

# Automatic Formal Verification for EPICS

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# UWMC Clinical Neutron Therapy System (CNTS)

*Hospital-based cyclotron and neutron radiation therapy*



# Safety requirements

We must ensure that the we satisfy this overall safety requirement:

- *The neutron beam can only turn on or remain on when the machine setup matches a prescription that has been selected by the operator.*

This overall requirement is composed of hundreds of detailed requirements, for example:

- *The actual gantry angle must match the prescribed angle within a given tolerance, when the machine is in therapy mode and that setting has not been overridden and ...*

These requirements cannot be checked with relays or PLCs.

General purpose computing in high-level languages is unavoidable.

# EPICS and safety-critical systems

Is it advisable to build a safety-critical system with EPICS?  
Some conventional wisdom says no:

2008: “(EPICS) code is not rigorously audited to the standards ... that would be needed (for medical applications). ...”  
[epics/tech-talk/2008/msg00803.php](http://epics/tech-talk/2008/msg00803.php)

Response: We reviewed and tested EPICS code ourselves.

2012: “EPICS should never be relied on for safety-critical operations ...”  
[epics/tech-talk/2012/msg01836.php](http://epics/tech-talk/2012/msg01836.php)

Response: We use a subset of EPICS in a restricted style.

## Using EPICS with confidence in safety-critical applications

Three related topics::

- Selecting an EPICS subset and a restricted programming style
- New tool for finding errors in EPICS databases (applications)
- New tool for testing EPICS core (runtime)

# Control Program: Limiting Complexity (1)

EPICS architecture:

- Embedded computers with EPICS runtime, called *IOCs*
- Application programs on IOCs, called *databases*
- User interface, database access etc. provided by separate *Client* programs running on different computers
- IOCs and clients communicate using *Channel Access (CA)* network protocol

Therapy control application architecture:

- Therapy control program runs on one IOC
- Therapy IOC alone executes control laws, achieves and maintains safe state
- Clients and CA are only used to make progress.  
For example, select and load prescription
- Do not depend on clients or CA for control laws or safety

Clients and CA not considered in our formal analyses and tools

## Control Program: Limiting Complexity (2)

Select an EPICS subset and use a restricted programming style.  
Just enough to support data flow from inputs to outputs:

- Only database records, StreamDevice .proto files, st.cmd
- No SNL, no subroutine records, no custom device support
- Database DB links only, no CA links
- Data flow is all “push” from inputs to outputs:  
SCAN PASSIVE, INP<sub>x</sub> NPP, OUT PP, FLNK
- 19 record types: `acalcout ai ao asyn bi bo calc calcout  
dfanout fanout longin longout mbbo scalcout seq  
stringin stringout subArray waveform`

Our formal analyses and tools only consider these.

# EPICS Symbolic Interpreter

The *EPICS Symbolic Interpreter* is a new tool for finding errors in EPICS databases (application programs).

Similar role to unit testing, but considers all possible input values.

Inputs:

- EPICS database: *.db .substitutions .template st.cmd*
- Property that relates PVs before and after processing:  
*actual gantry  $\neq$  prescribed gantry  $\Rightarrow$  interlock set*

Output: *everything is ok!* – property is satisfied – or:

- Counterexample: PVs with values that violate property –  
*Iso:GantryCouch:Gantry:Prescribed.VAL = 312*  
*Iso:GantryCouch:Gantry:Actual.VAL = 48 ...*
- Log: processing along counterexample data flow path

Now in use, found serious errors missed by reviews and testing



# EPICS symbolic interpreter (2)

Similar role to unit testing, *but* —

Testing:

- You try to guess an input value that violates the assertion.
- Passing tests are *not conclusive*, a different value might have failed.

Symbolic interpreter:

- Tool finds an input value that violates the assertion, if there is one.
- Verified properties are *conclusive*, all possible values are checked.

The symbolic interpreter can check all values because it considers CALC fields as symbolic formulas.

# EPICS Trace Verifier (1)

The *EPICS Trace Verifier* is a new tool for testing the EPICS runtime.

Does the EPICS runtime behave as we expect?

The trace verifier uses a *formal semantics* we derived from the EPICS Record Reference Manual (RRM).

The formal semantics is a new implementation of EPICS in a specialized programming language.

The trace verifier checks if a sample of IOC behavior is consistent with our formal semantics.

# EPICS Trace Verifier (2)

We compare of three things:

$$\begin{array}{ccc} & ? & ? \\ \text{EPICS RRM} & = & \text{Formal semantics} & = & \text{EPICS code} \\ & \text{manual} & & & \text{automatic} \\ & \text{(review RRM)} & & & \text{(trace verifier)} \end{array}$$

We can revise the formal semantics.

We observe discrepancies found by the trace verifier.

# EPICS Trace Verifier (3)

Checked traces from over 20 million randomly generated IOCs

No crashes, no outright errors where RRM makes a false statement.

Found two kinds of discrepancies:

- Our misreadings of the RRM
- Omissions, ambiguities in the RRM

Example omissions, ambiguities:

- *dfanout* (etc.) OMSL default is *supervisory*, not *closed\_loop*
- *calcout* with *DOPT = On Change* considers *inf*  $\neq$  *inf*, contrary to IEEE754
- *seq* uses callbacks even if all delays are zero. Callbacks might interleave with other records processing.
- *calc* etc. write from *INPA* to *A* before processing *INPB* (etc.). Observable if later input links refer to earlier fields (etc.)

None of these omissions or ambiguities affect our control program.

We can use EPICS with confidence in safety-critical applications.

We have demonstrated —

- Successful use of restricted EPICS in a safety-critical application
- Tool that finds errors in EPICS databases using exhaustive analysis
- Testing of the EPICS runtime against the RRM finds ambiguities and omissions, but no crashes or outright errors.