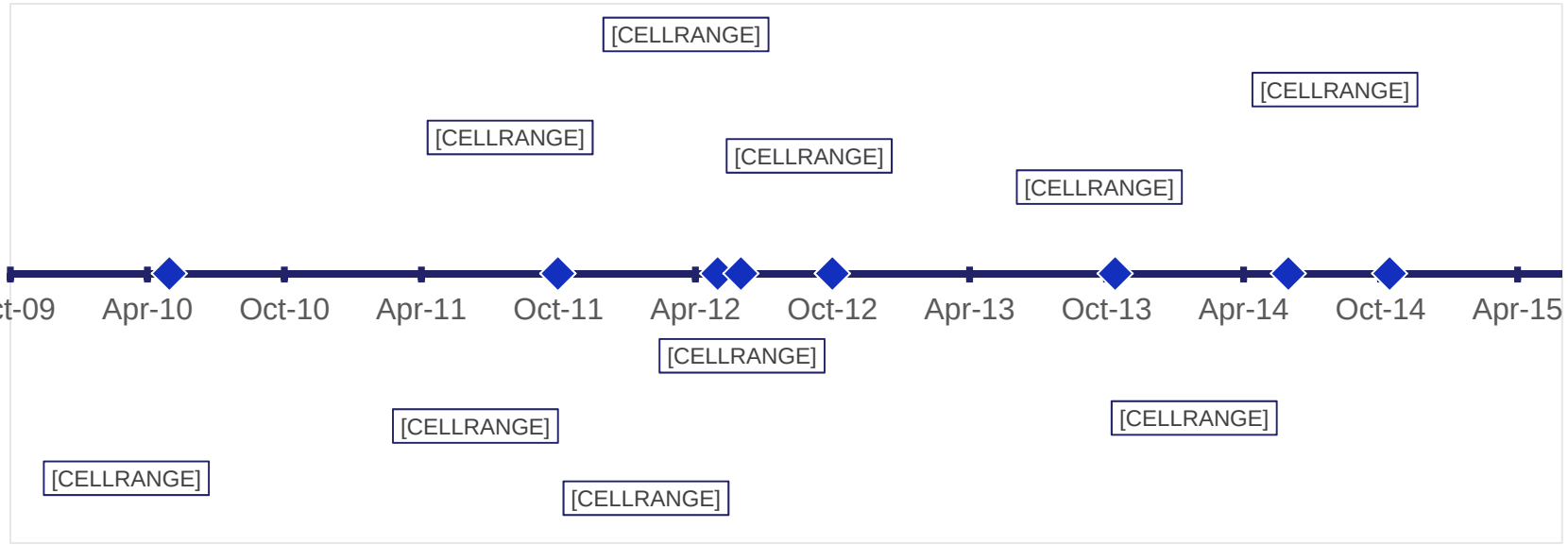
Core Flight Software (CFS) Background Context

- What is CFS?
  - NASA Agency Asset for Spacecraft Flight Software Reuse (http://cfs.gsfc.nasa.gov/)
    - Productized real-time flight software developed over several years by Goddard Space Flight Center to serve as reusable software framework basis for spacecraft missions, test missions, real-time systems
  - Fully tested, documented, operational with LRO spacecraft, several other operational missions since
  - Published Service Layer (cFE) and open source Operating System Abstraction Layer (OSAL) for common services
    - Pub/sub message bus, time services, events, tables, file, task execution (http://sourceforge.net/projects/coreflightexec/files/cFE-6.4.0/)
    - Runs on *multiple platforms and with several operating systems* (http://sourceforge.net/projects/osal/)
  - Apps or "bubbles" for common spacecraft functions provided as government open source reuse (available source forge shortly)
    - Scheduler, commanding, telemetry, communication, data recording, limits, system health, sequences
- Why use it?
  - Proven rapid deployment -- Saves software development/test time, costs, skilled resources
  - Provides up-front architectural framework and services needed commonly across spacecraft/real-time embedded command/control applications
    - Don't have to "reinvent the wheel" every spacecraft for common functions
  - Allows ease of development and integration by supporting multiple OS's and Platforms
- In-house experiences with CFS software development
  - High software productivity achieved starting with solid architecture (~15+ SLOC/day)
  - Ease of application and hardware/software integration
  - Decreased verification needed – mature code and architecture – Test Readiness Level (TRL9)
  - Excellent product line support from Goddard

CFS Project Use History – Non Exhaustive

Johnson Space Center CFS Usage Timeline



CFS Use in Some Current Spacecraft

Goddard Missions:

- Lunar Reconnaissance Orbiter (LRO) (2009)
- Solar Dynamics Observatory (SDO) (2010)
- Magnetospheric Multiscale Mission (MMS) (2014)
- Global Precipitation Measurement (GPM) (2014)

Ames Research Center Missions:

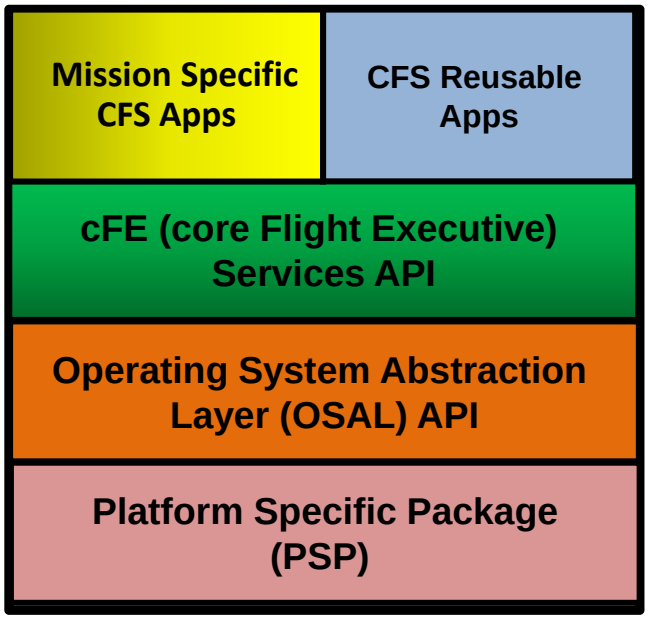
- Lunar Atmosphere and Dust Environment Explorer (LADEE) (2013)

Applied Physical Lab (APL) Missions:

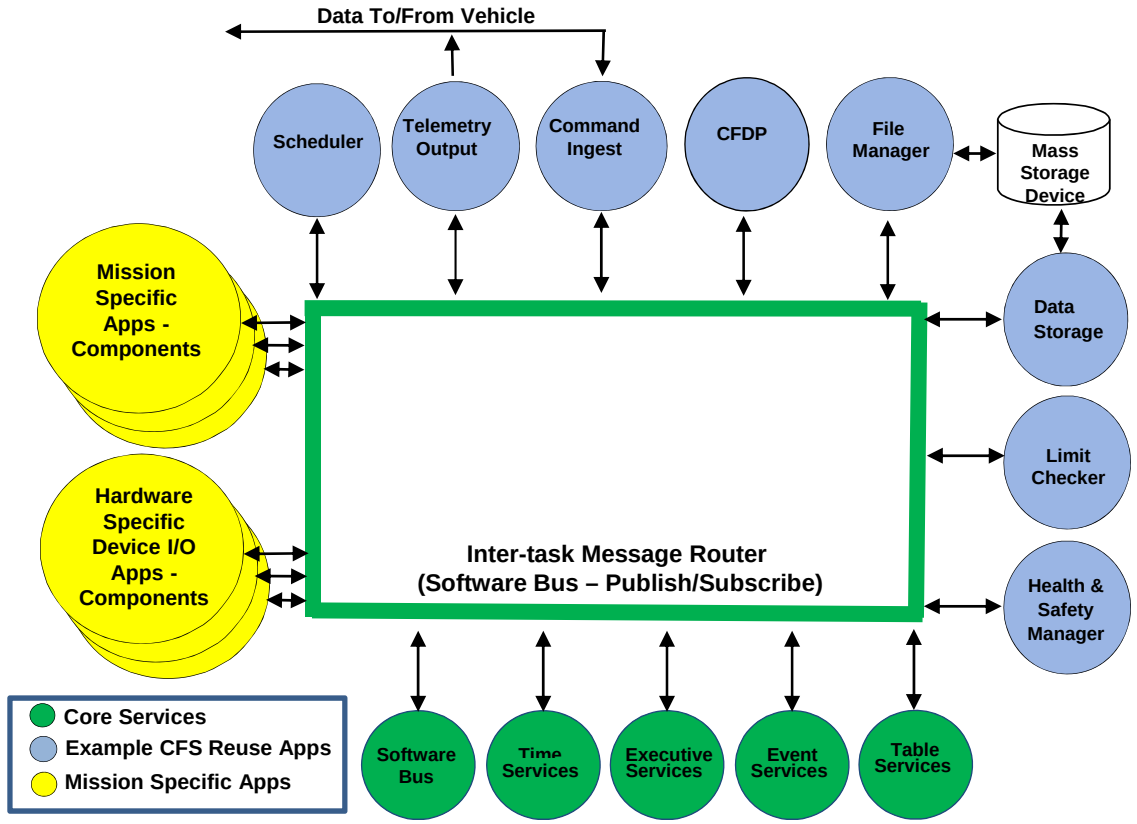
- Radiation Belt Storm Probes (RBSP) (Aug 2012)
- Solar Probe Plus (SPP) (2018)

Core Flight Software (CFS) Architecture Overview

Core Flight Software Framework- Architectural Layers



Notional CFS Application Software Architecture



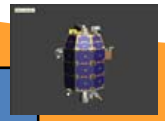
CFS Supported Platforms
(non-exhaustive)

Platform	OS	Project	Status / Notes
RAD750	vxWorks 6.4	LRO,RBSP, GPM	Project tested.
RAD750	RTEMS 4.10	ICESat-2/ATLAS	Early in instrument test program
Rad Hard Coldfire (5208)	RTEMS 4.10	MMS	Project tested.
LEON3	RTEMS 4.10	Solar Probe Plus	In Development for SPP mission
MCP750 PPC	vxWorks 6.4	cFE/CFS Project	Tested. Used as baseline CFS development platform.
PC / x86	Linux	n/a	Not formally tested. Used by JSC.
Coldfire MCF5235 board	RTEMS 4.10	n/a	Not formally tested. Used for RTEMS Development, and MMS board.
LEON3 – generic – (simulator, multiple COTS boards)	RTEMS 4.10	n/a	Not tested. Not in CFS CM. Used for LEON3 development. Can be used on LEON3 Simulator.
Coldfire Simulator (qemu 68k)	RTEMS 4.10	n/a	Not formally tested. Used for OSAL / cFE development
TILERA	Linux	Maestro IRAD (FY12)	Not formally tested. Compatible with Desktop PC linux version.
MCP750 PPC	vxWorks 6.x	Memory Protection IRAD (FY11)	Adds memory protection to standard cFE. Not formally tested. Not integrated with cFE repository.
PC x86	Linux	Multi-Core IRAD (FY12)	Adds multi-core CPU capability to cFE. Not formally tested. Not integrated with cFE repository.
Leon3	PikeOS	Virtualization IRAD (FY12)	Adds ability to run in partitioned OS. Prototype. Not integrated with cFE repository.

Platform	OS	Project	Status / Notes
Aitech S950 (PPC750FX)	vxWorks 6.7	Morpheus	In JSC CM. Integration tested on real Morpheus Vehicle hardware. Flown on Morpheus test vehicle.
RTD pc386-IDAN, PC104, Pentium M	RTEMS 4.10	ISS Downmass/ Micro Capsule	In JSC CM. Integration tested on real Micro Capsule hardware.
Acro Virtex 5	VxWorks 6.9	AEMU	In development.
Space Micro Proton P400k	VxWorks SMP 6.8	MMSEV, AAE	In JSC CM. In development for MMSEV FY13 work.
Maxwell SCS750	VxWorks 6.9 RTEMS 4.10	EAM, AAE	In JSC CM. EAM about to start using.
787FCM	Integrity ARINC	AES CFS	In development, producing ARINC653 cFE, OSAL.
OrionSCP	Integrity ARINC	AES CFS	In development, producing ARINC653 cFE, OSAL.
750FCR	VxWorks ARINC 6.8	AES CFS	In development, testing FTSS SW fault containment with a voting quad architecture.
Trick (simulation environment)	Linux	AES CFS	In development, for multi-project use.
LEON3	VxWorks 6.7	BFS	In JSC CM. BFS prototype.
AiTech SP0	VxWorks 6.7	RPM?	In JSC CM. RPM performance analysis.

Recently Developed
largely in support of AES projects

Broad Awareness/Use of the CFS



ARC- Using on LADEE (flight SW system on budget /schedule)

Commercial - Moon Express (Lunar X-Prize)

JPL – Evaluating architecture for robotic missions and ESTO missions, DTN

DOD
- Potential for standardization though Office of Director of National Intelligence (ODNI)
- 2012- met w/ Space Universal MOdular Architecture (SUMO) team led by Office of Director for National Intelligence (James Afarin (HQ))

GRC –Using on CPST, Suits

APL - Successfully used on RBSP. Proposing use on Solar Probe, DoD programs.

GSFC-Used Successfully on LRO, using on MMS, GPM, instruments. Plans for NICER, several others.

MSFC- Mighty Eagle Lander, prototyping for AES

JSC-Used Successfully on Morpheus. Using on Habitats and Suits (AES) – enhancing for human rated software.

KSC-Evaluating for AES, sounding rockets and UAV's

South Korea Aerospace Research Institute (KARI) - Lunar Exploration Research Team

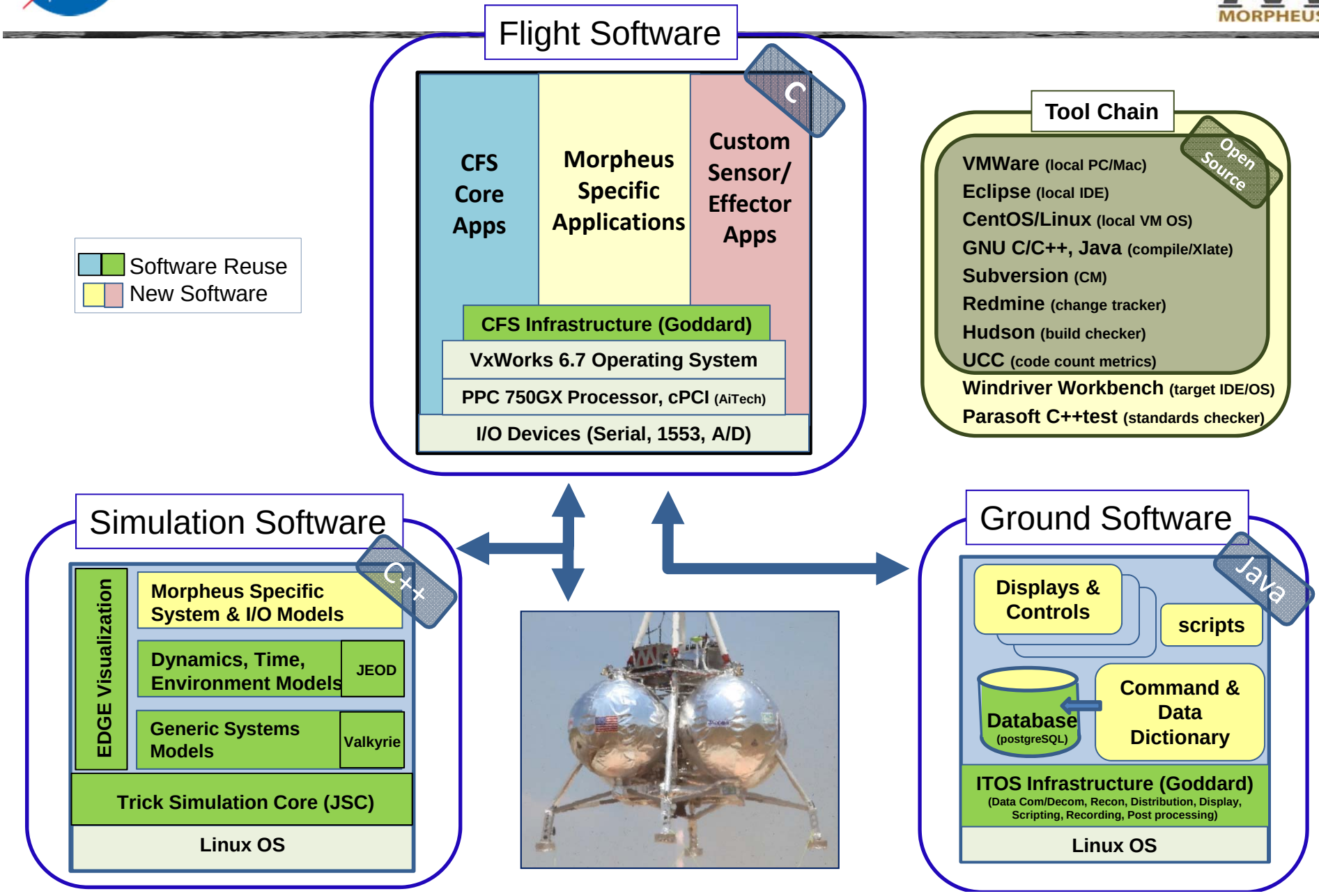
http://www.nasa.gov/mission_pages/lunarquest/robotic/12-085.html

Case Study: Project Morpheus Introduction

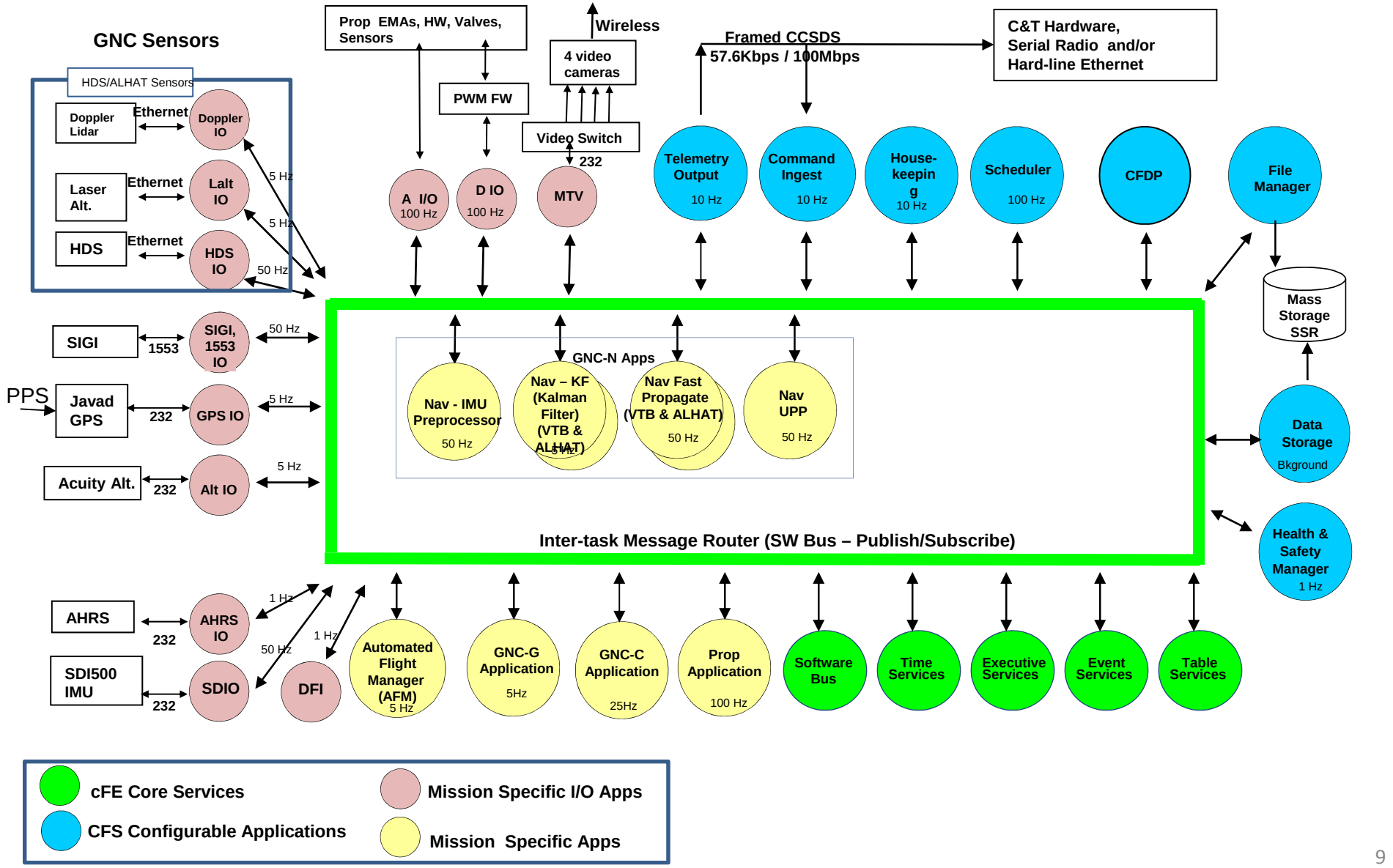
While technologies offer promise, capabilities offer potential solutions with application for future human exploration beyond LEO. Morpheus provides a bridge for evolving these technologies into capable systems that can be demonstrated and tested – in a relevant flight environment.

- Morpheus is a Full Scale Robotic Lander (500kg payload) built as a risk reduction test article
  - Morpheus system includes the vehicle, ground systems, operations
  - Developed, tested and operated in-house at Johnson Space Center and KSC
  - Example Video: http://www.youtube.com/watch?v=tdrSYP2gSbg
- Technologies:
  - Liquid oxygen/methane propulsion (cryogenic, green, safe for ground handling and crew)
  - Precision landing and hazard detection Sensors
  - Leverages GSFC's modular, reusable Core Flight Software
  - Technology incubator for advanced development efforts
- Tests complete: 12 hot fire, 34 tethered, and 14 free flights to date
- Lean Development Approach

Morpheus Software Components



Morpheus Flight Software Architecture



Sample CFS App Template

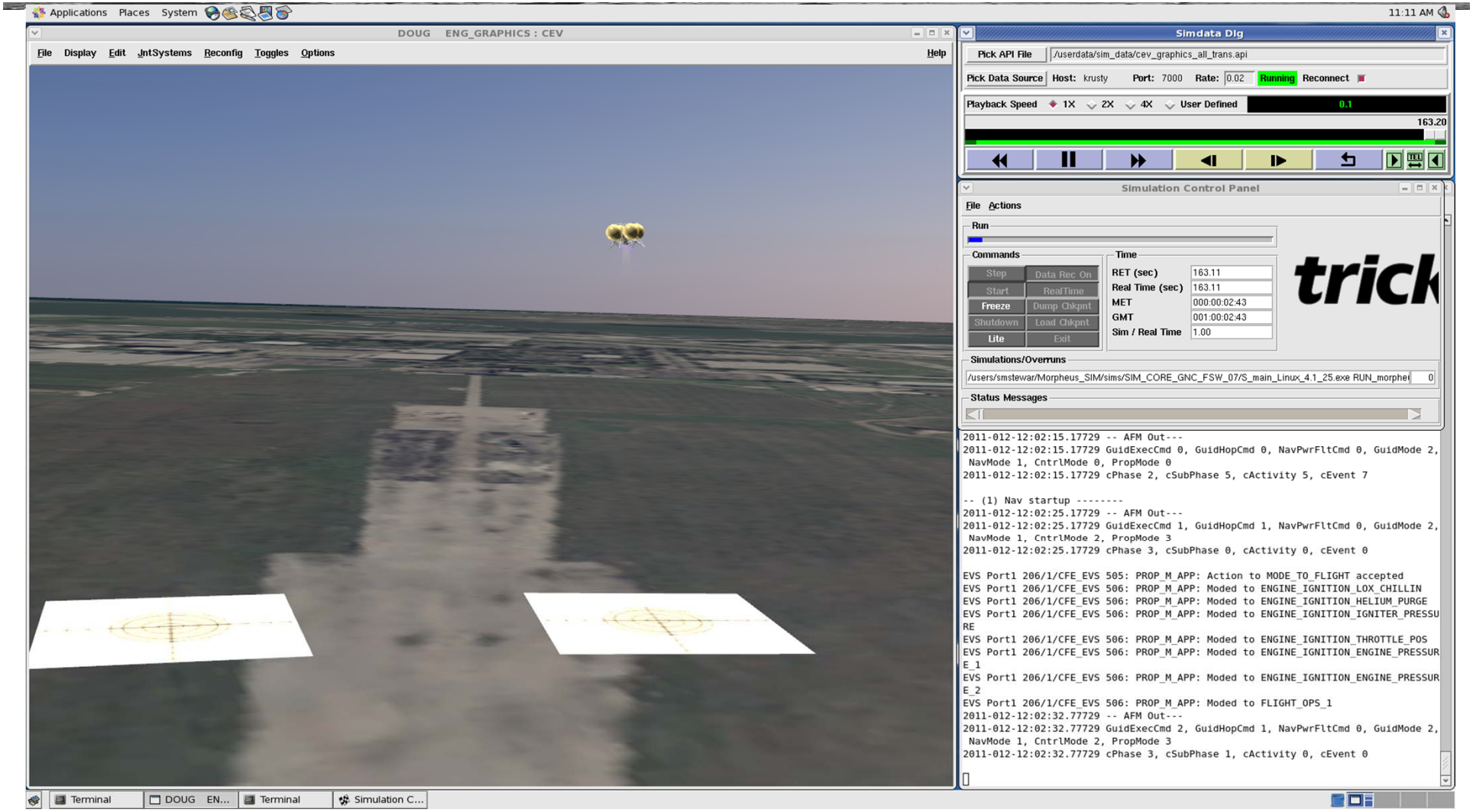
```
void XXX_AppMain()
{
    /* Perform application initializations */
    if (XXX_InitApp() != CFE_SUCCESS)
    {
        g_XXX_AppData.uiRunStatus = CFE_ES_APP_ERROR;
    }

    /* Application main loop */
    while (CFE_ES_RunLoop(&g_XXX_AppData.uiRunStatus)
== TRUE)
    {
        XXX_RcvMsg(CFE_SB_PEND_FOREVER);
    }

    /* Exit the application */
    CFE_ES_ExitApp(g_XXX_AppData.uiRunStatus);
}
```

```
int32 XXX_InitApp()
{
    int32  iStatus=CFE_SUCCESS;

    g_XXX_AppData.uiRunStatus = CFE_ES_APP_RUN;

    iStatus = CFE_ES_RegisterApp();
    if (iStatus != CFE_SUCCESS)
    {
        CFE_ES_WriteToSysLog("XXX - Failed to register the
app (0x%08X)\n", iStatus);
        goto XXX_InitApp_Exit_Tag;
    }

    if ((XXX_InitEvent() != CFE_SUCCESS) ||
        (XXX_InitPipe() != CFE_SUCCESS) ||
        (XXX_InitData() != CFE_SUCCESS))
    {
        iStatus = -1;
        goto XXX_InitApp_Exit_Tag;
    }

    /* Install the cleanup callback */

OS_TaskInstallDeleteHandler((void*)&XXX_CleanupCallback);

XXX_InitApp_Exit_Tag:
    if (iStatus == CFE_SUCCESS)
    {
        CFE_EVS_SendEvent(XXX_INIT_INF_EID,
CFE_EVS_INFORMATION,
                          "XXX - Application
initialized");
    }
    else
    {
        CFE_ES_WriteToSysLog("XXX - Application failed to
initialize\n");
```

Sample CFS App Template (continued)

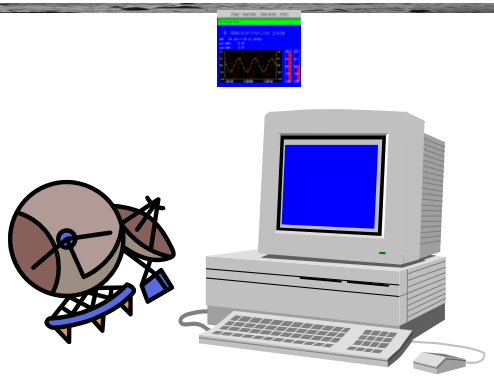

```
int32 XXX_RcvMsg(int32 iBlocking)
{
    int32           iStatus=CFE_SUCCESS;
    CFE_SB_Msg_t*   MsgPtr=NULL;
    CFE_SB_MsgId_t  MsgId;

    /* Wait for WakeUp messages from scheduler */
    iStatus = CFE_SB_RcvMsg(&MsgPtr, g_XXX_AppData.SchPipeId,
iBlocking);

    /* Start Performance Log entry - create initial entry */
    CFE_ES_PerfLogEntry(XXX_MAIN_TASK_PERF_ID);

    if (iStatus == CFE_SUCCESS)
    {
        MsgId = CFE_SB_GetMsgId(MsgPtr);
        switch (MsgId)
             {
            case XXX_WAKEUP_MID:
                XXX_ProcessNewCmds();
                XXX_ProcessNewData();

                /* TODO:  Add more code here to handle other
things
                   when app wakes up, like any cyclic
processing */

                /* The last thing to do at the end of this
Wakeup cycle
                   should be to automatically publish new
output. */
                XXX_SendOutData();
                break;

            /* TODO:  Add code here to handle other command
IDs, if needed.
               Normally, other app commands are added as
command codes
               to the app's CMD_MID and processed in
XXX_ProcessNewCmds().
               Adding another CMD_MID would also require adding
another
               command pipe. */

                default:
                    CFE_EVS_SendEvent(XXX_MSGID_ERR_EID,
CFE_EVS_ERROR,
                                      "XXX - Recvd invalid SCH msgId
(0x%08X)", MsgId);
            }
        }
        else if (iStatus == CFE_SB_NO_MESSAGE)
        {
            /* If there's no incoming message, you can do something
here,
               or do nothing */
        }
        else
        {
            /* This is an example of returning on an error.
            ** Note that a SB read error is not always going to
result in an
            ** app quitting, depends on the app.   Changing the run
status to
            ** CFS_ES_APP_ERROR will cause the app's main loop to
exit and the
            ** app to exit.
            */
            CFE_EVS_SendEvent(XXX_PIPE_ERR_EID, CFE_EVS_ERROR,
                                                "XXX: SB pipe read
error (0x%08X), app will exit", iStatus);
            g_XXX_AppData.uiRunStatus= CFE_ES_APP_ERROR;
        }

        /* Stop Performance Log entry */
        CFE_ES_PerfLogExit(XXX_MAIN_TASK_PERF_ID);

        return (iStatus);
}
```

Morpheus Simulation



Morpheus Ground Systems – ITOS Control Room

ITOS Information - Introduction



What is ITOS (Integrated Test and Operations System)?

- **A low-cost, highly configurable, control and monitoring system**

What are its current applications?

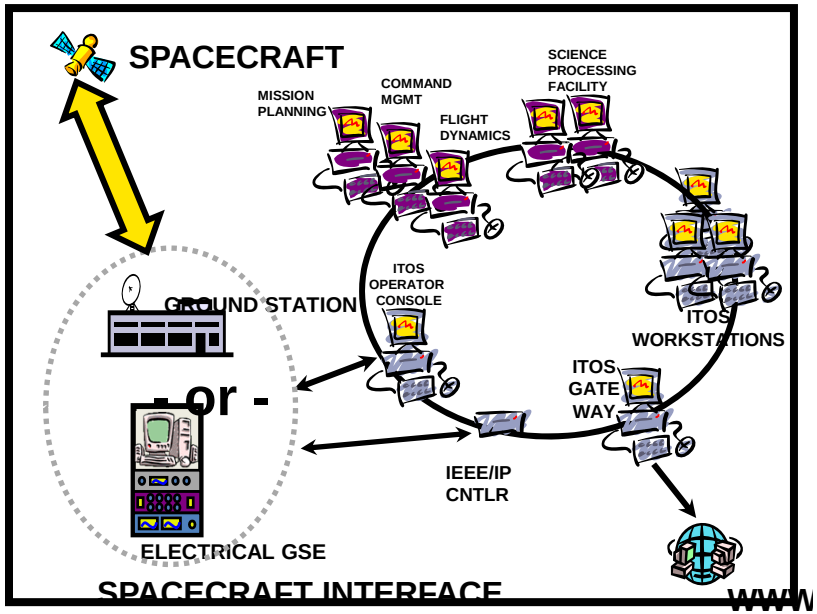
- **Satellite development, test, & operations**
- **Science instrument development, test, & operations**
- **Ground station equipment monitoring & control**

Who is using ITOS?

- **SAMPEX, TRACE, FAST, SWAS, WIRE,**
- **Spartan 201, 251, 401, 402**
- **HESSI, Swift, ULDB, Triana**
- **PiVot GPS, CIRS, Mars Pathfinder**

Who is commercializing ITOS?

- **Universal Space Network**
- **the Hammers Company**
- **Omitron**
- **AlliedSignal Technical Services Corporation**



From ITOS Promo Presentation: http://itos.gsfc.nasa.gov/

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ADVANCED EXPLORATION SYSTEMS (AES)
HUMAN EXPLORATION & OPERATIONS MISSION DIRECTORATE

CORE FLIGHT SOFTWARE (CFS) PROJECT SUMMARY

Core Flight Software

Lorraine Prokop, Ph.D. / JSC

Project Objectives

- Objectives
  - Provide a *reusable* software architecture suitable for human-rated missions
    - Reduce/offset per-project software development, test, and certification costs by performing that work *once* serving multiple projects
    - Address software and hardware issues unique or typical to human-rated systems
  - Provide reusable software products, tools, and artifacts directly usable by Class A projects/programs, and for general use across NASA
  - Support Advanced Exploration Systems projects as they develop toward flight missions

Build upon reuse of existing TRL-9 uncrewed spacecraft software framework for utilization in human-rated programs.

Leverage platforms, resources and skills from synergetic programs/projects for development of next generation human-rated space software systems.

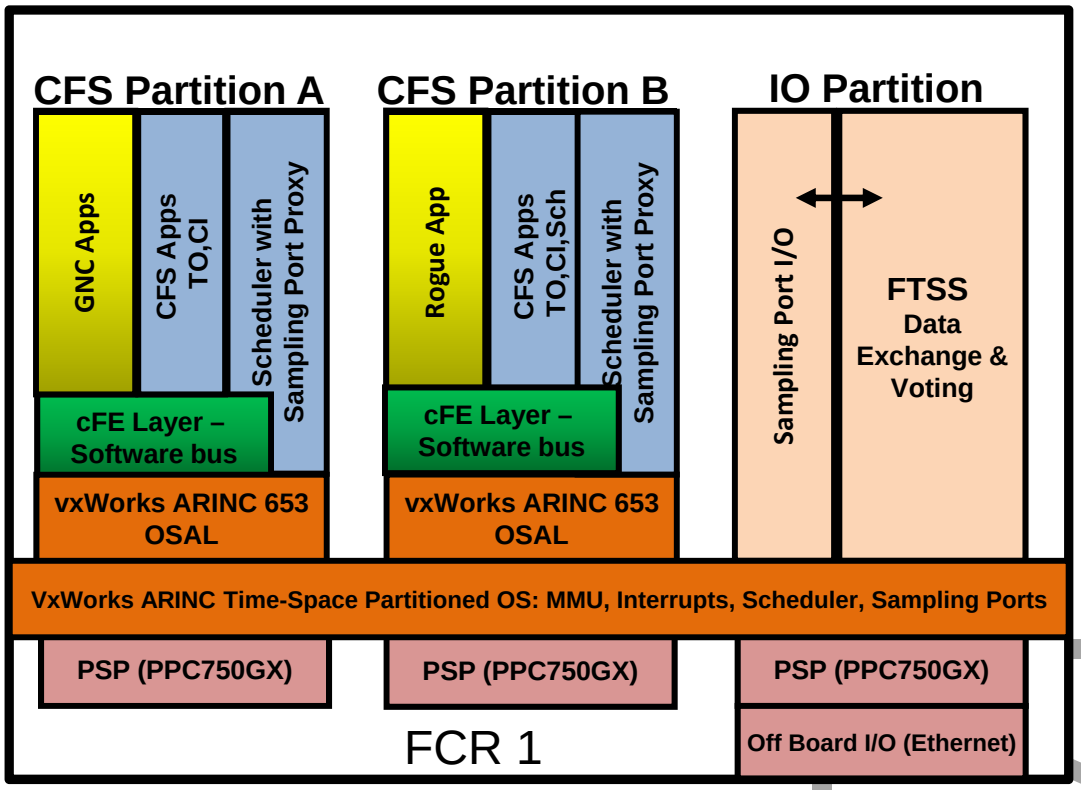
The Core Flight Software Project's objective is to evolve and extend the reusability of the Core Flight Software System into human-rated systems, thus enabling low cost, and rapid access to space.

Utilize these products in direct support of development and certification of future manned programs.

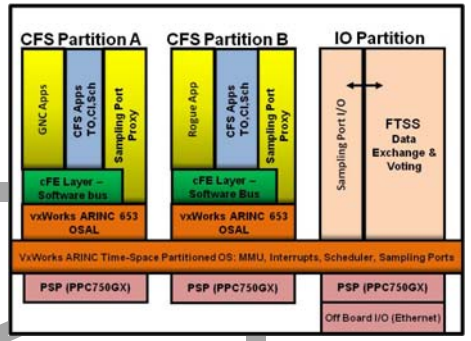
CFS AES Project
Product Summary to Date

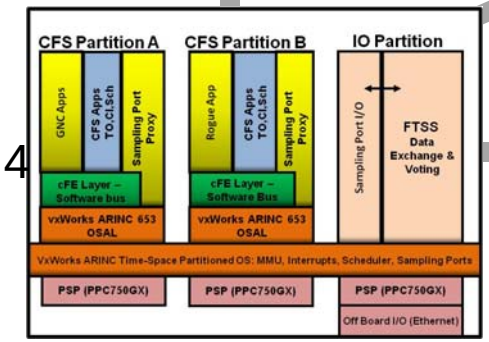
- FY13 Products
  - Quad-Voting CFS System – CFS on Partitioned VxWorks RTOS, synchronizing & voting 4 computers
  - CFS within Trick Simulation
  - Distributed CFS – network-based software bus
  - CFS on Orion/B787 Platform – CFS on Partitioned Green Hills RTOS
  - Reusable Certification Test Suite
- FY14 Products
  - Class A CFS Certification on Orion Platform
  - Performance Monitoring Tool Development
  - CFS Synch & Voting Software Development
  - Symmetric Multicore Processor (SMP) CFS Development
  - Product Line
  - Command & Data Dictionary Ground Database Tools
  - Education/Outreach
  - Orion Backup Computer Proof of Concept Demonstration

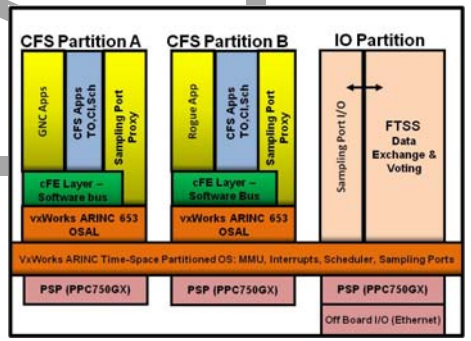
Flight Computer Architecture: CFS on ARINC and Voting Partition



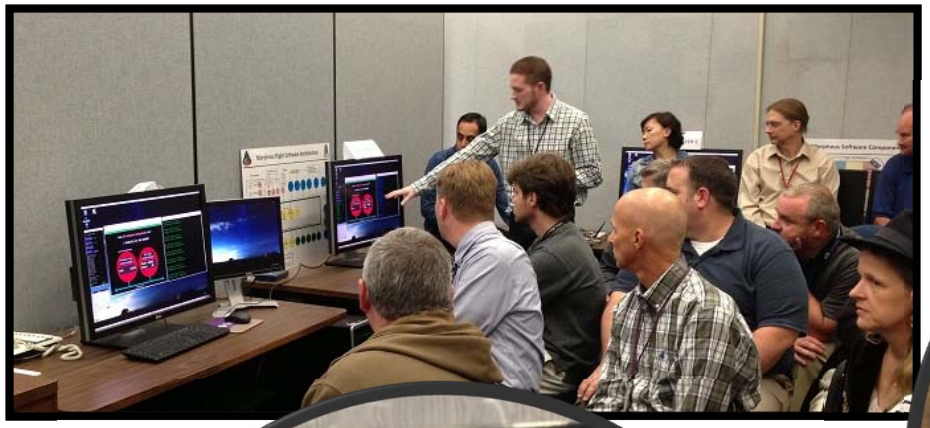
- Four fault-containment regions (FCRs)
  - 4 Flight Critical Computers (FCC)
- Software voting
- Ethernet
- Will accommodate 2 arbitrary non-simultaneous faults

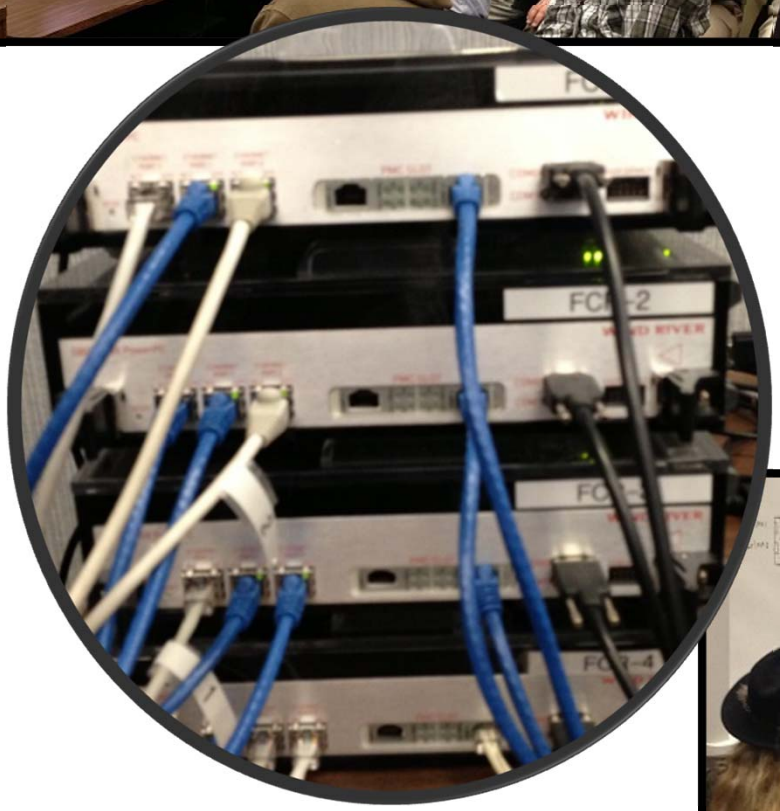


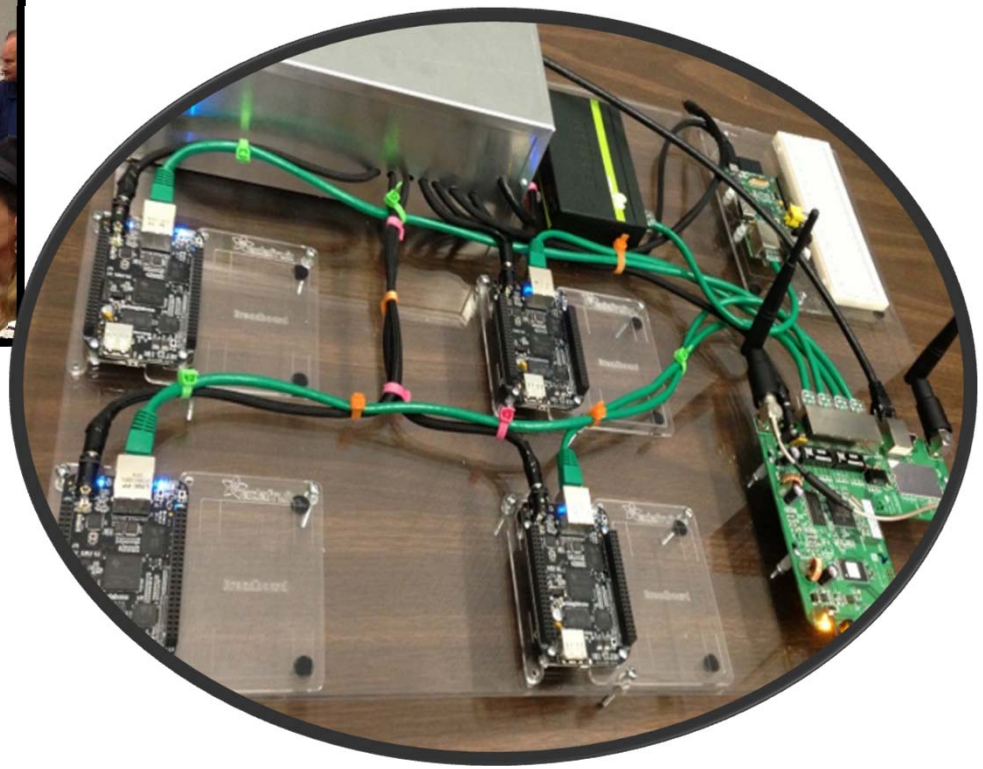




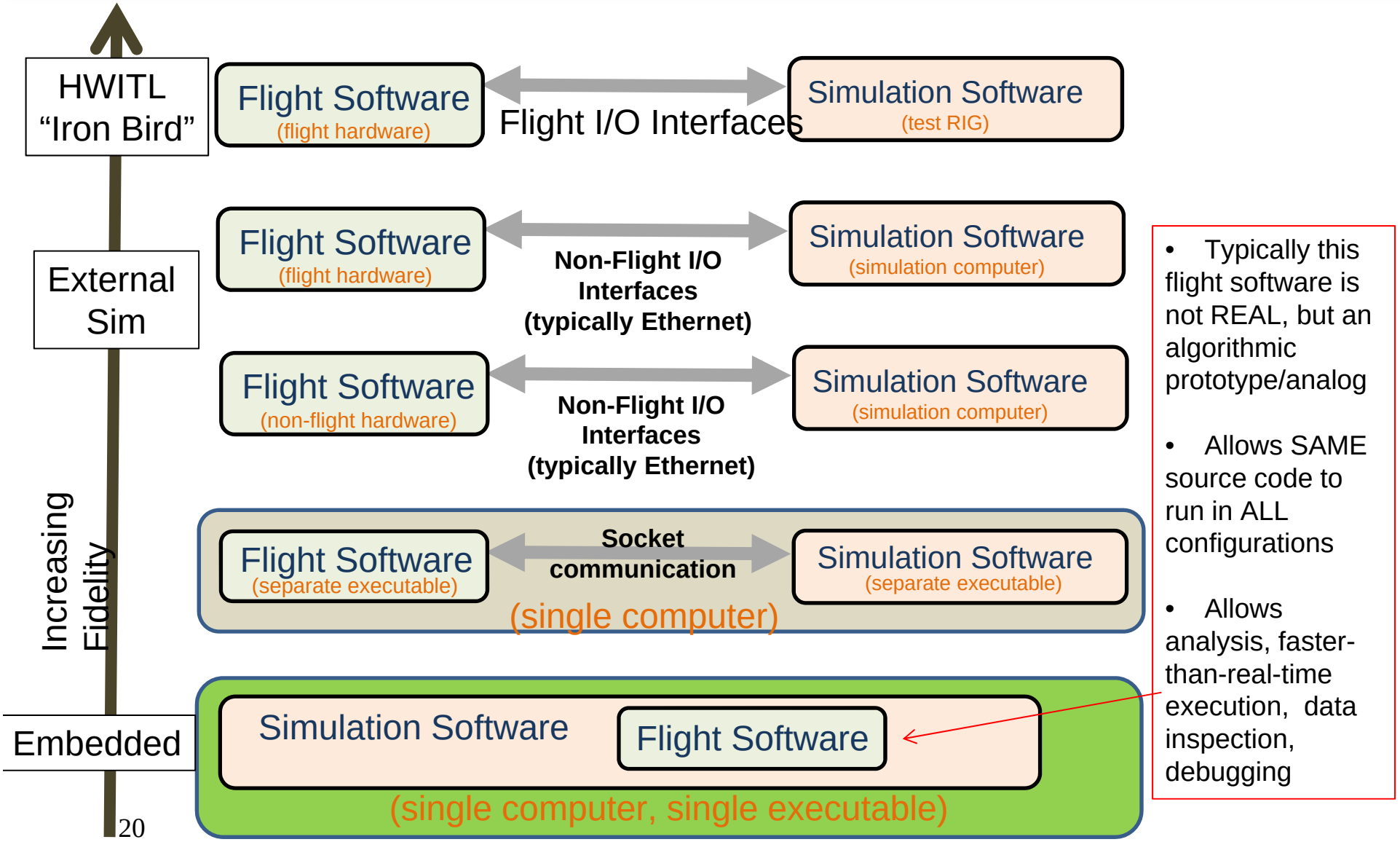
Synchronization & Voting





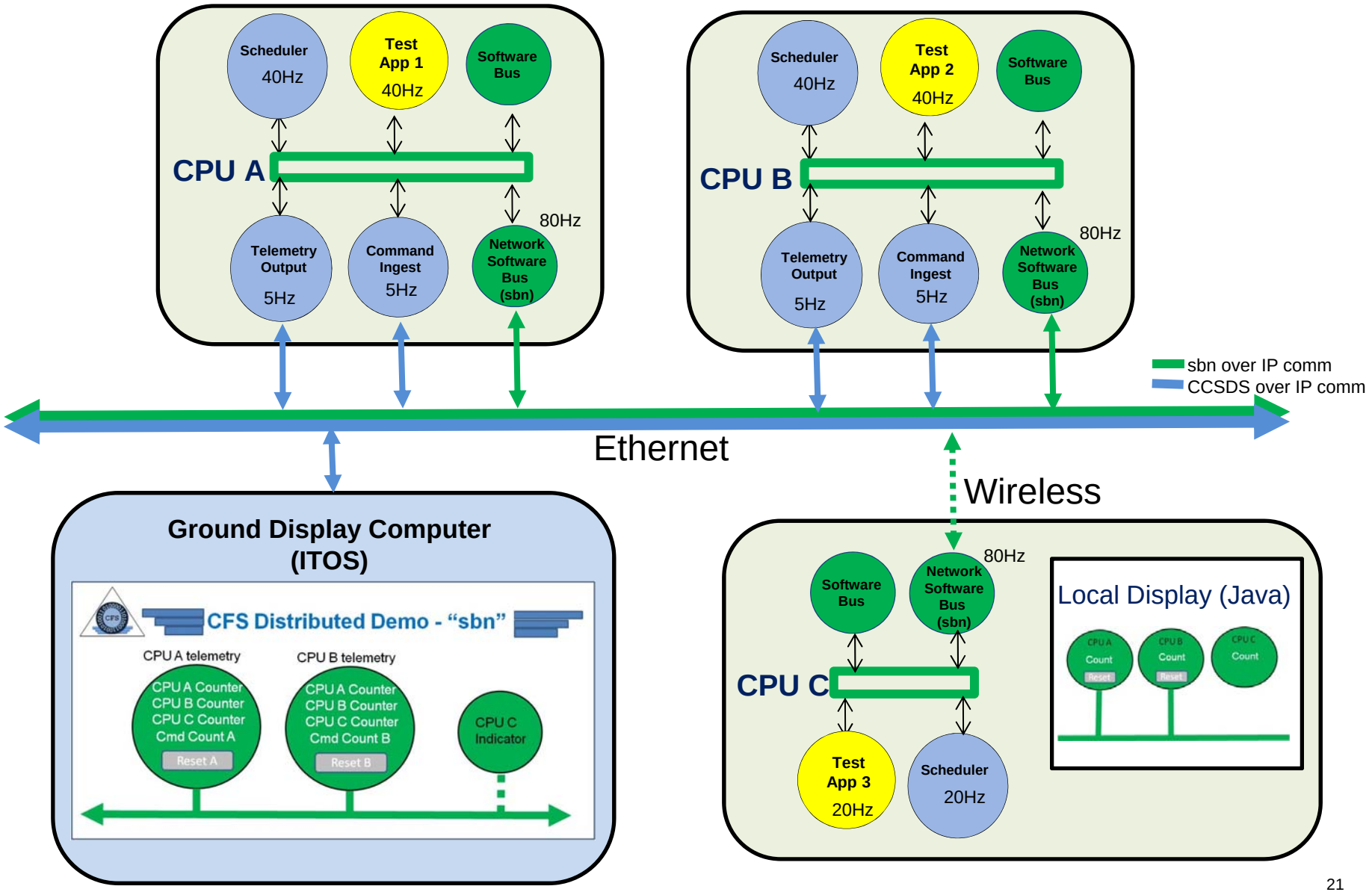


Embedded CFS-Trick Background
Flight Software - Simulation Philosophies

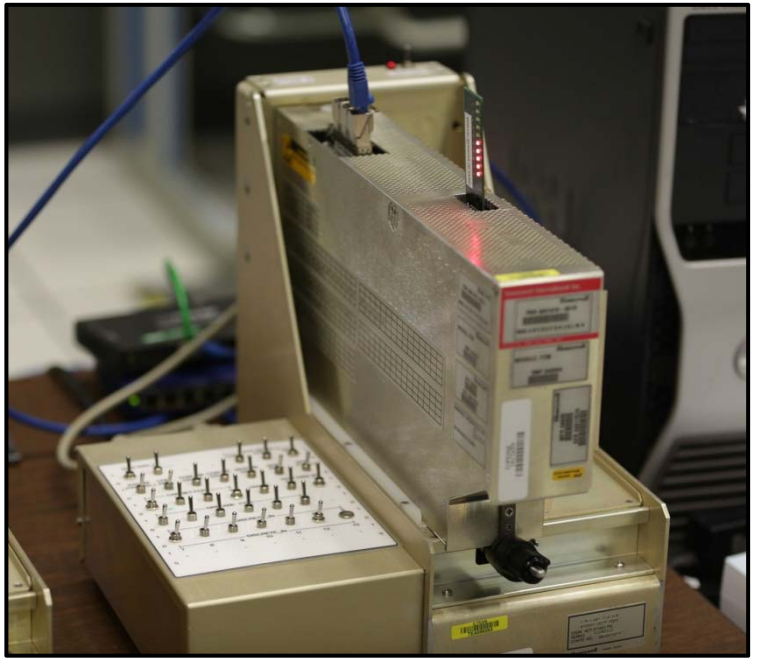


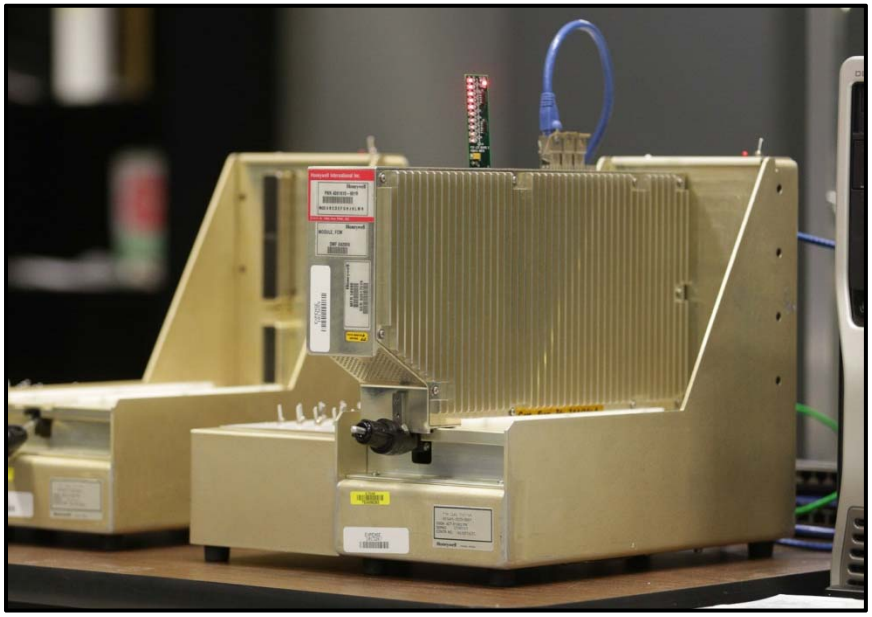
- Typically this flight software is not REAL, but an algorithmic prototype/analog
- Allows SAME source code to run in ALL configurations
- Allows analysis, faster-than-real-time execution, data inspection, debugging

Distributed CFS Demo Configuration



CFS on Partitioned OS/B787
Class A Product Team



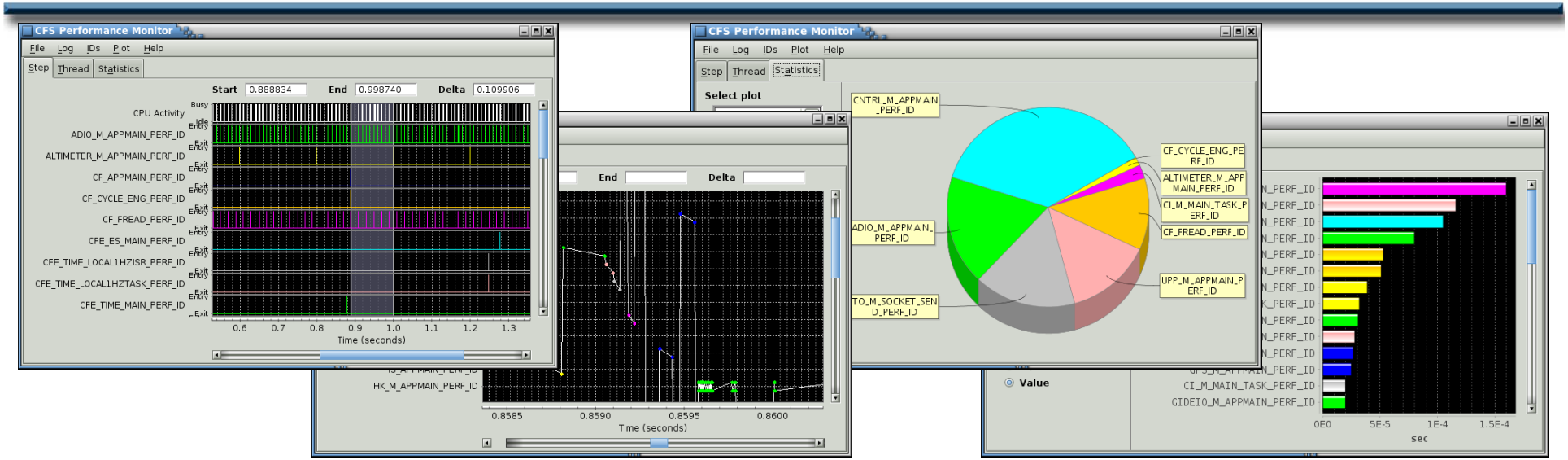


Test Suite Output Excerpt

```
...
-----
PASSED  [cFE.EVS.12.005] CFE_EVS_ResetAllFiltersCmd - Reset all filters - successful
-----
PASSED  [cFE.EVS.12.006] CFE_EVS_AddEventFilterCmd - Add event filter - successful
-----
PASSED  [cFE.EVS.12.007] CFE_EVS_AddEventFilterCmd - Add event filter - event already registered for filtering
-----
PASSED  [cFE.EVS.12.008] CFE_EVS_SetFilterMaskCmd - Set filter mask - successful
-----
PASSED  [cFE.EVS.12.009] CFE_EVS_ResetFilterCmd - Reset filter mask - successful
-----
PASSED  [cFE.EVS.12.010] CFE_EVS_ResetAllFiltersCmd - Reset all filters  - successful
-----
PASSED  [cFE.EVS.12.011] CFE_EVS_DeleteEventFilterCmd - Delete event filter - successful
-----
PASSED  [cFE.EVS.12.012] CFE_EVS_AddEventFilterCmd - Maximum event filters added
-----
PASSED  [cFE.EVS.13.023] CFE_EVS_VerifyCmdLength - Invalid command length with clear log command
-----
PASSED  [cFE.EVS.14.001] EVS_GetApplicationInfo - Get application info with null inputs
-----
PASSED  [cFE.EVS.14.002] CFE_EVS_WriteLogFileCmd - Write log data - successful
-----
PASSED  [cFE.EVS.14.003] CFE_EVS_SetLoggingModeCmd - Set logging mode - successful
-----
PASSED  [cFE.EVS.14.004] CFE_EVS_ReportHousekeepingCmd - Housekeeping report - successful
-----
PASSED  [cFE.EVS.14.005] CFE_EVS_CleanUpApp - Application cleanup - successful
-----
PASSED  [cFE.EVS.14.006] CFE_EVS_Register - Register application with invalid arguments
-----

ut_cfe_evs PASSED 175 tests.
ut_cfe_evs FAILED 0 tests.
```

Performance Monitoring Tool Screenshots



Performance ID Editor

Row	Show	Mask	ID	Name	Color	Freq	Events	Notes
1	☑	✔	0x000000d0	ADIO_M_APPMAIN_PERF_ID		0	330	
2	☑	✔	0x000000cd	ALTIMETER_M_APPMAIN_PERF_ID		0	16	
3	☑	✔	0x00000012	CF_CYCLE_ENG_PERF_ID		0	8	
4	☑	✔	0x0000000f	CF_FREAD_PERF_ID		0	164	
5	☑	✔	0x00000021	CI_M_MAIN_TASK_PERF_ID		0	34	
6	☑	✔	0x000000c2	CNTRL_M_APPMAIN_PERF_ID		0	82	
7	☑	✔	0x00000032	TO_M_SOCKET_SEND_PERF_ID		0	548	

New Up Show All Color Clear Save
Delete Down Hide All Print Reset Close

Log Data: perfLog

Index	ID	Name	Time Stamp (sec)	Entry/ Exit	Seq Err	Overrun (sec)	Notes
263	0x0000000f	CF_FREAD_PERF_ID	0.042382				
264	0x8000000f	CF_FREAD_PERF_ID	0.042426				
265	0x000000d0	ADIO_M_APPMAIN_PERF_ID	0.042436			0.002175	Find out what caused ADIO overrun
266	0x800000d0	ADIO_M_APPMAIN_PERF_ID	0.042461				
267	0x000000bf	EMA_IO_M_APPMAIN_PERF_ID	0.042470				
268	0x800000bf	EMA_IO_M_APPMAIN_PERF_ID	0.042498				
269	0x00000038	DS_APPMAIN_PERF_ID	0.042506				

Print Close

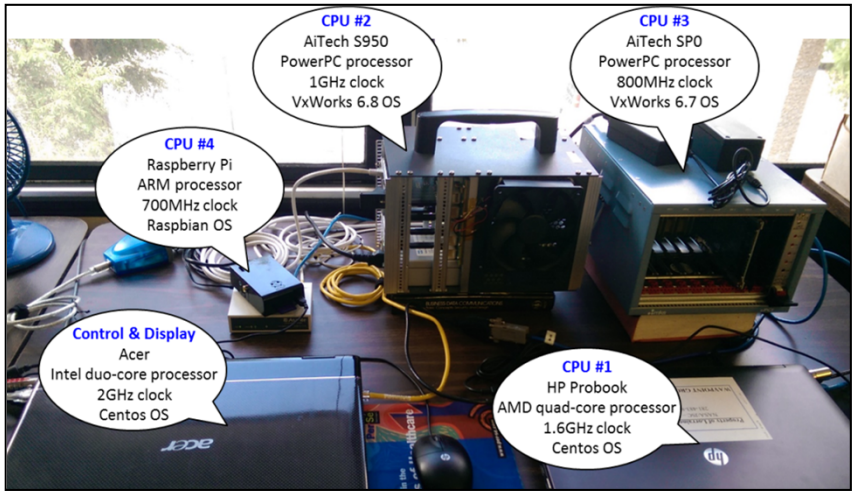
Log Statistics: perfLog

ID	Name	Entry Events	Exit Events	Avg Freq (evt/sec)	Time Act (sec)	Time Inact (sec)	Time Act (%)	Time Inact (%)	Min Act (sec)	Max Act (sec)	Min Int (sec)	Max Int (sec)	Min Over (sec)	Max Over (sec)
0x00000025	HK_M_APPMAIN_PERF_ID	1502	1502	915.29	0.001223	1.639792	0.075	99.925	0.000000	0.000094	0.000003	0.012941	n/a	n/a
0x00000038	DS_APPMAIN_PERF_ID	1492	1492	909.19	0.001509	1.639506	0.092	99.908	0.000000	0.000104	0.000001	0.012662	n/a	n/a
0x00000032	TO_M_SOCKET_SEND_PERF_ID	275	275	167.58	0.003817	1.637198	0.233	99.767	0.000005	0.000072	0.000008	0.100094	n/a	n/a
0x000000cf	DIO_M_APPMAIN_PERF_ID	166	166	101.16	0.024685	1.616330	1.504	98.496	0.000051	0.000458	0.000826	0.013286	n/a	n/a
0x000000d7	HDSIF_M_SOCK_PERF_ID	166	166	101.16	0.008247	1.632768	0.503	99.497	0.000001	0.000408	0.000009	0.022701	0.007390	0.012701
0x000000d0	ADIO_M_APPMAIN_PERF_ID	165	165	100.55	0.003445	1.637570	0.210	99.790	0.000009	0.000101	0.006989	0.012714	0.000002	0.002714
0x000000bf	EMA_IO_M_APPMAIN_PERF_ID	165	165	100.55	0.004131	1.636884	0.252	99.748	0.000009	0.000194	0.007197	0.012759	n/a	n/a
0x000000c9	PROP_M_APPMAIN_PERF_ID	165	165	100.55	0.011316	1.629699	0.690	99.310	0.000028	0.000308	0.007014	0.012940	n/a	n/a
	Overall	5000	5000	3046.89	0.105892	1.535123	6.453	93.547	0.000000	0.000458	0.000000	1.002590	0.000002	0.002714

Print Close

CFS Synchronization & Voting Development

- Voting System for Fault Tolerance
  - Description
    - Provides CFS framework solution for synchronization/redundancy between flight computers
  - Accomplishments
    - Designed System, held several design Inspections, held Demonstrations
    - Implementation underway
    - Supported Heterogeneous Voting Computer Demonstration 9/17/2014
  - Remaining Work (FY15)
    - Continue development
    - Improve system robustness/reliability
    - Analyze/Improve Performance
    - Support Time Triggered Systems

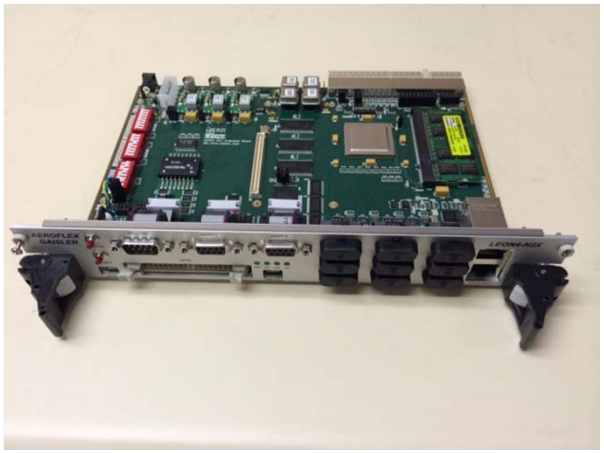


Symmetric Multiprocessing
CFS Development

- Symmetric Multiprocessing (SMP) Support
  - Description
    - Provide a generic SMP Operating System Abstraction Layer (OSAL) supporting multi-core processor architectures
  - Accomplishments
    - Prototype implementation of CFS on dual core Space Micro Proton board and VxWorks SMP complete
      - Apps can be allocated to specific cores to deterministically balance processing load or to improve performance of certain apps
  - Remaining Work (FY15)
    - Implement on SPARC LEON 4 quad-core, Tilera 36-core
    - Merge SMP support modifications into mainline CFS

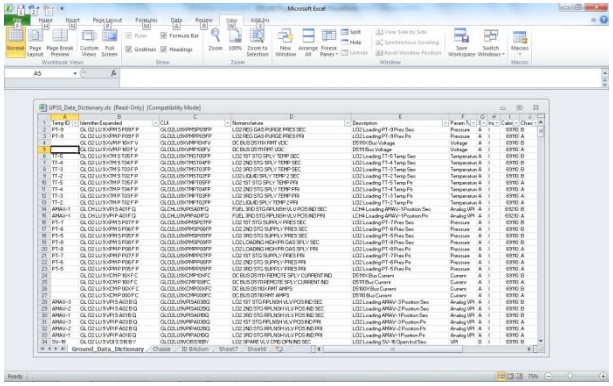
Proton

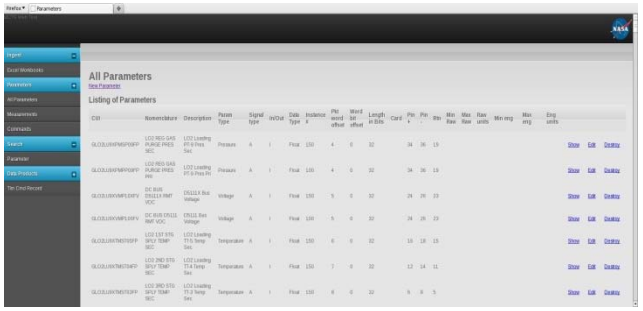
LEON4 quad-core



Tilera 36-core

Mobile Command and Telemetry System

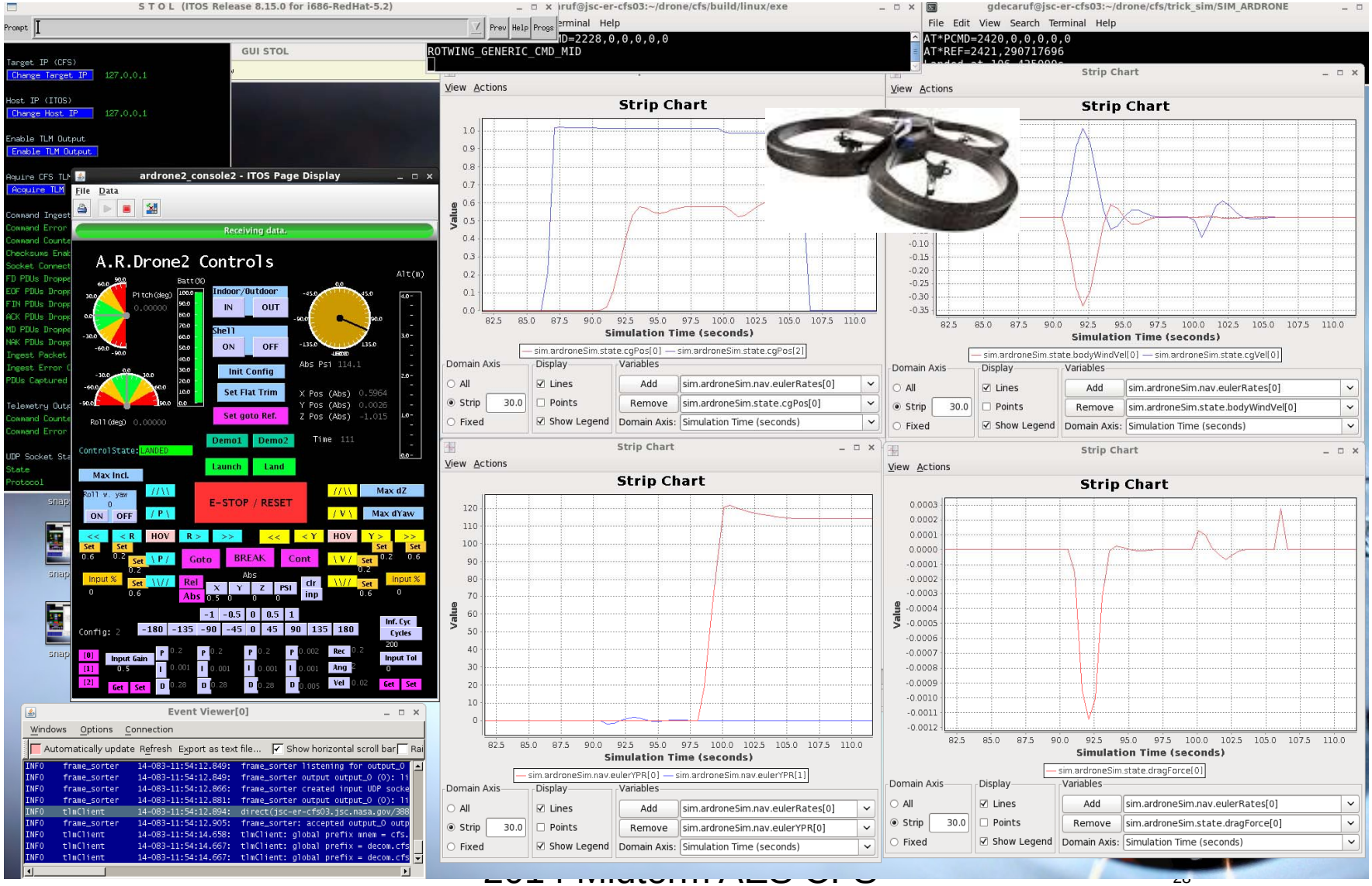





```
/*  Define graph for CCSDS processing of test PLC commands */
Graph gatewayCommandGraph{
        connections={
                /* Connect ccsds output to echo input */
                /* PortConnection{p1=cmd_ccsds.output  p2=echo.input},*/
                /* Connect echo output to network transmit input */
                        PortConnection{p1=echo.output  p2=UDP.input},
        },
        /*  Echo commands before they are transmitted  */
        itos.graph.EchoComponent.Type echo{},
        /*  Transmit command packets out gateway  */
        itos.graph.UDPSocketComponent.Type UDP{
                configuration{
                        foreign_host            {initialValue="XXX.XXX.XXX.XXX"},
                        foreign_port            {initialValue="YYYY"},
                        associate_on_start      {initialValue=1}
                }
        }
},
DiscreteConversion offOnConv{
        Dsc Off {range=0, bgColor=blue, fgColor=white}
        Dsc On {range=1, bgColor=green, fgColor=white}
}
DiscreteConversion unknownOpenConv{
        Dsc Unknown {range=0, bgColor=blue, fgColor=white}
        Dsc Open {range=1, bgColor=green, fgColor=white}
}
DiscreteConversion openClosedConv{
        Dsc Open {range=0, bgColor=blue, fgColor=white}
        Dsc Closed {range=1, bgColor=green, fgColor=white}
}
DiscreteConversion openCloseConv{
        Dsc Open {range=0, bgColor=blue, fgColor=white}
        Dsc Close {range=1, bgColor=green, fgColor=white}
}
DiscreteConversion unknownClosedConv{
        Dsc Unknown {range=0, bgColor=blue, fgColor=white}
        Dsc Closed {range=1, bgColor=green, fgColor=white}
}
/*  Define graph entry point for PLC commands */
CommandDestination gatewayCommandDestination{
        port=gatewayCommandGraph.echo.input
},
```

- KSC developed general purpose data integration tool for managing command and telemetry metadata
- Intended to be generic in nature and applicable to any project using CFS or ITOS
- Web based interface built with Ruby on Rails
- Data can be ingested from a variety of formats including flat text files or Excel spreadsheets
- Imported into PostgreSQL relational database on which a wide variety of queries and reports can be run from MCTS provided GUI screens
- Currently capable of exporting data directly into ITOS compatible data record format
- Future enhancements include exporting data to XTCE format files as well as ‘C’ type data structure statements for compiling into CFS application code
- Demonstration held August 2014

Education/Course Idea: CFS on AR Drone Embedded with Trick Controls & Simulation



CFS Project "To Do List"
FY14 Work, FY15 Planned

- Class A Products, Human Ratable
  - Certify Class A on Orion primary Platform
  - Certify Class A on Orion backup (vxWorks/LEON3) Platform
- Testing
  - Reusable test suite additions for vxWorks
  - Cross-platform test framework
  - White-box testing of OSAL layer
  - Integrated unit test execution/post processing/reports
  - Build interface/instrument CFS code for performance testing, monitoring, display interface
  - Reusable performance test suite
- Human Spacecraft Support Activities
  - Support for Redundancy
    - Symmetric (same OS & shared mem) Multiprocessor Support (SMP) (Dual core, 4 core, 36 core)
    - Asymmetric Multiprocessor CFS support
    - Open source Quad CFS voting layer (continued in FY15)
  - VML – (virtual machine language) integration w/ CFS
  - Support for Distributed Systems (sbn additions)
  - User Interface Display Support – OpenGL Interface
  - Backup Flight Systems Architecture exploration
- Development Tools - Productivity / Interoperability
  - Performance Monitoring / Profiling Tool (Linux/Java)
  - Data Definition / Ground Integration Tools (continued FY15)
  - Autogeneration of application from a variety of tools - Matlab/Simulink/Rhapsody/sysML/Eclipse,
  - Matlab/Simulink simulation of CFS layers
  - Top-Coder effort to start with CodeReview Redmine Tool
- Additional Operating Systems / Hardware Platforms
  - iOS
  - Other real-time: real-time Linux, eCos
  - Additional Hypervisor prototyping- picos
  - FPGA with soft cores, PSP's for hybrid chips with hard cores
- Specific Support Needed or AES Projects
  - DTN-CFS integration development
  - AMO-CFS integration
  - AAE project platforms / chosen architectures
  - RPM development
  - Exploration Augmentation Module development
  - Advanced EVA development support
- Outreach Maturation – Quad Copter
  - Develop Sim of Quad Copter, Basic GNC Apps
  - Develop product distribution for outreach (CFS, Apps & Trick)
- CFS Institutional Support/Infrastructure
  - Configuration Control, evolution, product planning
  - Website: how-to, wiki, FAQ, downloads
  - Product support & releases, training
  - SARB Recommended fixes
- Possible Flight Projects
  - ISS Flight Computer shadow
  - Orion Backup flight computer prototype, Leon3 processor
  - Software partition for Asteroid Retrieval Mission

Core Flight Software System (CFS)/ Core Flight Executive (cFE) Training Material

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GSFC/Code 582

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cFE - Overview

- **A set of** *mission independent, re-usable, core* **flight software services and operating environment**
  - Provides standardized Application Programmer Interfaces (API)
  - Supports and hosts flight software applications
  - Applications can be added and removed at run-time (eases system integration and FSW maintenance)
  - Supports software development for on-board FSW, desktop FSW development and simulators
  - Supports a variety of hardware platforms
  - Contains platform and mission configuration parameters that are used to tailor the cFE for a specific platform and mission.
- **cFE services include:**
  - Executive Services
  - Software Bus Services
  - Time Services
  - Event Services
  - Table Services
- **Layered on the Operation System Abstraction**

Motivation

- About six years ago GSFC was tasked two large in-house missions with concurrent development schedules (SDO, GPM)
- GSFC was to build the spacecraft bus, both avionics and software, and integrate the whole spacecraft
- Without the staff for both, we were directed to find a better way
- So management said, “you engineers figure out how to make the schedule and keep the cost in line”
  - We had about a year to figure it out before staffing up
    - This is before full cost accounting

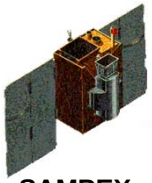
Approach

- **Formed a team of senior FSW engineers to strategize and develop a better way**
- **Each had experience on a few different missions and immediately saw all the commonality we could have had**
- **Team then decided to:**
  - Determine impediments to good flight software reuse
  - Utilize best concepts from missions ranging from Small Explorer class to the Great Observatories
  - Design with reusability and flexibility in mind
  - Take advantage of software engineering advances
  - Be Composable
- **Management helped isolate team engineers from short term mission schedules**
- **Team established architecture goals**

Goals

1. Reduce time to deploy high quality flight software
2. Reduce project schedule and cost uncertainty
3. Directly facilitate formalized software reuse
4. Enable collaboration across organizations
5. Simplify sustaining engineering (AKA. On Orbit FSW maintenance) Missions last 10 years or more
6. Scale from small instruments to Hubble class missions
7. Build a platform for advanced concepts and prototyping
8. Create common standards and tools across the center

Mission Heritage

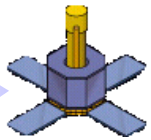


SAMPEX

(launched 8/92)

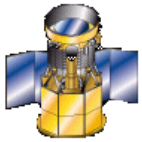
SWAS

(launched 12/98)



TRACE

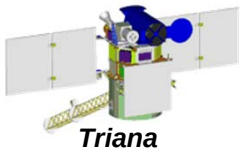
(launched 3/98)



WIRE

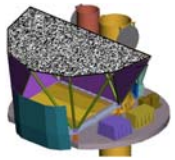
(launched 2/99)

SMEX-Lite



Triana

(cancelled)



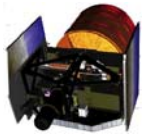
Swift BAT

(12/04)

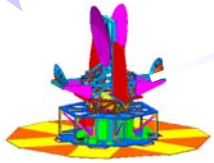
XTE *(launched 12/95)*

TRMM *(launched 11/97)*

JWST ISIM (2013)

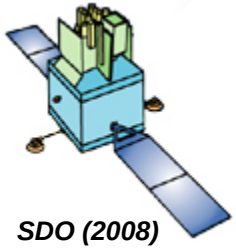


IceSat GLAS *(01/03)*

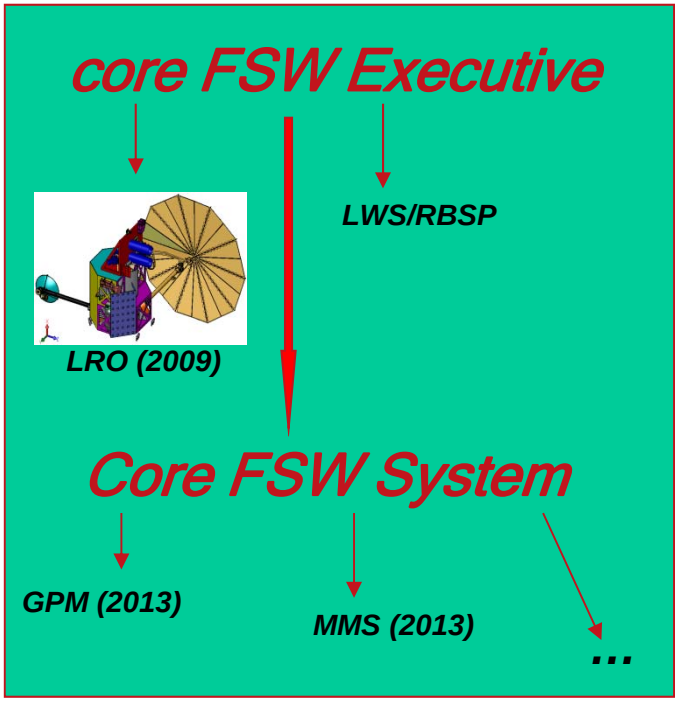


MAP *(launched 06/01)*

ST-5 *(5/06)*



SDO (2008)



Heritage , what worked well

- **Message bus**
  - All software applications use message passing (internal and external)
  - CCSDS standards for messages (commands and telemetry)
  - Applications were processor agnostic (distributed processing)
- **Layering**
- **Packet based stored commanding (AKA Mission Manager)**
  - Absolute Time Sequence (ATP), Relative Time Sequence (RTP)
- **Vehicle FDIR based on commands and telemetry packets**
- **Table driven applications**
- **Critical subsystems time-triggered on network schedule**
  - 1553 bus master TDMA
- **Clean application interfaces**
  - Component based architecture (The Lollipop Diagram)

Heritage , what worked well

- **Lots of innovation**
  - Constant pipeline of new and varied missions
  - Teams worked full life cycle
    - Requirements through launch + 60days
    - Maintenance teams in-house and in contact with engineers early in development
  - Teams keep trying different approaches
    - Rich heritage to draw from

Heritage: what didn't work so well

- **Statically configured Message bus**
  - Scenario: GN&C needs a new diagnostic packet
    - Give the C&DH team your new packet definition file
    - Wait a week for a new interim build
    - Rinse and Repeat
  - How do I add a new one on orbit? (FAST mission example)
- **Monolithic load (The "Amorphous Blob")**
  - Raw memory loads and byte patching needed to keep bandwidth needs down
- **Reinventing the wheel**
  - Mission specific common services ("Look , I've got a new and improved version!")
- **Application rewrites for different OSes**

Re-use in the Past

- **In the past, GSFC's Flight Software Branch (FSB) has realized little cost savings via FSW reuse**
  - No product line. Instead heritage missions were used as starting point
  - Changes made to the heritage software for the new mission were not controlled
    - New flight hardware or Operating System required changes throughout FSW
    - FSW Requirements were sometimes re-written which effects FSW and tests.
    - FSW changes were made at the discretion of developer
    - FSW test procedure changes were made at the discretion of the tester
    - Extensive documentation changes were made for style
  - Not all Products from heritage missions were available
  - Reuse was not an formal part of FSB development methods
  - Reuse was not enforced

Concepts and Standards

- Layered Architecture
- Standard Middleware/Bus
- Standard Application Programmer Interface for a set of core services

} **Core Flight Executive (cFE)**

- Plug and Play Reusable Applications
- Command & Telemetry database

} **CFS Applications**

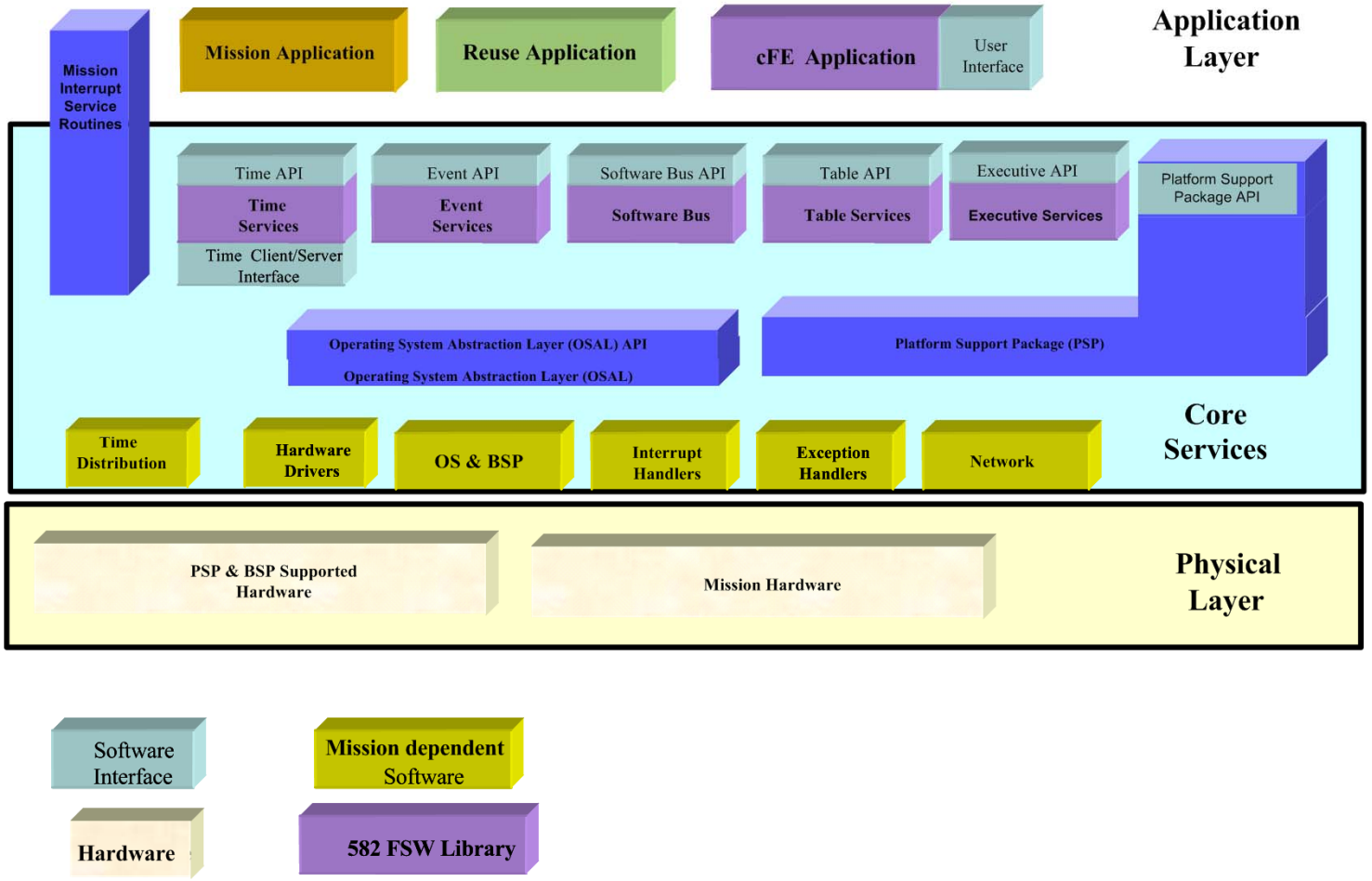
- Reuse Requirements Management
- Reuse Standards
- Reuse Repository

} **Library & CM**

- Configuration Tool for Mission Users
- Development Tools

} **Integrated Development Environment**

cFE Layers


Mission Interrupt Service Routines
Mission Application
Reuse Application
cFE Application
User Interface
Application Layer
Time API
Time Services
Time Client/Server Interface
Event API
Event Services
Software Bus API
Software Bus
Table API
Table Services
Executive API
Executive Services
Platform Support Package API
Operating System Abstraction Layer (OSAL) API
Operating System Abstraction Layer (OSAL)
Platform Support Package (PSP)
Time Distribution
Hardware Drivers
OS & BSP
Interrupt Handlers
Exception Handlers
Network
Core Services
PSP & BSP Supported Hardware
Mission Hardware
Physical Layer
Software Interface
Mission dependent Software
Hardware
582 FSW Library

Standard Middleware Bus

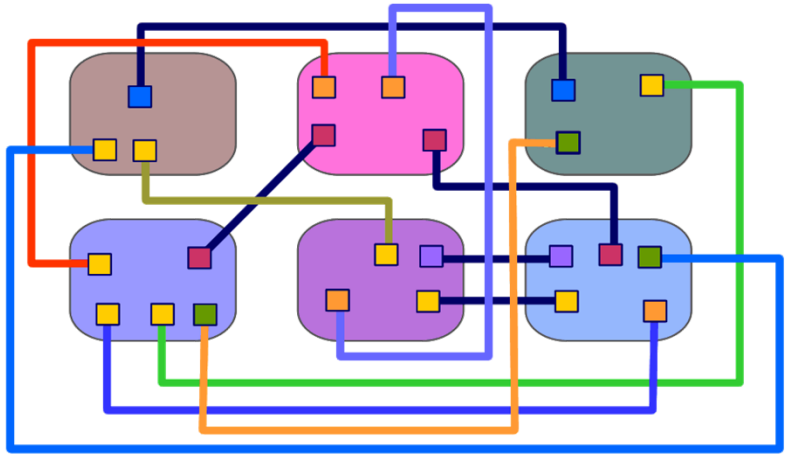
Publish/Subscribe

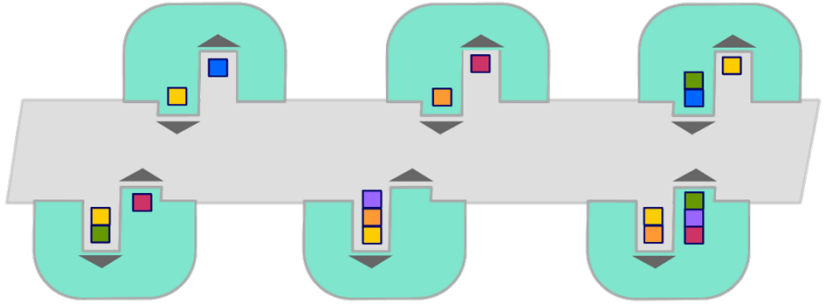
- Components communicate over a standards-based Message-oriented Middleware/Software Bus.
- The Middleware/ Software Bus uses a run-time Publish/Subscribe model. Message source has no knowledge of destination.
- No inherent component start up dependencies

Impact:

- Minimizes interdependencies
- Supports HW and SW runtime “plug and play”
- Speeds development and integration.
- Enables dynamic component distribution and interconnection.

Legacy: Tightly-coupled, custom interfaces- data formats - protocols, internal knowledge, component interdependence





Publish/Subscribe: loosely-coupled, standard interface, data formats, protocols, & component independence

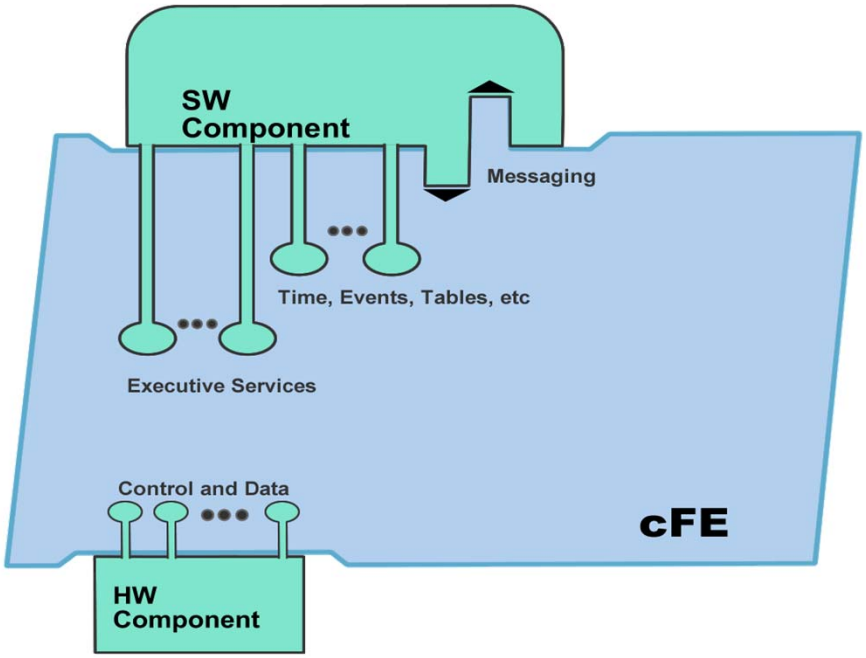
Standard Application Programmer Interface API

Application Programmer Interfaces

- CFS services and middleware communication bus has a standardized, well-documented API
- An abstracted HW component API enables standardized interaction between SW and HW components.

Impact:

- Allows development and testing using distributed teams
- With the framework already in place, applications can be started earlier in the development process
- Can do early testing and prototyping on desktops and commercial components
- Simplifies integration



API supplies all functions and data components developers need.

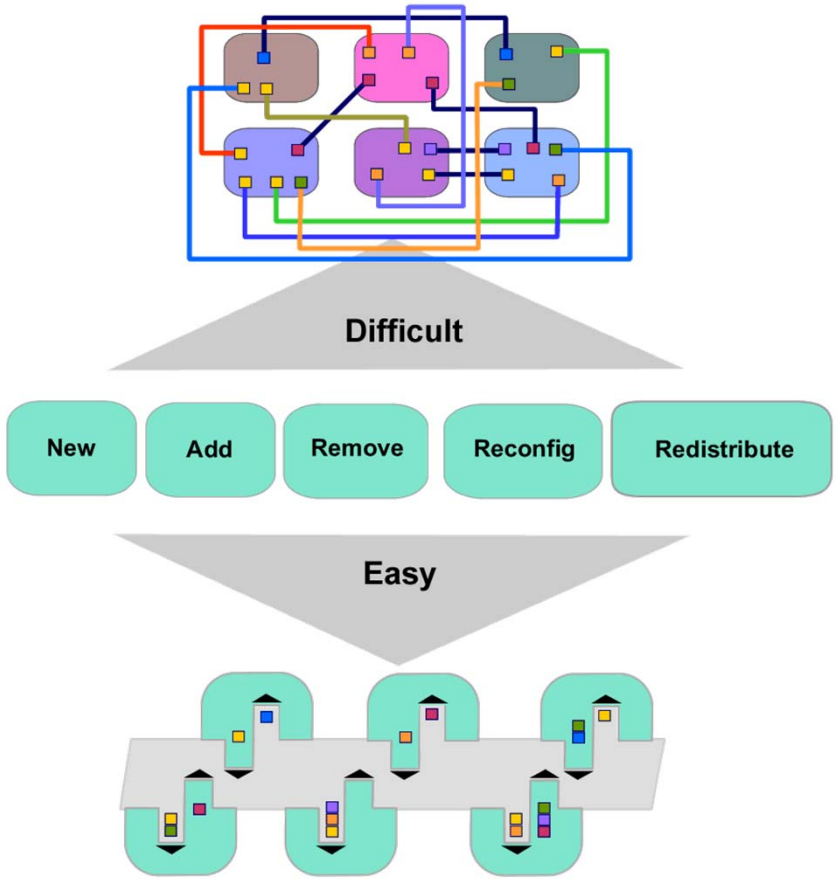
Plug and Play

Plug and Play

- cFE API's support add and remove functions
- SW components can be switched in and out at runtime, without rebooting or rebuilding the system SW.
- Qualified Hardware and CFS-compatible software both "plug and play."

Impact:

- Changes can be made dynamically during development, test and on-orbit even as part of contingency management
- Technology evolution/change can be taken advantage of later in the development cycle.
- Testing flexibility (GSE, test apps, simulators)



This powerful paradigm allows SW components to be switched in and out at runtime, without rebooting or rebuilding the system SW.

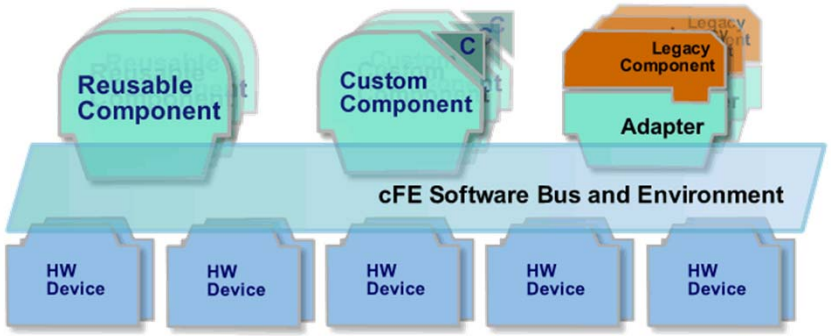
Reusable Components

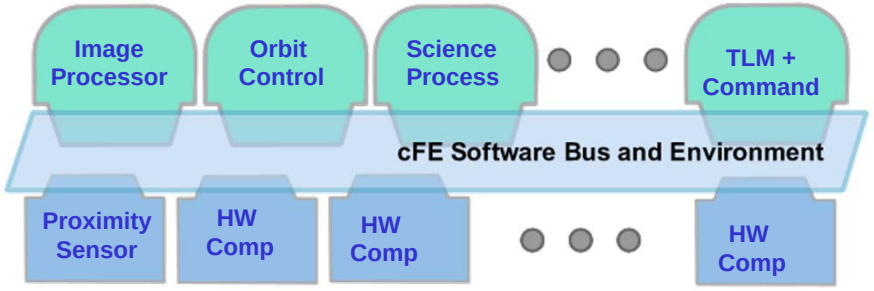
Reusable Components

- **Common FSW functionality has been abstracted into a library of reusable components and services.**
- **Tested, Certified, Documented**
- **A system is built from:**
  - Core services
  - Reusable components
  - Custom mission specific components
  - Adapted legacy components

Impact:

- **Reuse of tested, certified components supplies savings in each phase of the software development cycle**
- **Reduces risk**
- **Teams focus on the custom aspects of their project and don't "reinvent the wheel."**





Sample CFS Reusable Applications

Application	Function
Command Ingest	Reusable component for spacecraft commanding
Telemetry Output	Reusable component for sending and packaging telemetry
CFDP	Transfers/receives file data to/from the ground
Checksum	Performs data integrity checking of memory, tables and files
Data Storage	Records housekeeping, engineering and science data onboard for downlink
File Manager	Interfaces to the ground for managing files
GN&C Framework	Provides framework for plugging in ACS models and objects
Housekeeping	Collects and re-packages telemetry from other applications.
Health and Safety	Ensures that critical tasks check-in, services watchdog, detects CPU hogging, and calculates CPU utilization
Limit Checker	Provides the capability to monitor values and take action when exceed threshold
Math Libraries	Scalar, vector, matrix and quaternion functions
Memory Dwell	Allows ground to telemeter the contents of memory locations. Useful for debugging
Memory Manager	Provides the ability to load and dump memory.
Scheduler	Schedules onboard activities (eg. hk requests)
Stored Command	Onboard Commands Sequencer (absolute and relative).

Health and Safety App / Housekeeping App

- **Health and Safety App**
  - Monitor Applications
    - Detect when defined applications are not running and take a defined action
  - Monitor Events
    - Detect table defined events and take a table defined action
  - Manage Watchdog
    - Initialize and periodically service the watchdog
    - Withhold periodic servicing of the watchdog if certain conditions are not met
  - Manage App Execution Counters
    - Report execution counters for a table defined list of Application Tasks

- **Housekeeping App**
  - Build combined telemetry messages containing data from applications
  - Notify the ground when expected data is not received

Data Storage App / File Manager App

- **Data Storage App**
  - Stores Software Bus messages (packets) to data storage files.
  - Filters packets according to packet filter table definition
  - Stores packets in files according to destination table definition

- **File Manager App**
  - Manages onboard files
    - Copy, Move, Rename, Delete, Close, Decompress, and Concatenate files providing file information and open file listings
  - Manages onboard directories
    - Create, delete, and providing directory listings
  - Device free space reporting

Limit Checker App / Memory Dwell App

- **Limit Checker App**
  - Monitors Table Driven Telemetry Watch points
    - Each watch point compares a telemetry data value with a constant threshold value
  - Evaluates Table Driven Action points
    - Each action point analyzes the results of one (or more) watch points

- **Memory Dwell App**
  - Samples data at any processor address
  - Augments telemetry stream provided during development and debugging
  - Dwell Packet Streams are Specified by Dwell Tables
  - Up to 16 active Dwell Tables
  - Dwell Tables can be populated either by Table Loads or via Jam Commands

Scheduler App / Stored Command App

- **Scheduler App**
  - Operates a Time Division Multiplexed (TDM) schedule of Applications via Software Bus Messages
    - Synchronized to external Major Frame (typically 1 Hz) signal
    - Each Major Frame split into a platform configuration number of smaller slots (typically 100 slots of 10 milliseconds each)
    - Each slot can contain a platform defined number of software bus messages (typically 5 messages) that can be issued within that slot

- **Stored Command App**
  - Executes preloaded command sequences at predetermined absolute or relative time intervals.
  - Supports Absolute Time Tagged Sequences
  - Supports Relative Time Tagged Sequences

Checksum App / Memory Manager App

- **Checksum App**
  - Monitors the static code/data specified by the users and reports all checksum miscompares as errors.
  - CS will be scheduled to wakeup on a 1Hz schedule
  - CS will be byte-limited per cycle to prevent CPU hogging

- **Memory Manager App**
  - Performs Memory Read and Write (Peek and Poke) Operations
  - Performs Memory Load and Dump Operations
  - Performs Diagnostic Operations
  - Provides Optional Support for Symbolic Addressing

Other CFS Apps

- **CFDP App**
  - Implements flight portion of CCSDS CFDP Protocol
- **Command Uplink App**
  - Implements flight portion of CCSDS Command uplink
  - Usually mission specific
- **Telemetry Output App**
  - CCSDS Telemetry downlink
  - Usually mission specific
- **Memory Scrub App**
  - Memory Scrub – Scrubs SDRAM check bits
  - Usually mission specific
- **CI Lab & TO Lab**
  - UDP sockets based uplink and downlink apps for lab testing

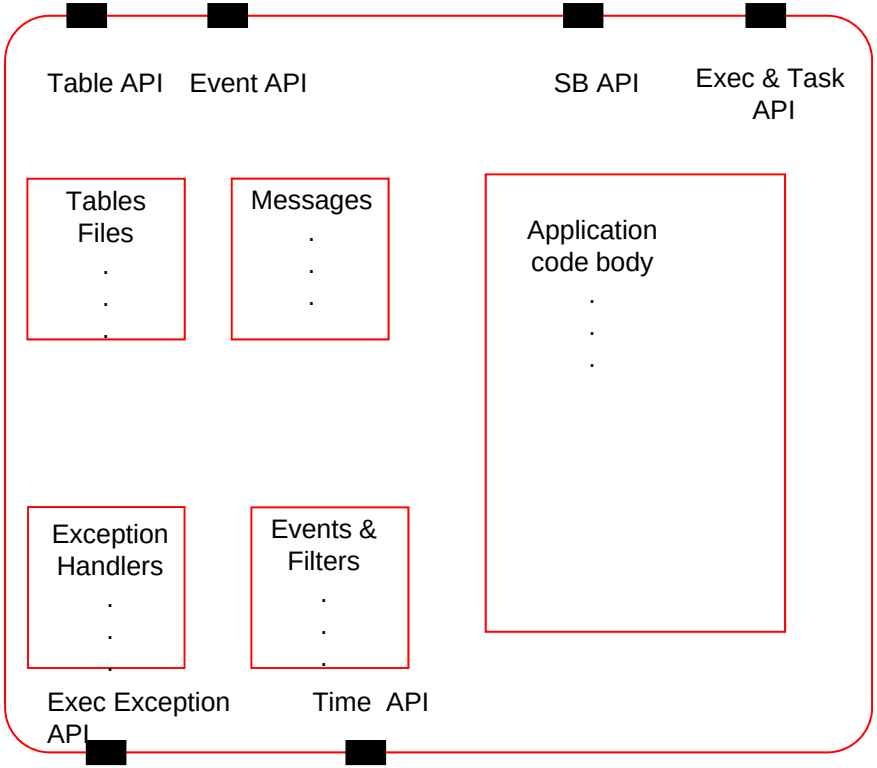
Component Example

• Interface only through core API's.

• A components contains all data needed to define it's operation.

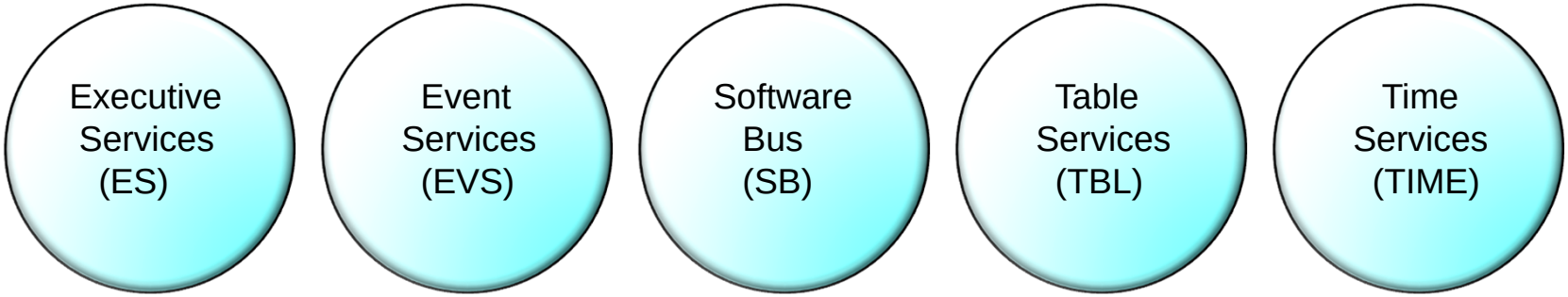
• Components register for services
  - Register exception handlers
  - Register Event counters and filter
  - Register Tables
  - Publish messages
  - Subscribe to messages

• Component may be added and removed at runtime. (Allows rapid prototyping during development)



cFE Core - Overview

- **A set of** *mission independent, re-usable, core* **flight software services and operating environment**
  - Provides standardized Application Programmer Interfaces (API)
  - Supports and hosts flight software applications
  - Applications can be added and removed at run-time (eases system integration and FSW maintenance)
  - Supports software development for on-board FSW, desktop FSW development and simulators
  - Supports a variety of hardware platforms
  - Contains platform and mission configuration parameters that are used to tailor the cFE for a specific platform and mission.

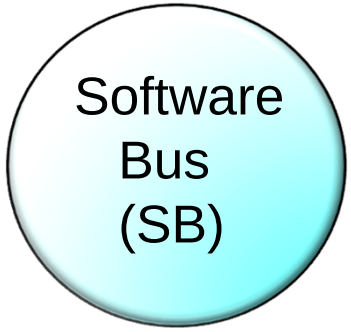


cFE Core - Executive Services (ES)

- Manages the cFE Startup
- Provides ability to start, restart and delete cFE Applications
- Manages a Critical Data Store which can be used to preserve data (except in the case of a power-on reset)
- Provides ability to load shared libraries
- Logs information related to resets and exceptions
- Manages a system log for capturing information and errors
- Provides Performance Analysis support

cFE Core - Software Bus (SB)

- Provides a portable inter-application message service
- Routes messages to all applications that have subscribed to the message.
  - Subscriptions are done at application startup
  - Message routing can be added/removed at runtime
- Reports errors detected during the transferring of messages
- Outputs Statistics Packet and the Routing Information when commanded

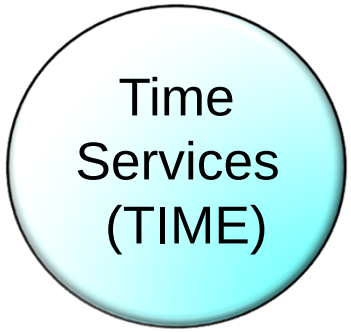


cFE Core - Event Services (EVS)

- Provides an interface for sending asynchronous informational/error messages telemetry to ground
  - Provides a processor unique software bus event message containing the processor ID, Application ID, Event ID, timestamp, and the request-specified event data (text string including parameters)
- Provides an interface for filtering event messages
- Provides an interface for registering an application's event filter masks, types, and type enable status
- Provides an interface for un-registering an application from using event services
- Provides an interface for enabling/disabling an application's event filtering
- <optional> Provide an interface for logging event into a local event log

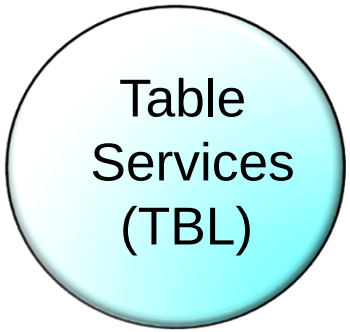
cFE Core - TIME Services

- Provides a user interface for correlation of spacecraft time to the ground reference time (epoch)
- Provides calculation of spacecraft time, derived from mission elapsed time (MET), a spacecraft time correlation factor (STCF), and optionally, leap seconds
- Provides a functional API for cFE applications to query the time
- Distributes of a “time at the tone” command packet, containing the correct time at the moment of the 1Hz tone signal
- Distributes of a “1Hz wakeup” command packet
- Forwards tone and time-at-the-tone packets



cFE Core - Table Services

- Manages all CFS table images
- Provides an API to simplify Table Management
- Table Registry is populated at run-time eliminating cross coupling of Applications with flight executive at compile time
- Performs table updates synchronously with the Application that owns the table to ensure table data integrity
- Shares tables between Applications
- Allows Non-Blocking Table updates in Interrupt Service Routines
- Provides a common ground/user interface to all tables



Operating System Abstraction Layer (OSAL) Overview

- **A standalone project, separate from the cFE**
  - The cFE is built on the OSAL to provide portability
- **Available as Open Source on NASA's Open Source Website**
  - http://opensource.gsfc.nasa.gov
- **Allows execution of FSW on multiple Real Time OSs**
  - Build Verification testing done using VxWorks 6.4
- **Allows execution of FSW on simulators and desktop computers**
- **Support three primary targets**
  - POSIX
    - OSX
    - Linux
    - Cygwin
  - RTEMS 4.10
  - VxWorks 6.x

Platform Specific Package Overview

- **Supports the following Hardware Platforms/Operating Systems (non exhaustive)**
  - Flight Hardware Environments
    - MCP750/vxWorks 6.x
    - BAE RAD750/VxWorks 6.x
    - Coldfire/RTEMS 4.x
    - MCP405/linux (Spacecube)
  - Desktop FSW Test Environments
    - MAC/OSX
    - MAC/linux
    - PC(x86)/linux, Cygwin