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JET Plasma Control System Upgrade using MARTe2.

Adam Stephen et. al., UKAEA

14th IAEA CODAC TM,

San Paulo, Brazil, 15 - 18 July 2024

Engineering and Physical Sciences Research Council

This work was funded by the RCUK Energy Programme
[Grant number EP/W006839/1]

Talk Overview

- Introduction – the JET plasma control system context.
- Upgrade project motivation and design choices.
- Focus on constraints of modifying JET at a critical time (DT).
- Factors which supported change and how these have future relevance.
- Conclusions regarding the JET experience, and similar topics in other projects.
- Challenges for future machines to stimulate debate this week.

JET PCS Architecture

High level elements

Distributed

Separation of concerns

Integration via

- Aggregate services

- Coordinated configuration

Heterogeneous

- Due to project breakdown

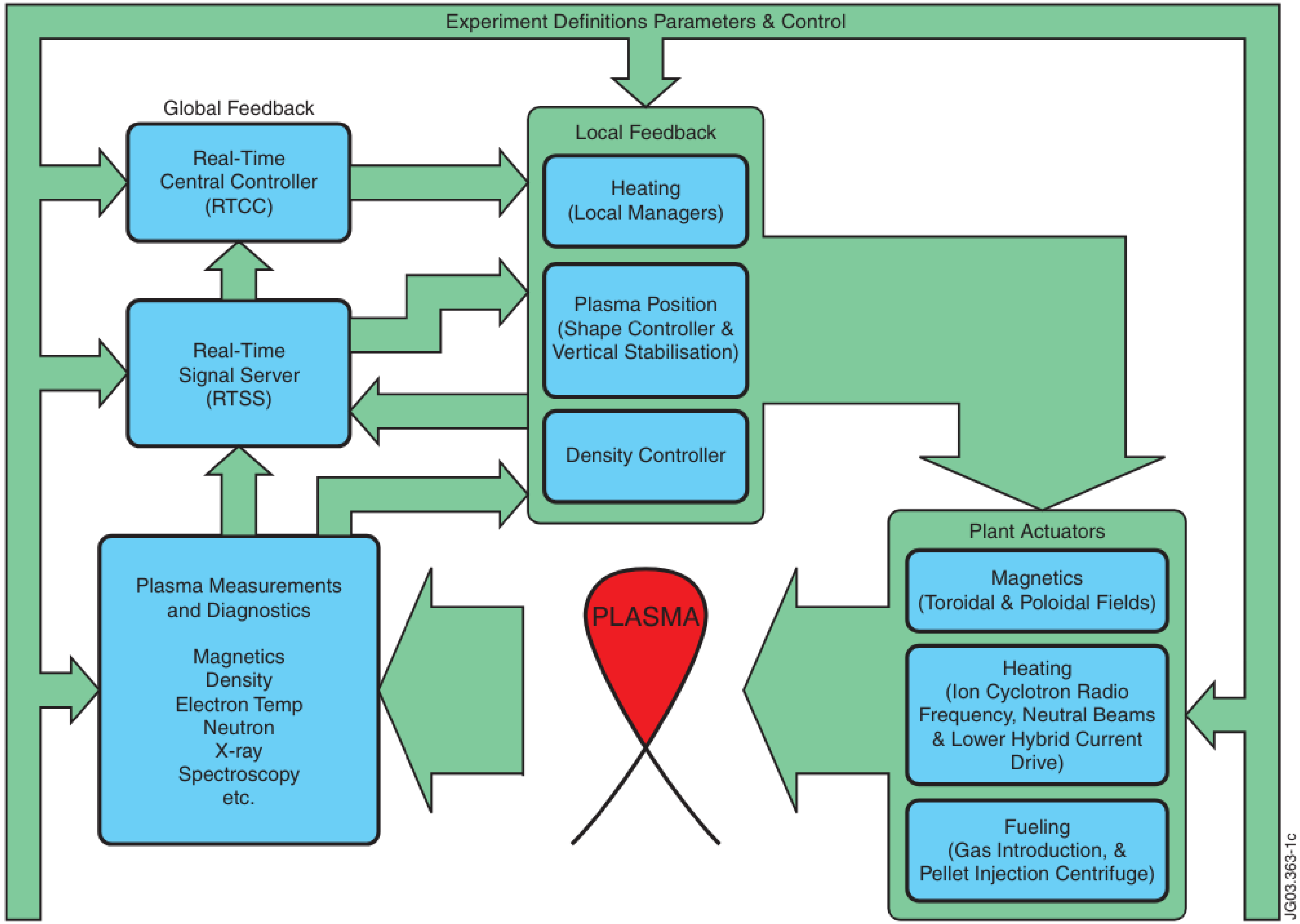
- Due to in-kind systems

- Due to evolution/technology

- In Hardware

- In Software

Unified by protocols/standards



JET CODAS Software Design Principles

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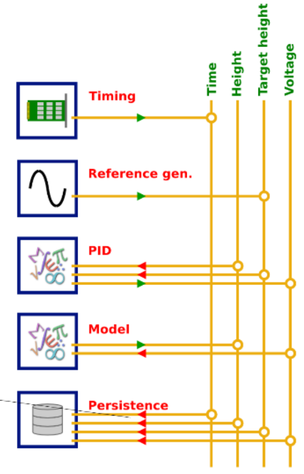
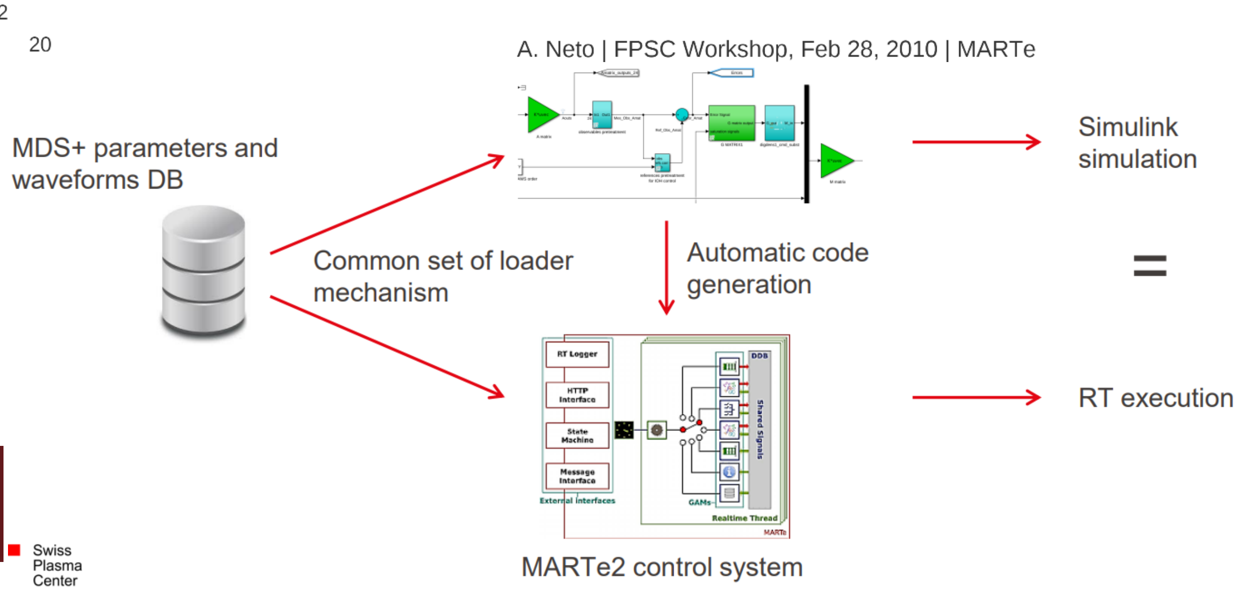
- Frameworks/reusable runtimes
  - Fortran EPICS-like system
  - Scripting languages perl/Tcl/Python
  - C object/component oriented framework
  - Local Manager copy/paste reuse
  - **MARTe2** adoption for RT
- Data driven / Configuration driven
  - Configuration tree/editors/lookup tables
  - Structured configuration/mini languages
  - Level-1 parameter/code development environment (database, apps, UI)
  - CODAS Configuration Language – general purpose internally hosted DSL
  - MARTe/2 Configuration Language – extensible external DSL
- Interprocess/Intersystem Comms
  - Message protocol, Data collection protocol
  - Intra-host and Inter-host
  - Configuration, Control, Data exchange
  - Real-Time Data Network + RTDN Database

```
+Thread_1 = {
    ...
    +Collection = {
        Class = CollectionGAMs::DataCollectionGAM
        EventTrigger = {
            TimeWindow0 = {
                NOfSamples = 40000
                UsecPeriod = 250
            }
        }
        Signals = {
            CLOCK = {
                SignalName = usecTime
                JPFName = "TIME"
                SignalType = int32
            }
            WaterHeight = {
                SignalName = waterHeight
                JPFName = "WaterHeight"
                SignalType = float
            }
            ...
```





Tuesday

JET CODAS The Final Status

Instituto de Física da Universidade de São Paulo

Dr John Waterhouse

09:00 - 09:20

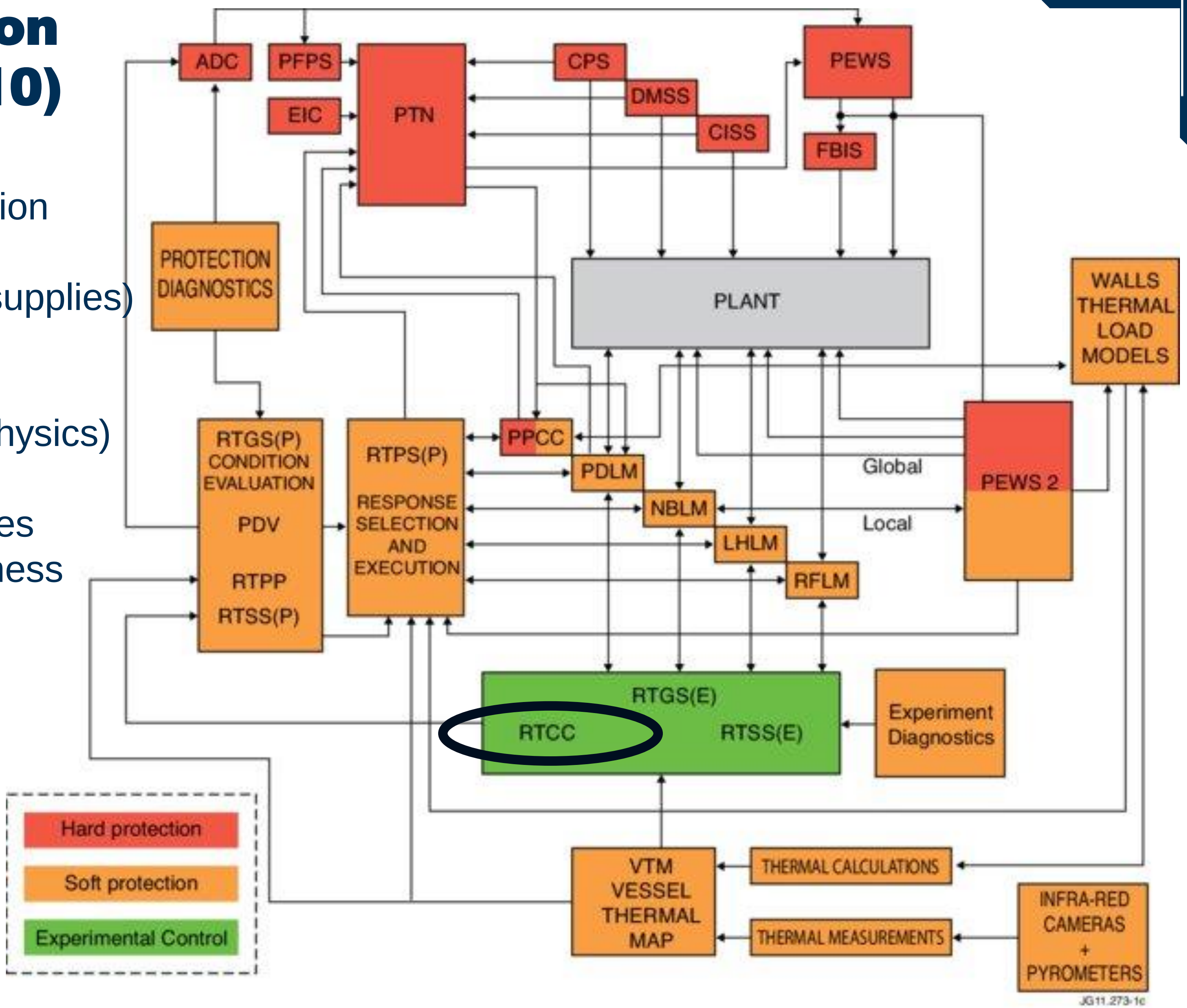
JET Real-Time Protection (post ITER-like Wall 2010)

Defence in depth
- Hardwired low level investment protection
- Hierarchy of sacrificial compromises
(worst case, preserve coils over power supplies)

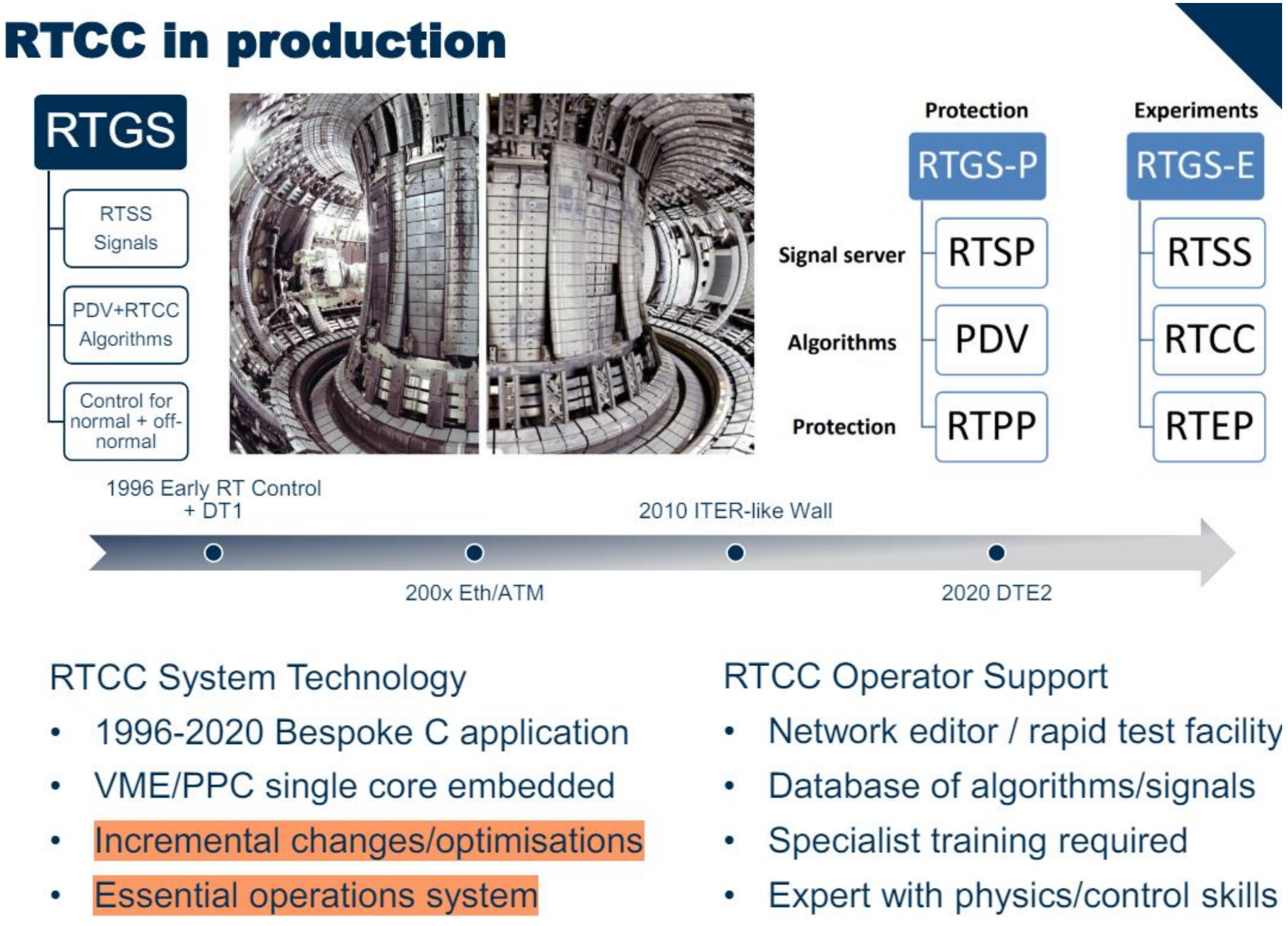
Layered Protection
- Higher layers should maintain control
- Intrinsically more complex (software, physics)

Overall consistency
- Enough interaction to optimise outcomes
- Enough separation to preserve robustness

Engineering and Quality Assurance
- Unit/Integrated tests
- Restart process/procedure
- System commissioning procedures
- Integrated commissioning procedures
- Strict deployment controls



Real Time Central Controller (RTCC)



Inputs : all diagnostics

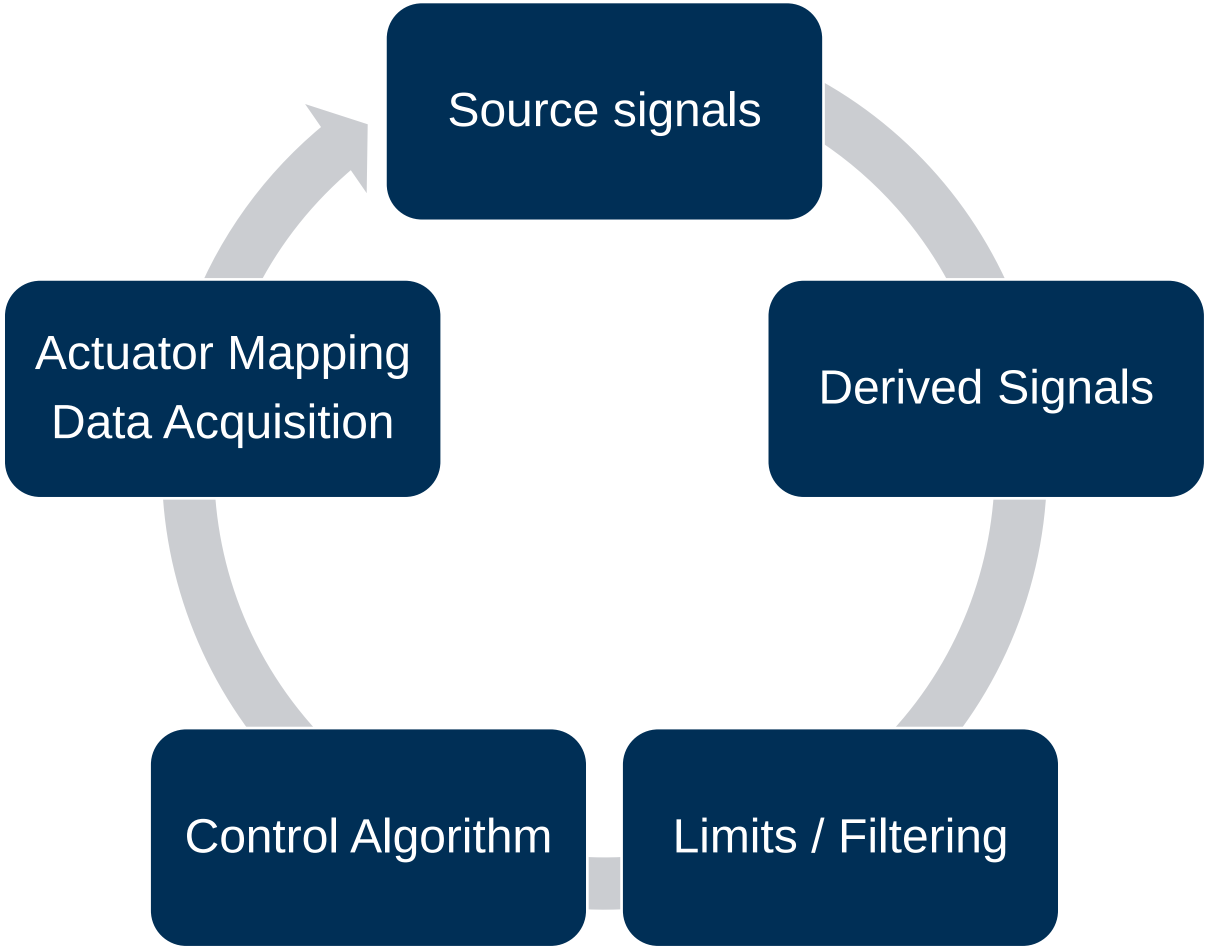
Block library / language / editor

Interfaces provide sandboxed options

Environment externally qualified thus permitting just-in-time creation/modification of controls.

Same architecture, independent configuration management used for protection (high confidence developed over 20 years)

Workflow / Functional Requirements



RTCC – operations tool for physics team
- access to comprehensive diagnostics signals
- block like controls description system
- up to 4 concurrent controllers, possibly linked
- incrementally build confidence in new ideas rapidly
- save/restore from old shots
- support for testing/validating on old data

RTCC2 Motivations to Upgrade / Design Choices

RTCC Limitations
- Hardware resources limited (CPU, memory)
- Tools and interfaces need special training
- Restriction to scalar data types
- Limitations on testing
(custom hardware/proprietary OS)

Capacity constraints
- Limits in #nodes, #signals
- Restrictions in data collection
- Risk of cycle time over-run

Usability constraints
- Need for **specially trained staff**[1]
- Cumbersome for physicists to develop algorithms
- Expensive to develop new software components (large codebase with many specialised techniques)
- Unintuitive UI

RTCC2

CPU upgrade : from 1GHz single core PPC -> 4 Core 2.4GHz i7
Memory upgrade : from 500MB to 32GB
Connectivity : 100Mbps ethernet + 155 Mbps ATM to Dual Gbps ethernet/SDN
OS : VxWorks 5.x running in kernel mode to Linux 5.x using core isolation
RT tuning : RT PREEMPT patches within Centos or Rocky or Custom Yocto
Compiler : from gcc 3.4.3 to gcc 4.8.5
Software stack : From bespoke C to MARTe 2.0
DevOps : from none to git + CI + unit tests + MARTe 2 QA + SonarQube

System Upgrade Requirements
- Capacity++ : modern hardware
- Multicore PC, RT Linux, C++
- Feasible implementation time/cost
- Leave future exploitation open

Operator Requirements
- QA to modern standards/DevOps
- Backwards compatibility
- Better usability
- Better maintainability
- Lower cost/risk of new features

Tabular Algorithm Editor in Level-1

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GIM desired opening to requested opening (inverse hysteresis)

The signal Aw, Bw or Cw is not then sent directly to the GIMs, because it does not account for hysteresis. There is a single model of hysteresis for all GIMs (which may not be totally accurate across them all, but is what is available) which can be roughly inverted to work out what opening to send to the actuator in order to actually get the flow you would achieve if you had no hysteresis in effect (e.g. because you opened straight from 0% to Aw, Bw or Cw).

This hysteresis model is applied in RTCC as follows (again see 100793 for an example, PDO logs here):

79	unused/unused	#### Hysteresis Compensation ###
80	gain/Sig(one)_Gain(21.3)	GIMm:
81	gain/Sig(GIMm)_Gain(0.0228)	GIMmd:
82	gain/Sig(one)_Gain(9202.8)	TIMm:
83	gain/Sig(TIMm)_Gain(1.37e-05)	TIMmd:
84	delay/Sig(Au)_Delay(0.002)	Audel: Delayed opening
85	varLimit/Sig(Audel)_High(Au)_Low(minus)	Adwd: Opening is decreasing
86	varLimit/Sig(Au)_High(Aomax)_Low(minus)	Abigr: Opening is greater than previous max
87	varLimit/Sig(fcOffOp)_High(Au)_Low(minus)	Alow: Opening is tiny, valve starts closing?
88	timer/Run(Alow)_InvRun(No)_Rst(Alow)_InvRst(Yes)_AlmRst(No)_AlmTime(0.050)	Aoff: Opening is tiny,valve closes,max resets
89	prod/Ip1(GIMmd)_Ip2(Aomax)_Ip3(0)_Ip4(0)	Amdomx: TIM/GIM hyst model ***
90	select/EnSig(Au)_DisSig(Aomax)_Control(Abigr)	Aomx0: Maximum should follow highest ever value
91	select/EnSig(Au)_DisSig(Aomx0)_Control(Aoff)	Aomax: Max=Highest ever (unless off so reset)
92	sum/Ip1(Aw)_Gain1(1)_Ip2(Amdomx)_Gain2(-1)_Ip3(0)_Gain3(0)_Ip4(0)_Gain4(0)	Ainvn: Inverse hysteresis numerator
93	sum/Ip1(one)_Gain1(1)_Ip2(GIMmd)_Gain2(-1)_Ip3(0)_Gain3(0)_Ip4(0)_Gain4(0)	A1-md: Inverse hysteresis denominatorT/Gmod***

For New Controls – XMARTe

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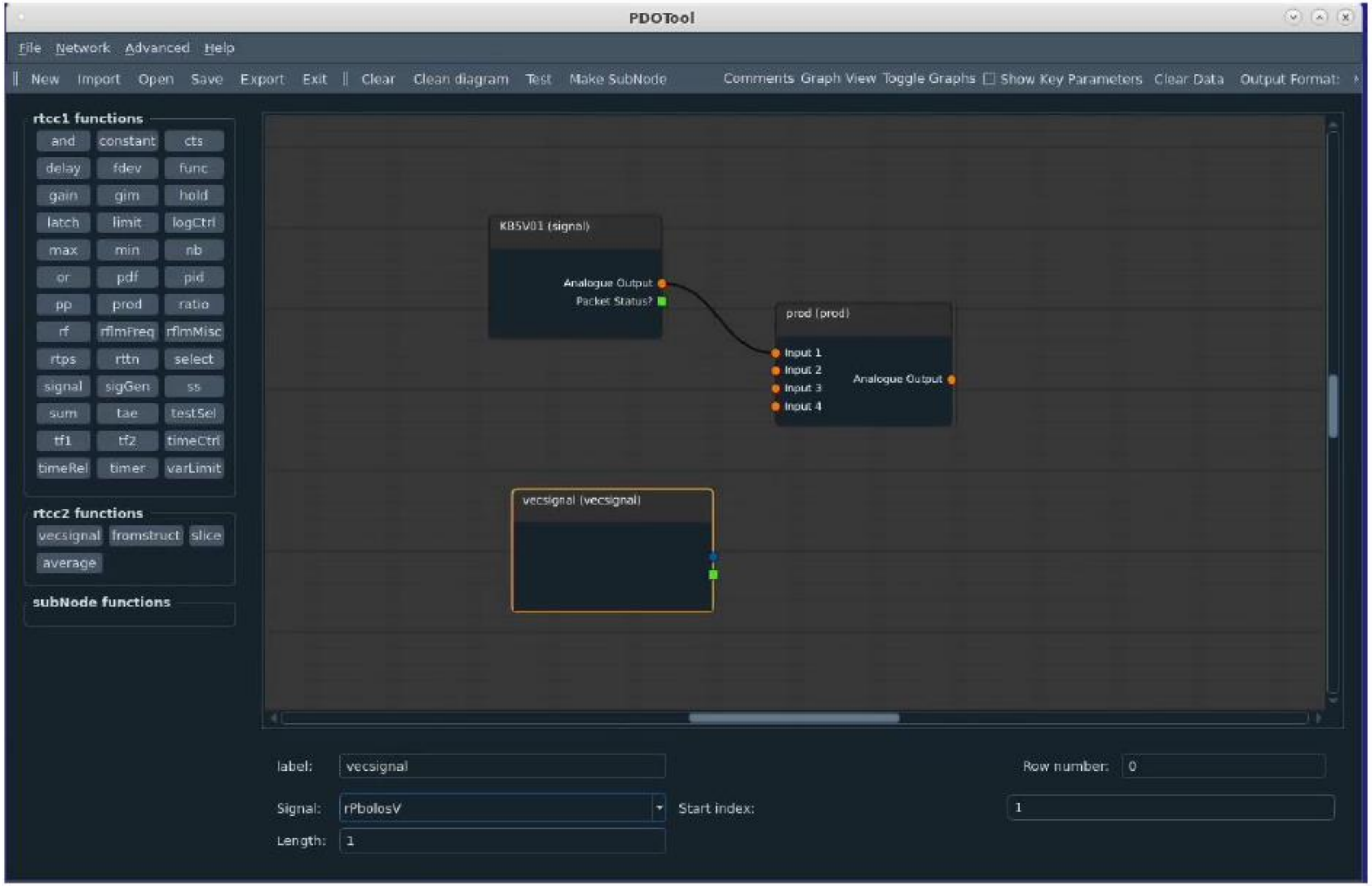
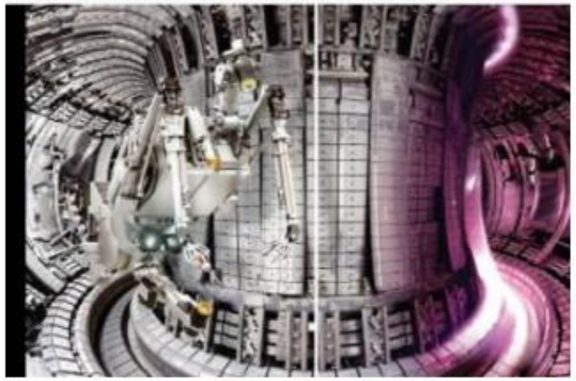


Partly motivated by startup feedback
Pilot project bringing MARTe2 to industry
BEIS funded
UK Gov Office of Tech Transfer
Knowledge Asset Grant Fund

Partly to support engineers/scientists coming from different traditions

Previous Summary at 13th TM



Chris Stuart et al.
IAEA 13th TM
July 2021

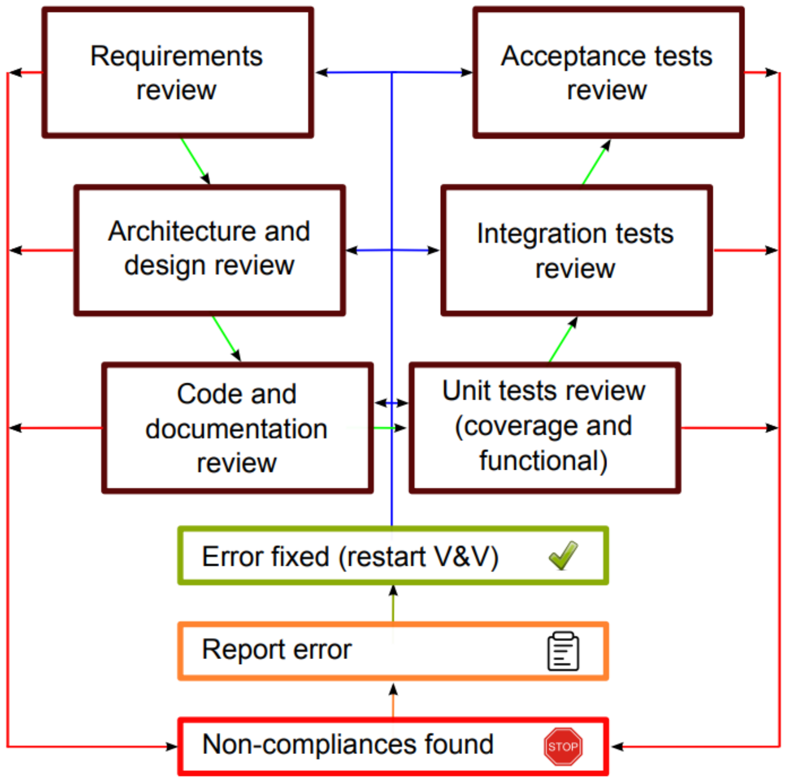
Phase 1: Feasibility : (a) Proof Of Concept (b) Prototype

Phase 2: Deploy dual servers operating parasitically but not controlling

Phase 3: Switch to RTCC2 for routine operations (increased capacity)

Correctness / Validation and Verification

FUSION FOR ENERGY



An agile quality assurance framework for the development of fusion real-time applications

June 2016

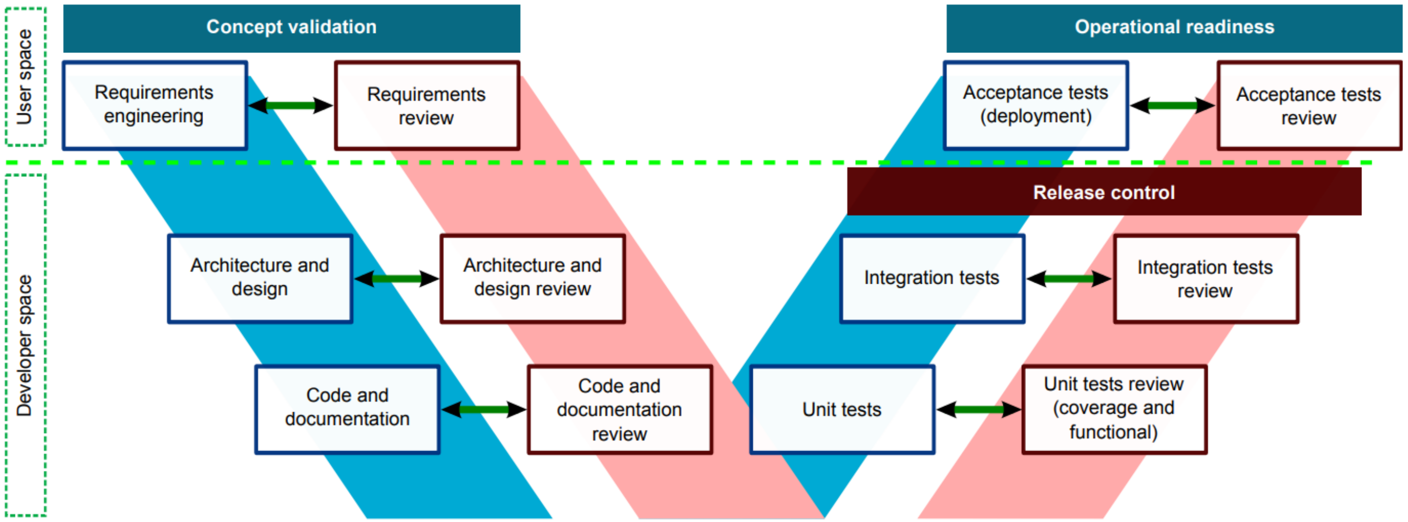


Fig. 2. The blue V is in charge of developing the MARTe framework. The red V guarantees the framework quality assurance. It should be noted that this double-V-model does not prescribe any given software lifecycle methodology.

“Having the user-stories reviewed using the same structure of the QA audit greatly simplifies the writing of the final auditing.”

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Incremental Deployment Plan

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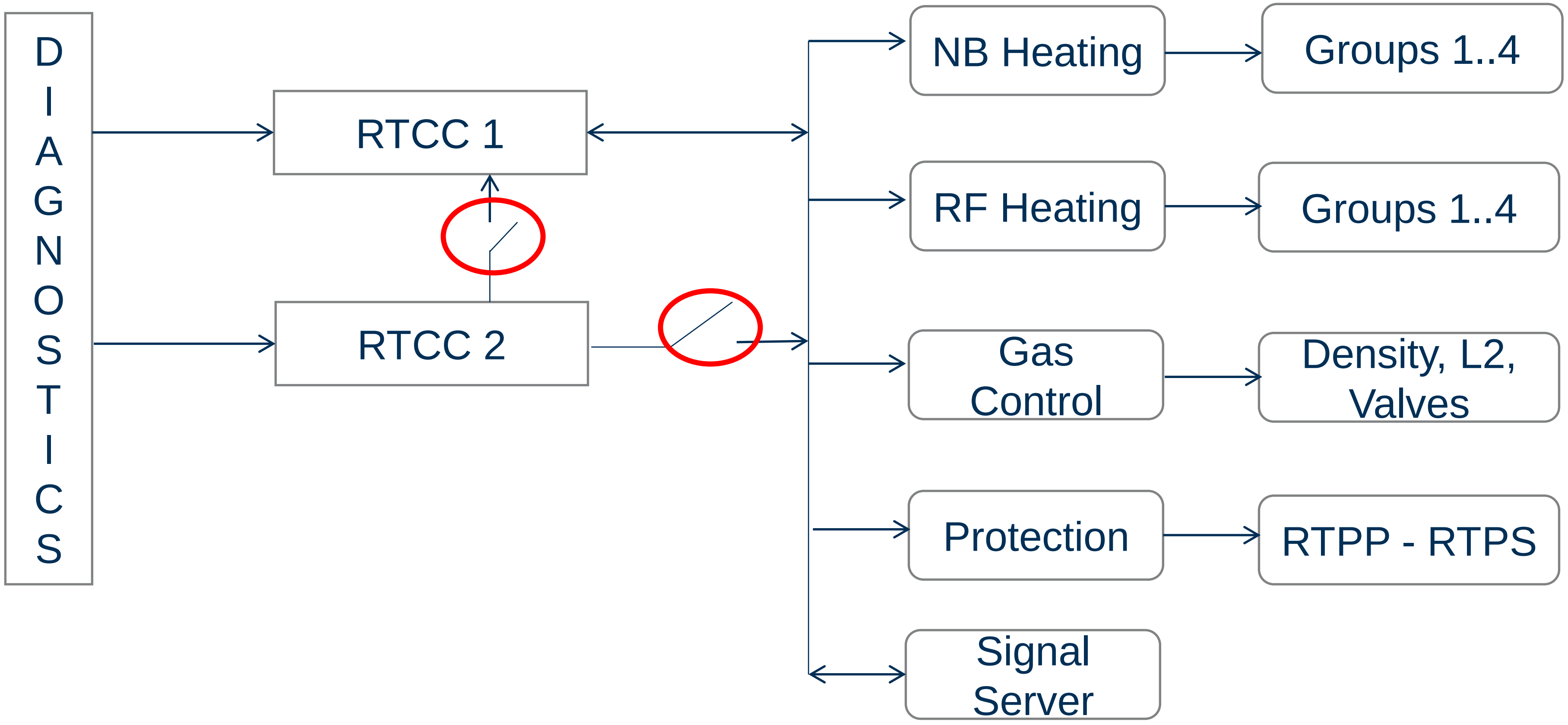
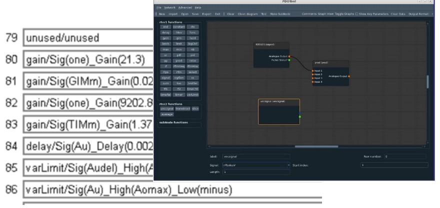
Bare Bones System Level View



Integrated Software View



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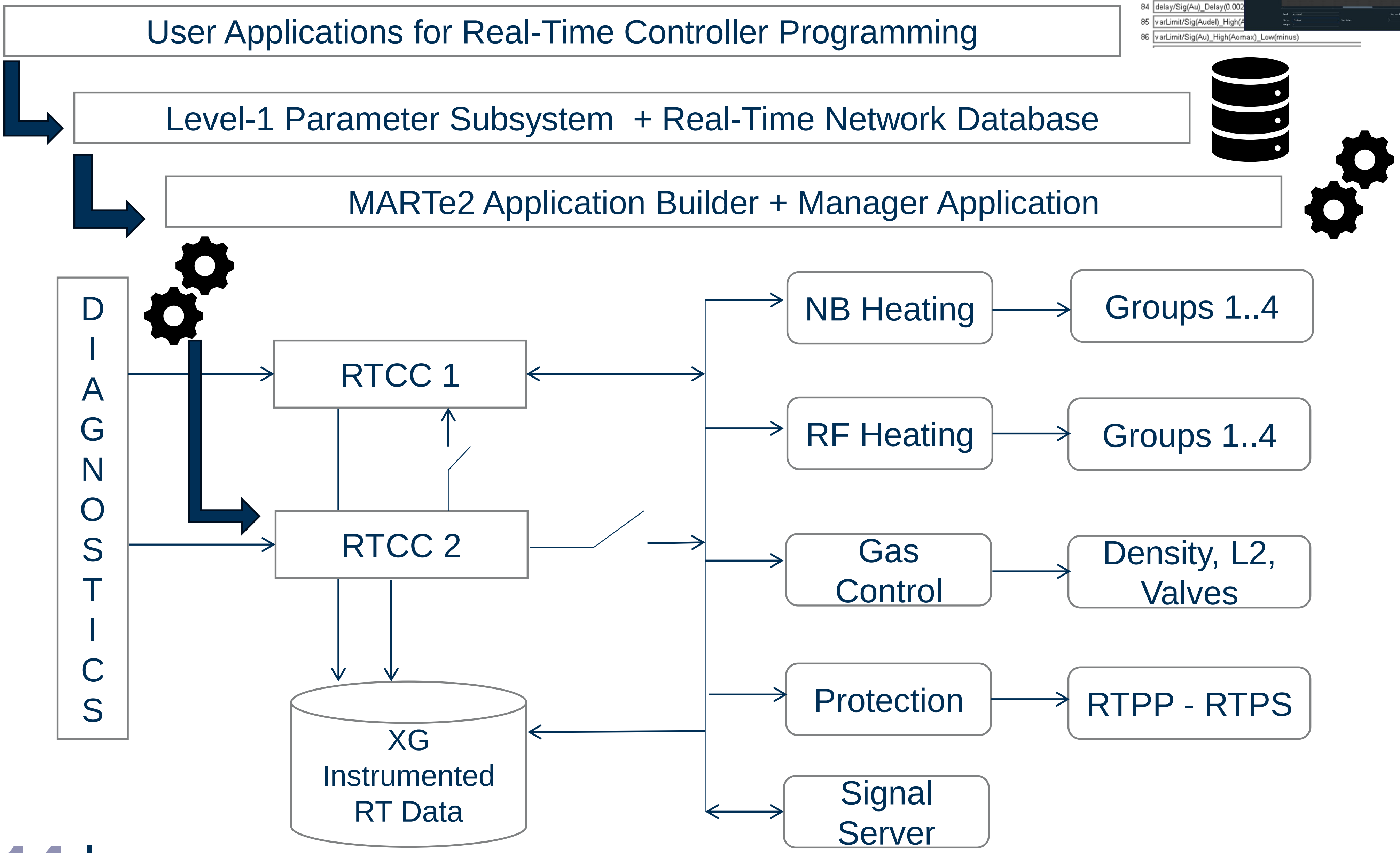

Verification and Validation Plan

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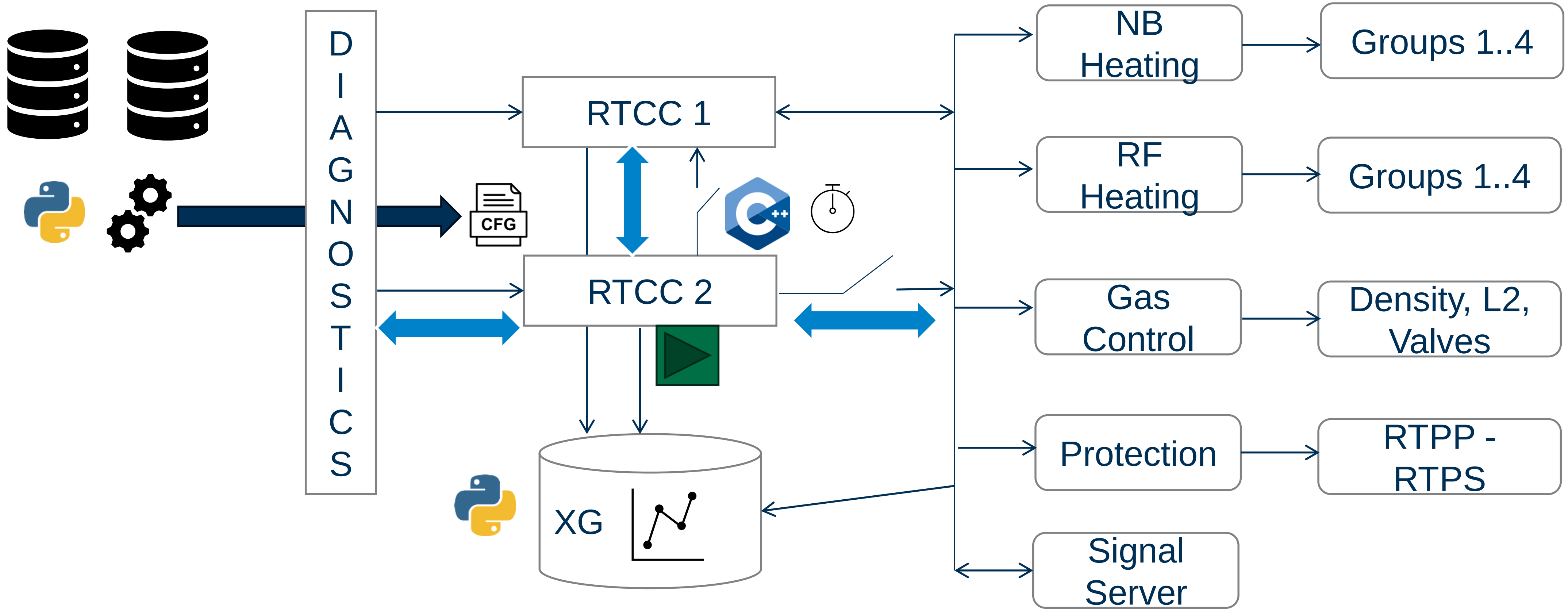
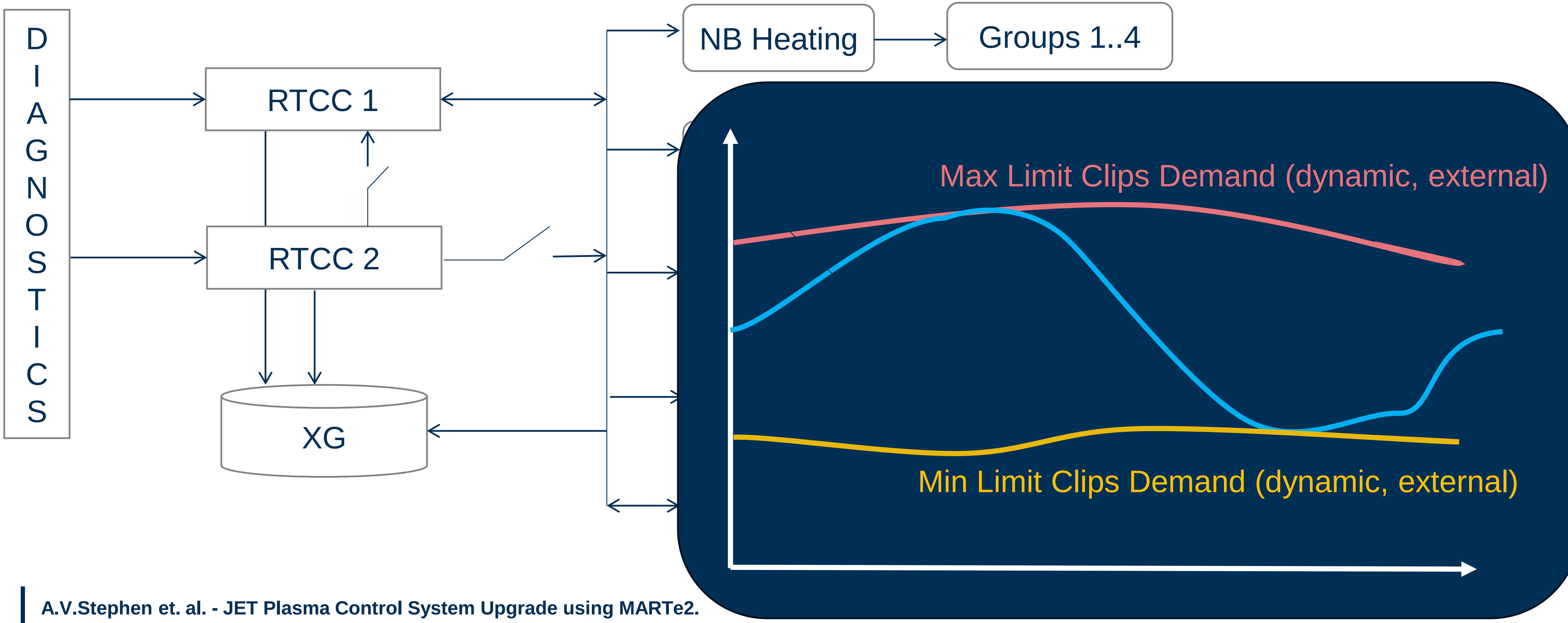


Function	Config Component	Software Components	V&V Method
Communication	Database Definition	Protocol Header Generator SDN Library + MARTe2 Datasource	Manual review / Live Checks
Configuration	Level-1 Database / New Config	Xpsedit + XMARTe Python Application Builder	Regression tests to prove translation Runtime validation to prove new cfg.
RTCC2 Supervisor	Deployment file YML	Python application	Manual checks
Runtime	MARTe2 Config	DataSources + Functions	Unit and Integration Tests in CI/CD

Restricted Control Limits

Real-time controller (for experiment/performance) dynamically limited



Benefit of Decoupled Software Layers

- Divide Commissioning Procedure
  - Communications
  - Real-time components
  - Configuration tools

Can check independently

	Communications	Real-time Components	Configuration Tools
Offline Verification	✓	✓	✓
Online Verification (between pulses)	✓	✓	✓
End to End Verification (pulse / parasitic)	✓	✓	✓
End to End Verification (pulse / controlling)	✓	✓	✓

Commissioning Procedure : Managing Scope Effectively

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CP	Reference
CP:1257	POG/COM/2022/RTCC2/01.01

Title
Commissioning of RTCC2 with plasma

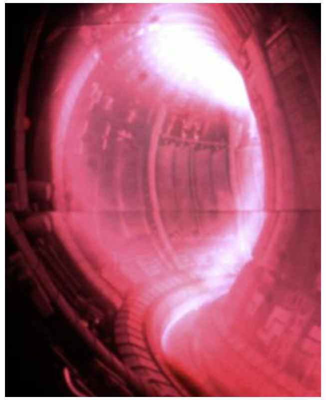
Requirements (1)

Test/Commissioning Procedure: Commissioning procedure (danielv, 1)

Activities, Holdpoints

Interfaces

Role	Person
Responsible person	Daniel Valcarcel
Coord. chairman	et al
- RTCC and RTDN CODAS RO	Alex Goodyear
- Plasma Operations Expert	Peter Lomas
- RTPS RO	Adam (Computing) Stephen
- CODAS	John Waterhouse
- Torus ATO holder	Penny Middleton
Group leader	Daniel Valcarcel



Section		Description
A		**Documentation**
B		**Scope**
	B1	Systems Involved and Services Required
	B2	List of systems or signals tested in this document
C		**Equipment**
D		**General Test Procedures**
	D1	Prerequisites before Commissioning
	D2	General procedure - specific to these commissioning tests
	D3	Test protection actions relating to the Safety Case for Tritium Operations
E		**Test Reports**
	E1	Prerequisites
	E2	Test report

B2 List of systems and signals tested in this document

RTCC2 will be tested by taking control of each actuator, at a time window in the pulse and delivering a waveform compatible with the activities being performed at that moment. Actuators can be tested in separate pulses or combining several in a single pulse. Pulses are successful if the programmed waveform is delivered as expected in each actuator.

- **Section C Equipment**

Mention below all the Equipment needed to perform the commissioning

1. RTCC2 must be operational and run successfully in pulses where it is not connected to the actuators.

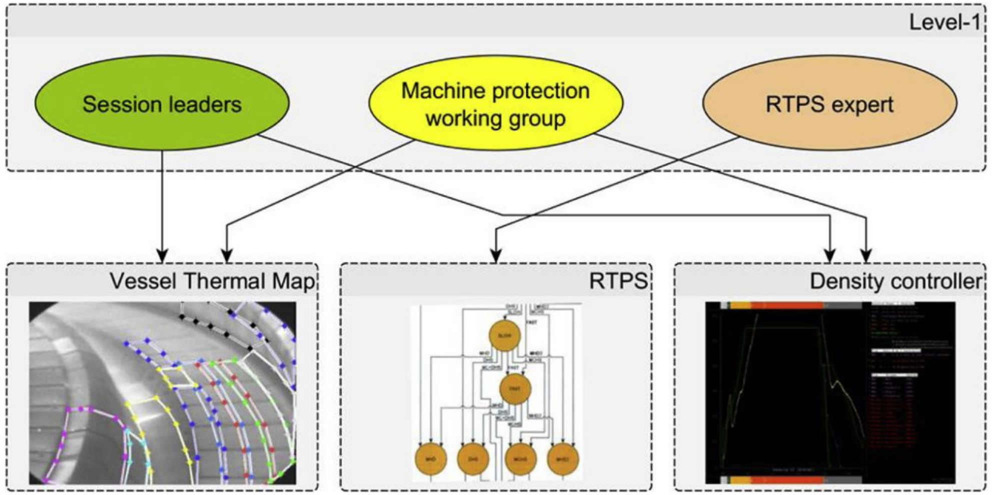


Fig. 1. Separation of concerns by Level-1 when protecting the ILW against hot spots.

Precedent : RTPS ILW

Justifications

New Software Elements under CI/CD
- MARTe2 new functions for RTCC2
- Application builder scripts
- Integrated test tooling
- GUI tools (usability/ops time)
- OS/Yocto

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…underpinned by…

Using Continuous Integration in the development and verification of a new central controller for JET

Tuesday

Edward Jones

11:30 - 11:50

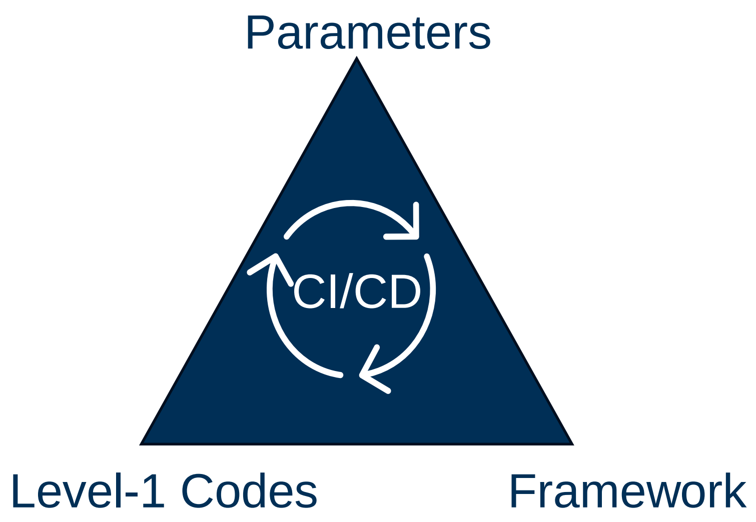
Trusted Software Stacks

MARTe2
- F4E Quality Process
- Experience from ITER Magnetics
- Used on TCV
- Used in ITER CODAC
- Selected for ITER APS

ITER (and JET) **SDN**
- Designed by ITER CODAC
- Tested and used in several ITER projects
- Integrated on JET and in use since 2016

Real-Time Signals (**RTS**)
- Support for ephemeral signals
- Self describing data (**XG**) allows tools to adapt

Deployment Processes



RTCC2 Deployment

Early Commissioning

- November 22 (JPN 101487 onward)
- Connected in read only mode to the JET real-time networks
- Demonstrated ability to run example networks with live data
- Incrementally proved the operations integration facilities
- Building confidence in production environment

RTCC2 Exploitation

1. New capabilities advertised to WPTE RT teams Jan 23.
2. New components developed to support X point radiation tracker (vector support, peak detector).
3. Vector support reduces network complexity.
4. Used during detachment control experiments.

Observations

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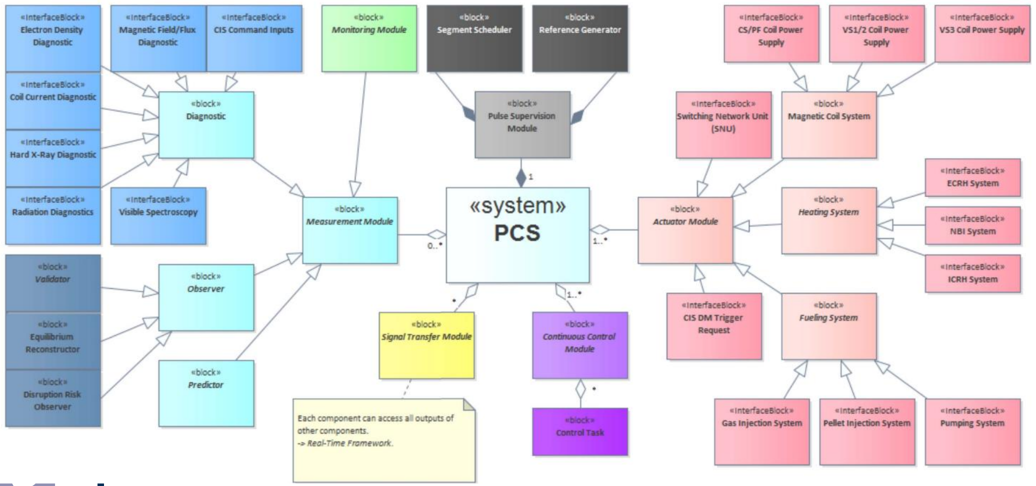
Design Patterns and Challenges

“**Reusability**”. Solutions span a range of **granularities**. **Tool support** to manage span the composite modules, to simple aggregation and filtering blocks. **Consistent naming** and reuse of compound blocks is non-trivial. Code generators struggle to generate meaningful names.

Separation of **infrastructure**/data transport/compute capacity **from algorithm** development/testing remains a design goal. The increasing use of MBSE and other design tools with code generation has benefits and challenges.

Resilience/Robustness. Distinguishing how to deal with off-normal conditions remains an unsolved topic in general. There are a number of techniques and approaches. Some are applied at the system architecture level (conventional control/interlock/safety). Others within systems.

From : ITER PCS DB DOI: 10.1109/TPS.2019.2945715



Lessons Learned

1. Good tools offer many potential benefits, but making the case for investment can be difficult. Especially true if projects can deliver acceptable outcomes with minimum budgets. Need metrics to demonstrate potential ROI.
2. Lifecycle planning needs to provide early/incremental routes to upgrades to spread risk and maintain knowledge/capability.
3. Much of the system complexity exists at conceptually simple levels. Signal semantics, qualities, propagation and error handling need to be treated holistically. ***Potential to align with data/analytics communities to address this.***
4. Overall system performance depends on contributions from interdisciplinary teams. Effective co-design and shared responsibility is important.

Wednesday

Mr Samuel Jackson
Towards an Analysis-Ready, Cloud-Optimised service for FAIR fusion data
09:00 - 09:30

Jonathan Hollocombe
Mapping Alcator C-Mod data into IMAS using the UDA JSON mapping plugin
10:10 - 10:30

Conclusions

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Summary

JET PCS Architecture enabled upgrades even late in the project and during very sensitive operations (DT) due to

- Heterogeneous distributed design limiting the risk from changing any single system.

- Decoupled boundaries for actuator demands with depth of defence against limits.

- Separation of protection and control functionality.

- Integrated management of configuration information.

- Domain specific language approaches and code generation

- Modularity that decouples functional reuse from non-functional reuse.

- Organisational support for incremental upgrades (OS, network, frameworks, tools, central parameter tooling)

Operations risk appetite imposed additional costs

- Greater complexity in RT systems to be able to operate old/new/hybrid modes

- Need to maintain consistent end user interfaces during roll out reduced overall benefits

Outcomes and Benefits

1. Achieved intended objectives of expanding capacity and functionality of the JET PCS.
2. Project took longer than predicted, mostly due to integration issues.
3. Project team included several staff new to the Fusion environment – beneficial in terms of knowledge and experience transfer for future projects (MAST-U, STEP).
4. New system was mainly implemented using future relevant technologies (MARTe2, SDN).
5. New tools were developed with the intent to support future projects (XMARTe, Functions, Python tools).

Future PCS Systems : Trends and Comments

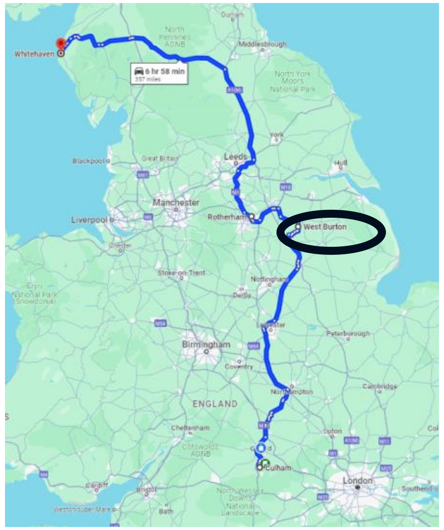
1. ITER architecture combines Matlab/Simulink controller design and test (PCSSP) with a real-time deployment framework (RTF) which has similarities to MARTe2 (C++, component oriented).
2. TCV are successfully applying Matlab/Simulink design with MARTe2 deployment and MDSplus data and configuration support.
3. JET RTCC2 design pattern offers a third reuse option, which is to reuse controller designs which are mapped into component configuration language. A different granularity of module reuse.
4. Each approach has common needs for managing software quality and correctness. This is both at unit test level and integration test level. Qualification and certification requirements are yet to emerge, but the toolchain and methodology need to be considered in addition to the specific functionality.
5. Each approach needs to be combined with easy to use, scalable test harnesses which can operate software in the loop tests against historic data, augmented data, and models.
6. Hardware in the loop testing is important to validate performance, and to stress test resilience and reliability of algorithms which are well proven in the software only tests.
7. Meta data and machine processable techniques for dealing with the data/algorithm/technology complexity and providing assurance and tooling to help with lifecycle management are important.

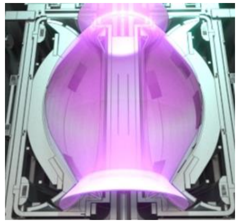
Future Fusion Powerplant Landscape

UKAEA STEP Programme

"STEP will build on developments made over decades at UKAEA in multiple aspects of fusion science and engineering to deliver a **working integrated prototype energy plant**."

"STEP also has a second critical aim. Through delivering a new prototype plant STEP will **develop a new fusion supply chain**."





STEP up in expectations

- Industrial grade solutions
- Vendor / partnership delivery
- Lifecycle support
- Eliminate NREs
- Amortize investment
- Enough flexibility to avoid fragility
- Enough stability to manage cost/risk
- Cyber secure, mostly automated
- Mostly automated
- Skills, Capabilities, Capacity

Wednesday

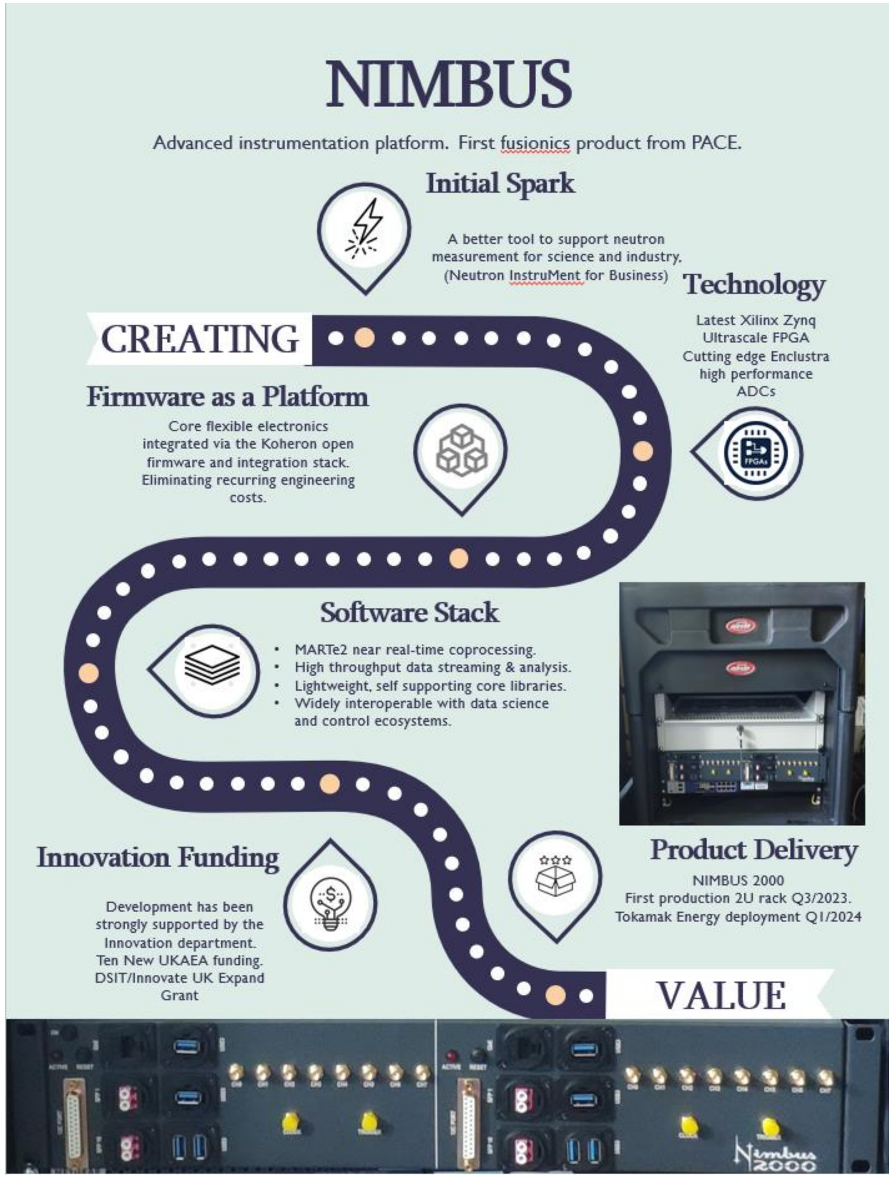
Developing JET Gas Controllers with Uncertainty Quantified Deep Learning Models for Plasma Control

Hudson Baker

Steps forward in Technology 2030..2040

- From MBSE up to Digital Twin
  - from exascale to HPC
  - to control system compute fabric.
- Evolving processing options
  - (CPU|GPU|FPGA|AI Accelerators|Hybrid)
- Evolving networking options
  (On chip, 400Gbps+, SDN)
- Alternative sensing/diagnostic
- Containerisation/virtualisation
- Cloud/Edge
- OS, RTOS, Bare Metal
- Secure/performant languages :
  - C++ -> Rust
- AI/ML – everywhere
  - Control components
  - LLMs as "developer" co-pilots
  - Data exploitation
  - In combination with human judgement ?

PACE / FUSIONICS



Acknowledgements

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All MARTe Contributors

The JET CODAS and Plasma Operations Groups

The whole of the JET Team – Operations and Science

CCFE, Culham Campus, Abingdon, Oxfordshire, OX14 3DB, UK.

The views and opinions expressed do not necessarily reflect those of UKAEA and Fusion for Energy which are not liable for any use that may be made of the information contained herein.

JET, which was previously a European facility, is now a UK facility collectively used by all European fusion laboratories under the EUROfusion consortium. It is operated by the United Kingdom Atomic Energy Authority, supported by DESNZ and its European partners. This work, which has been carried out within the framework of the Contract for the Operation of the JET Facilities up to 31 October 2021, has been funded by the Euratom Research and Training Programme. Since 31 October 2021, UKAEA has continued to work with the EUROfusion Consortium as an Associated Partner of Max-Plank-Gesellschaft zur Förderung der Wissenschaft e.V represented by Max-Plank-Institut fur Plasmaphysik ("IPP") pursuant to Article 9.1 of the EUROfusion Grant Agreement for Project No 101052200. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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شكرا لك أي أسئلة

Спасибо, есть вопросы?

Obrigado - alguma dúvida?

Merci – quelques questions ?

谢谢-还有问题吗？

Gracias - ¿alguna pregunta?