Predictable Execution with IEC 61499

Li Hsien Yoong
The University of Auckland

Sequence of presentation

- What has been achieved:
  - Deterministic behaviour of centralized IEC 61499 systems
- Current goal:
  - Deterministic behaviour and predictable timing of distributed IEC 61499 systems
- Industrial application:
  - Video and tool demonstration

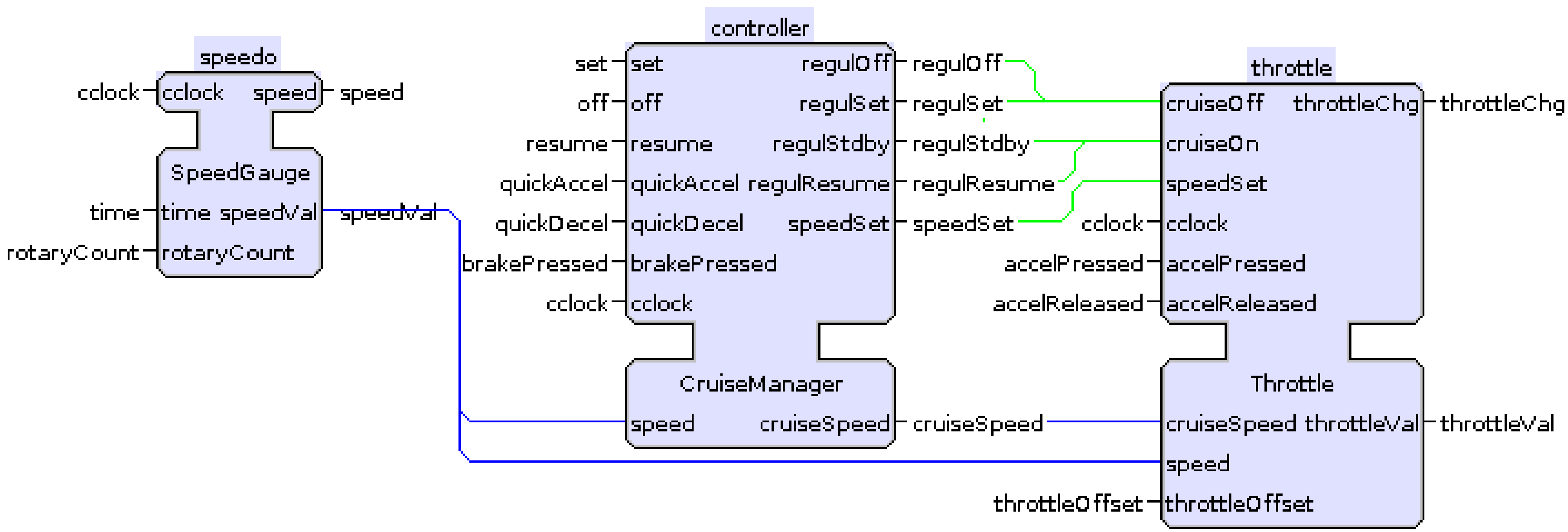
What is the IEC 61499?

An open standard of the International Electrotechnical Commission (IEC)

Component-oriented approach for designing distributed industrial-process control systems
to meet future requirements of intelligent automation

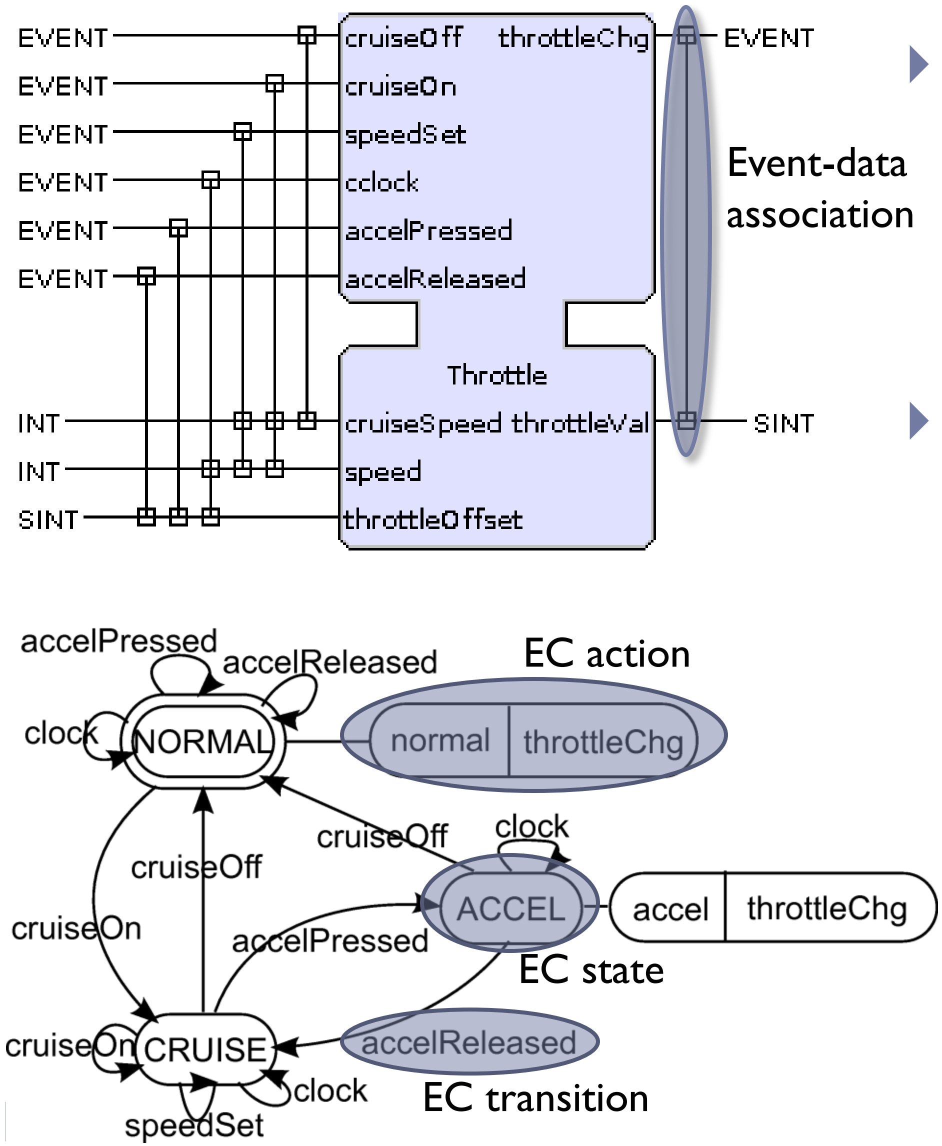
- Model-based development for industrial control software
  - Graphical – *function blocks*
  - Target-independent
  - Supports reuse of IEC 61131
  - System-level design of distributed systems

An IEC 61499 example



- Model of a cruise control system
  - Each block encapsulates a sub-component
  - Clearly defined event/data flow between components

An IEC 61499 example



- Function blocks consist of input/output interface:
  - Events
  - Data
- Three types of function blocks:
  - Basic
  - Composite
  - Service interface

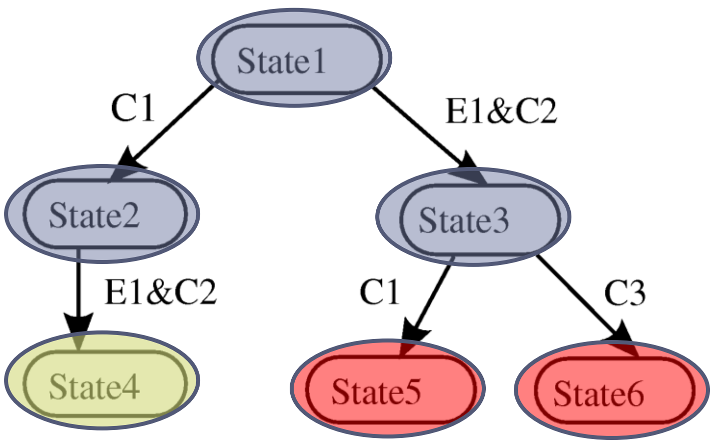
Design artifacts in IEC 61499

- Hierarchy of design artifacts:
  - Function block – encapsulates a functional unit of software
  - Resource – independent unit of software made up of a network of function blocks
  - Device – programmable controller that executes function blocks
  - System – a collection of devices implementing the desired control function

Some ambiguities…

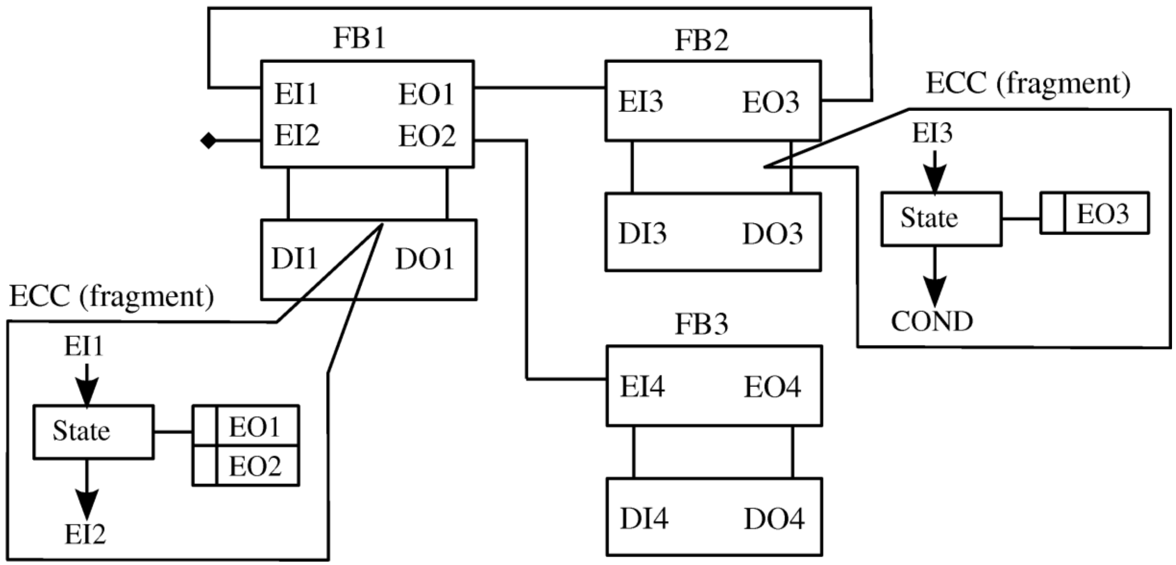
- Execution semantics of function blocks is not fully defined in standard.
- Two main deficiencies:
  - *Lack of any notion of time* – What is the lifetime of events? Are events simultaneous?
  - *Lack of any notion of composition* – How do blocks communicate? Is there a (partial) order for block execution?
- Different solutions from different vendors:
  - Function Block Run-Time (FBRT)
  - 4DIAC Run-Time Environment (FORTE)
  - ISaGRAF

Problem 1: Transition evaluation in an ECC



- Lifetime of events
  - E1 occurs, C1 and C2 are true.
  - Should transition to State4 be taken?
- Eventless transitions
  - E1 occurs, C2 is true, C1 and C3 are false.
  - Will State5 or State6 ever be reached?

Problem 2: Composition of blocks in a network



- *Race conditions* – FB1 may be triggered by FB2 before it can complete its execution.
- *Starvation* – FB3 may be left unattended while FB1 and FB2 monopolize the execution.

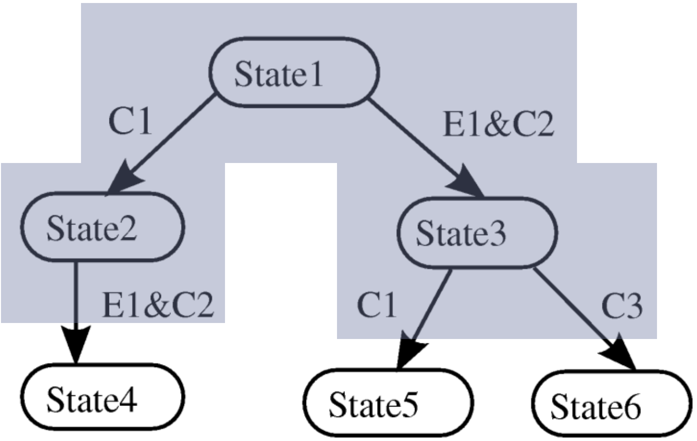
Key issues addressed

- Formal model for function block systems
  - Globally asynchronous locally synchronous paradigm for distributed IEC 61499 systems
- Software synthesis
  - Automated generation of efficient code without run-time environment or middleware
- Abstract communication patterns for distribution
  - Specify communication semantics using known patterns

Mapping function blocks to Esterel

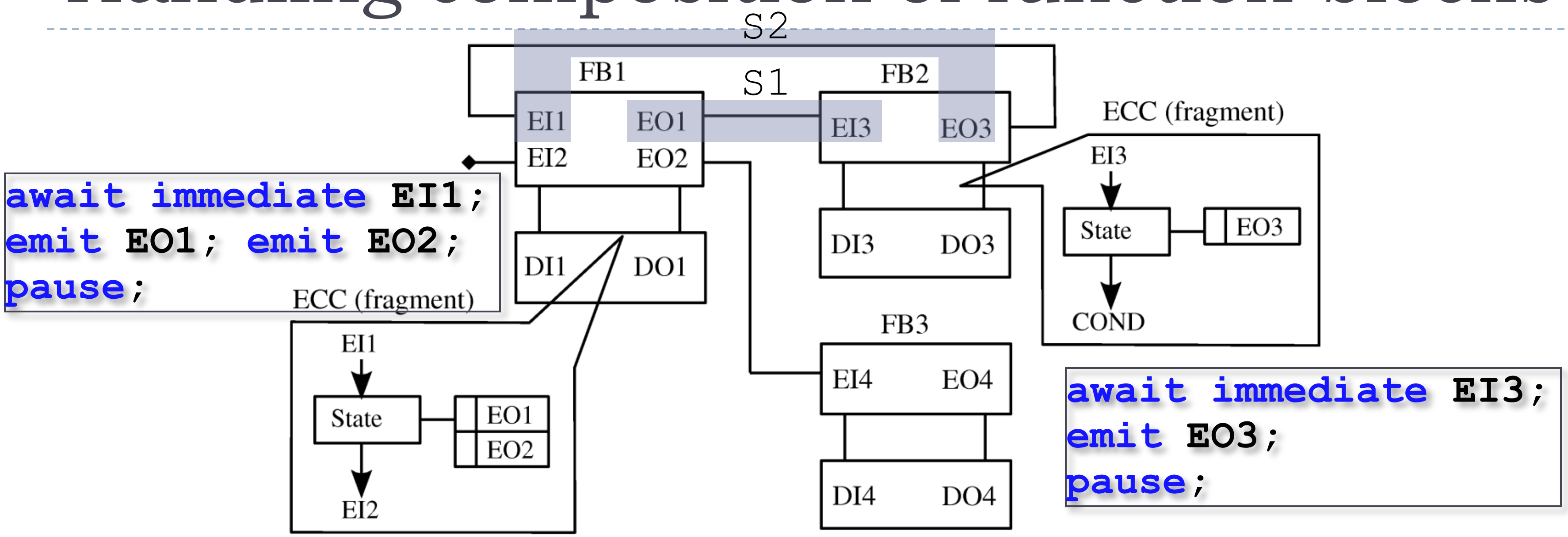
Function block element	Esterel feature
Function blocks	Modules
Events	Pure interface signals
Data	Value-only interface signals
Internal variables	Value-only local signals
EC states	Demarcated by `pause` statements
Algorithms	Instantaneous modules
Transition conditions	`await` statements
Function block network	Parallel composition of modules

Handling transition evalutions




```
// State1
pause;
await
   case immediate ?C1 do
      // State2
      pause;
      await immediate E1 and ?C2;
      // State4
      pause;
   case immediate E1 and ?C2 do
      // State3
      pause;
      await
         case immediate ?C1 do
            // State5
            pause;
         case immediate ?C3 do
            // State6
            pause;
      end await
end await
```

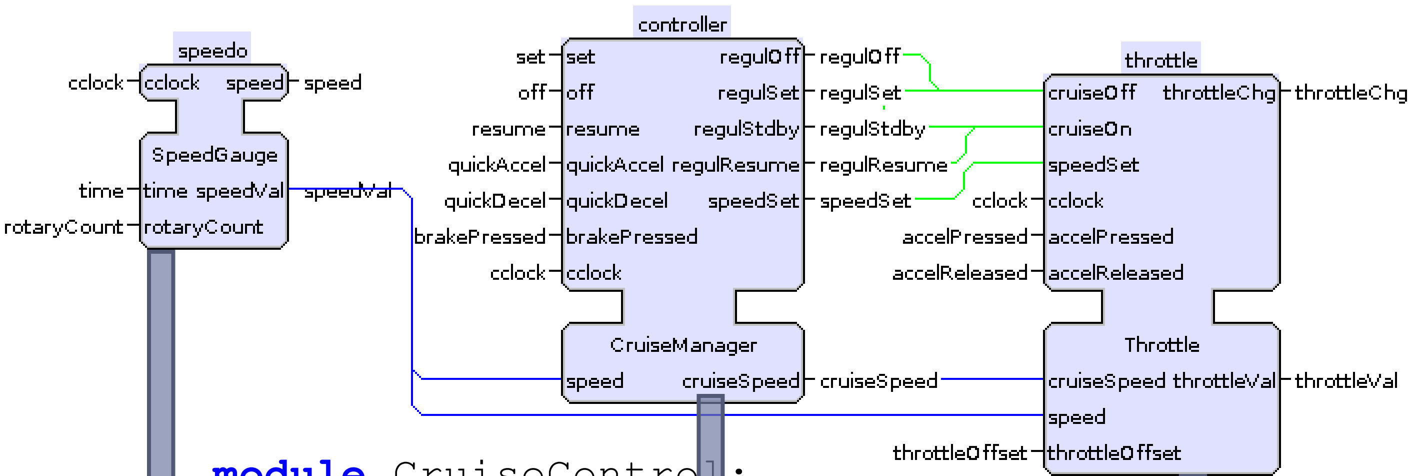
Handling composition of function blocks




```
  await immediate S2; emit S1; emit EO2; pause;
||
  await immediate S1; emit S2; pause;
```

```
  await immediate pre(S2); emit S1; emit EO2; pause;
||
  await immediate pre(S1); emit S2; pause;
```

Translating function blocks to Esterel

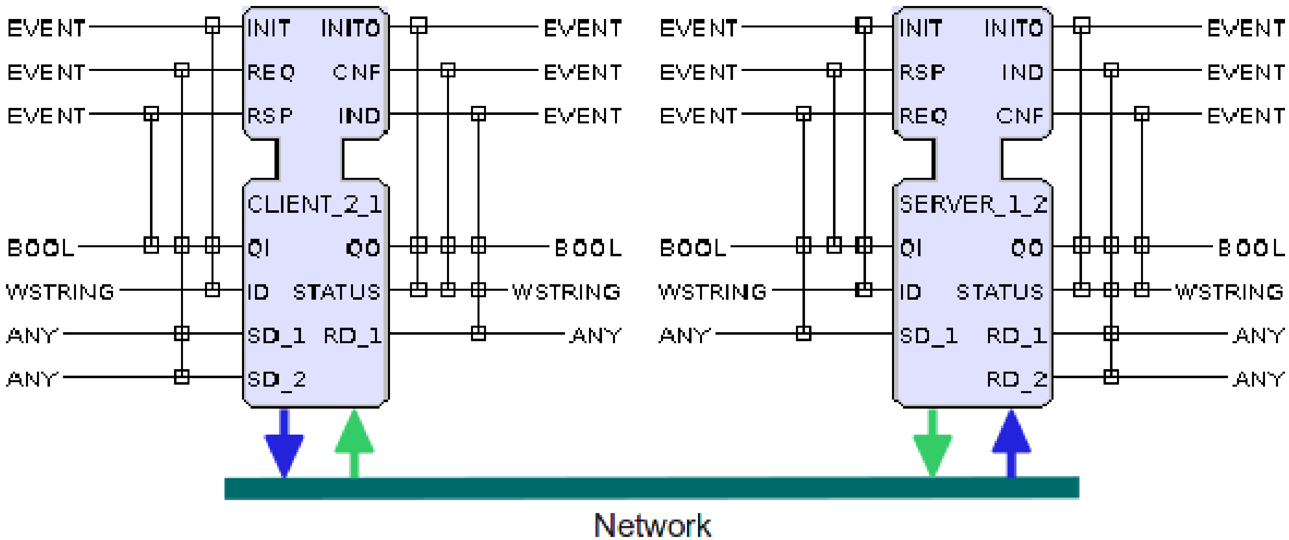



```
module CruiseControl:
  input cclock, set, off, resume, quickAccel, quickDecel;
  // other inputs ommited
  output speed, speedSet, throttleChg, regulOff;
  // other outputs ommited
  signal s0 : value signed<[16]>, s1, s2, s3, s4, ... in
    run CruiseManager [...]
  ||
    run Throttle [...]
  ||
    run SpeedGauge [...]
  ...
  end signal
end module
```

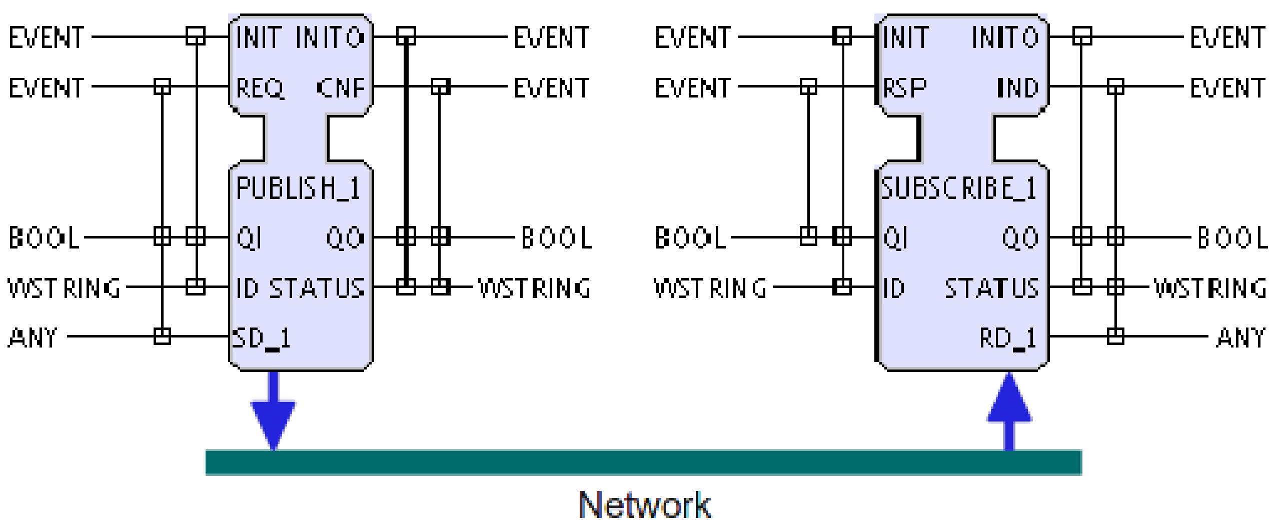
GALS model for distributed systems

- IEC 61499 is a standard for distributed control systems. Concurrency arises from 2 sources:
  - Parallelism in the controlled environment (*logical* parallelism) – disciplined synchronization
  - Distribution of the control systems (*literal* parallelism) – communicate only when necessary
- GALS model for distributed IEC 61499 systems
  - *Resources* are synchronous islands.
  - Resources communicate with each other using *communication function blocks.*
- Communication function blocks encapsulate various communication patterns.

Communication function blocks

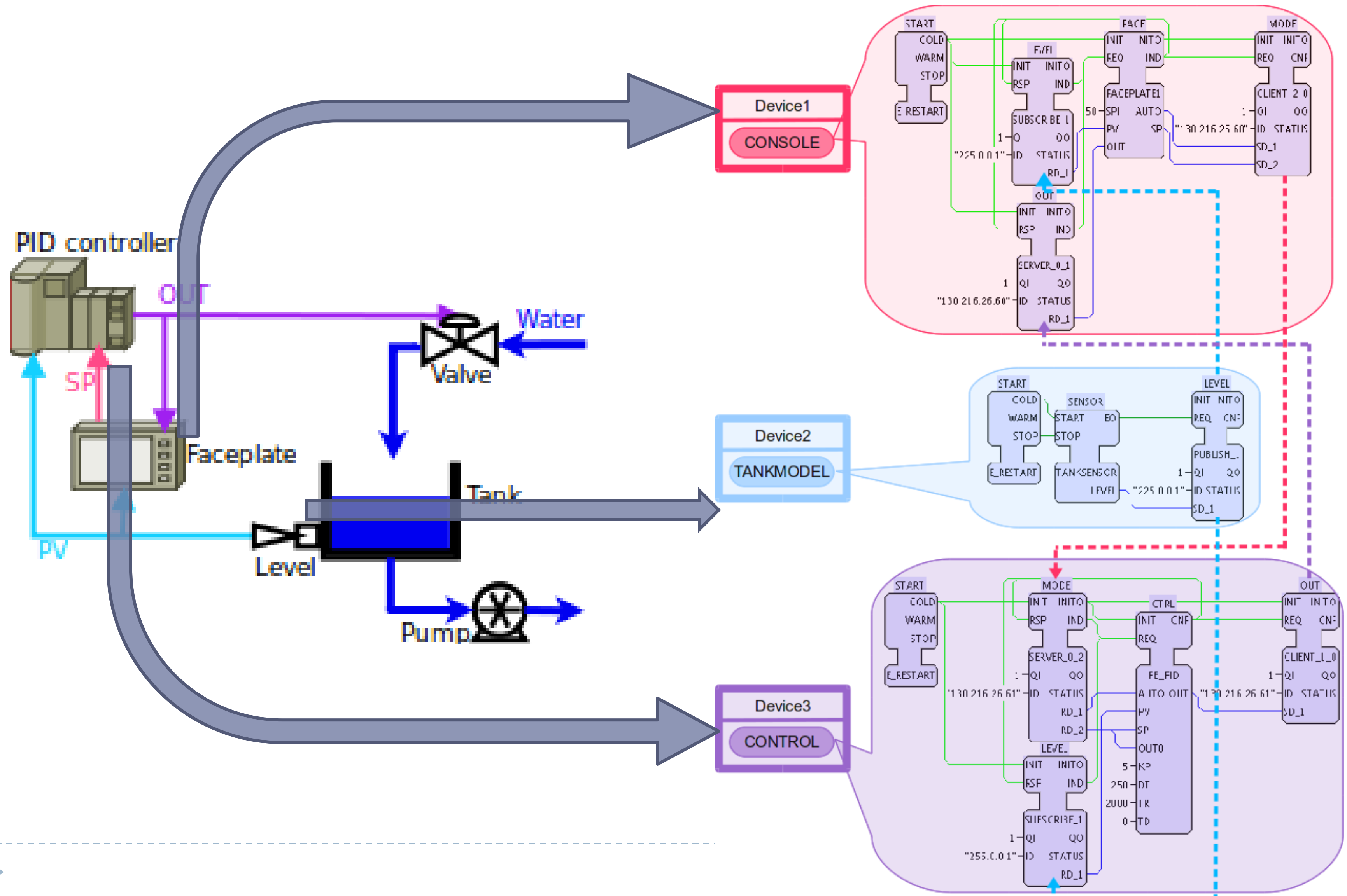


Client-server function blocks

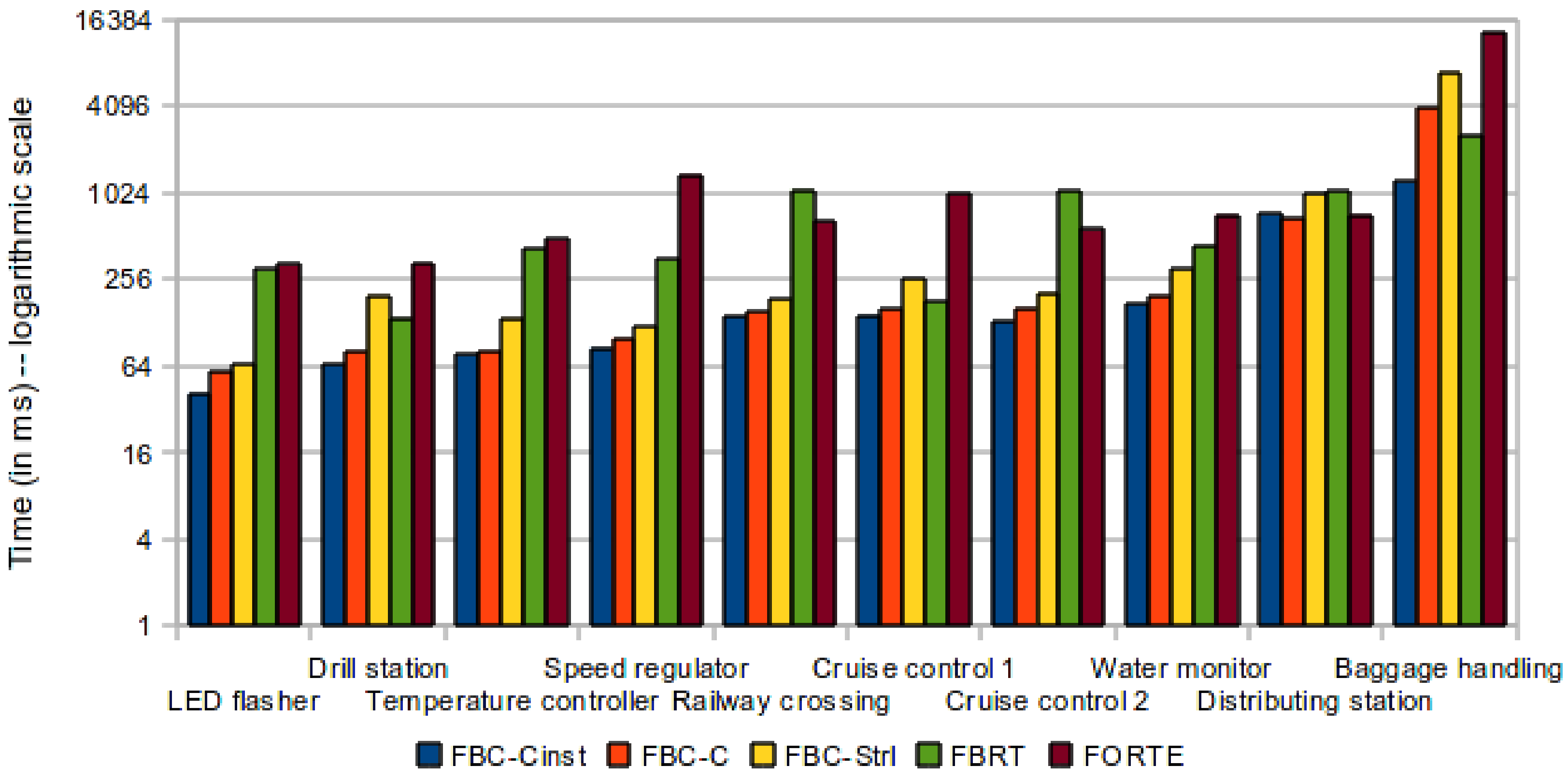


Publish-subscribe function blocks

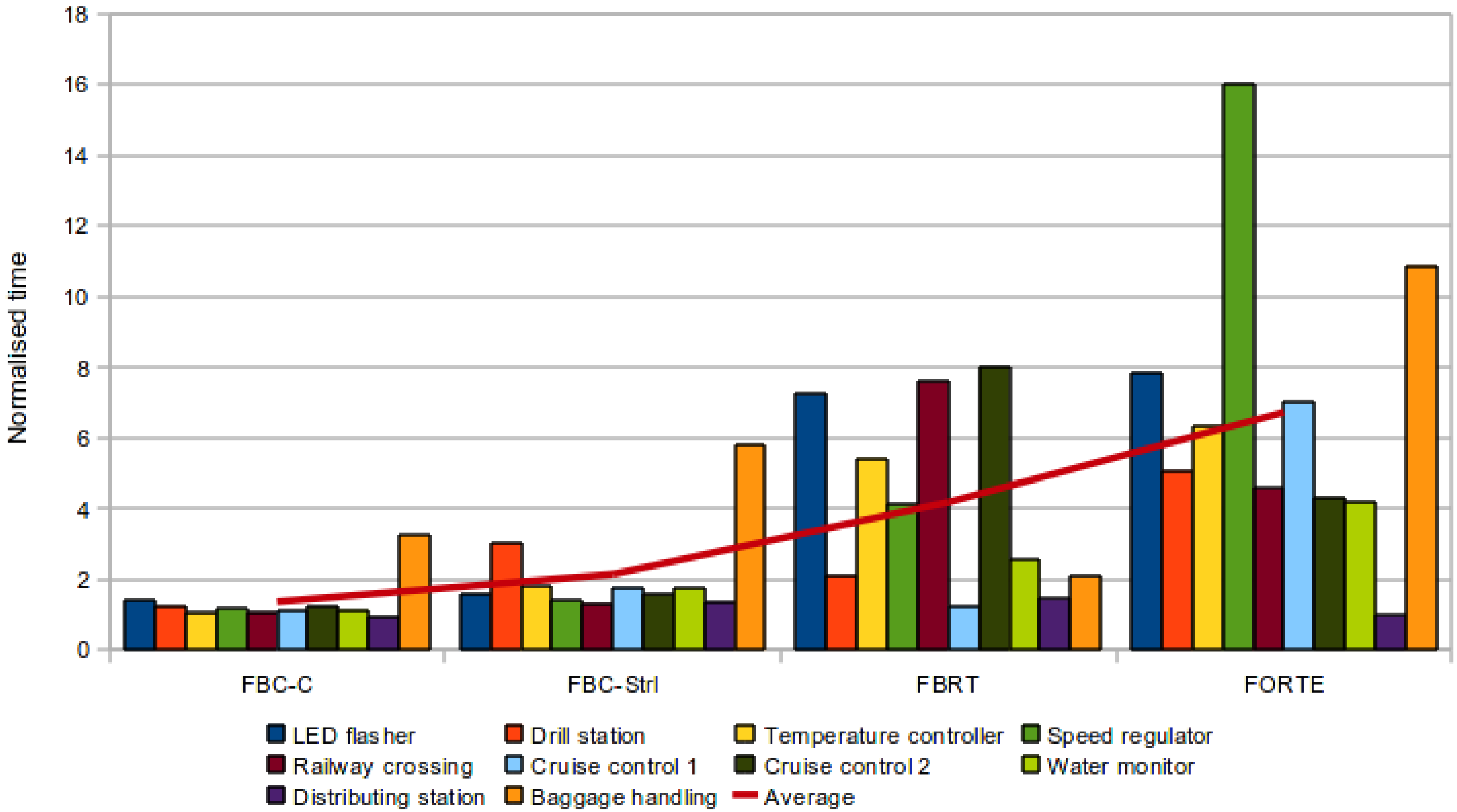
Example of a distributed system



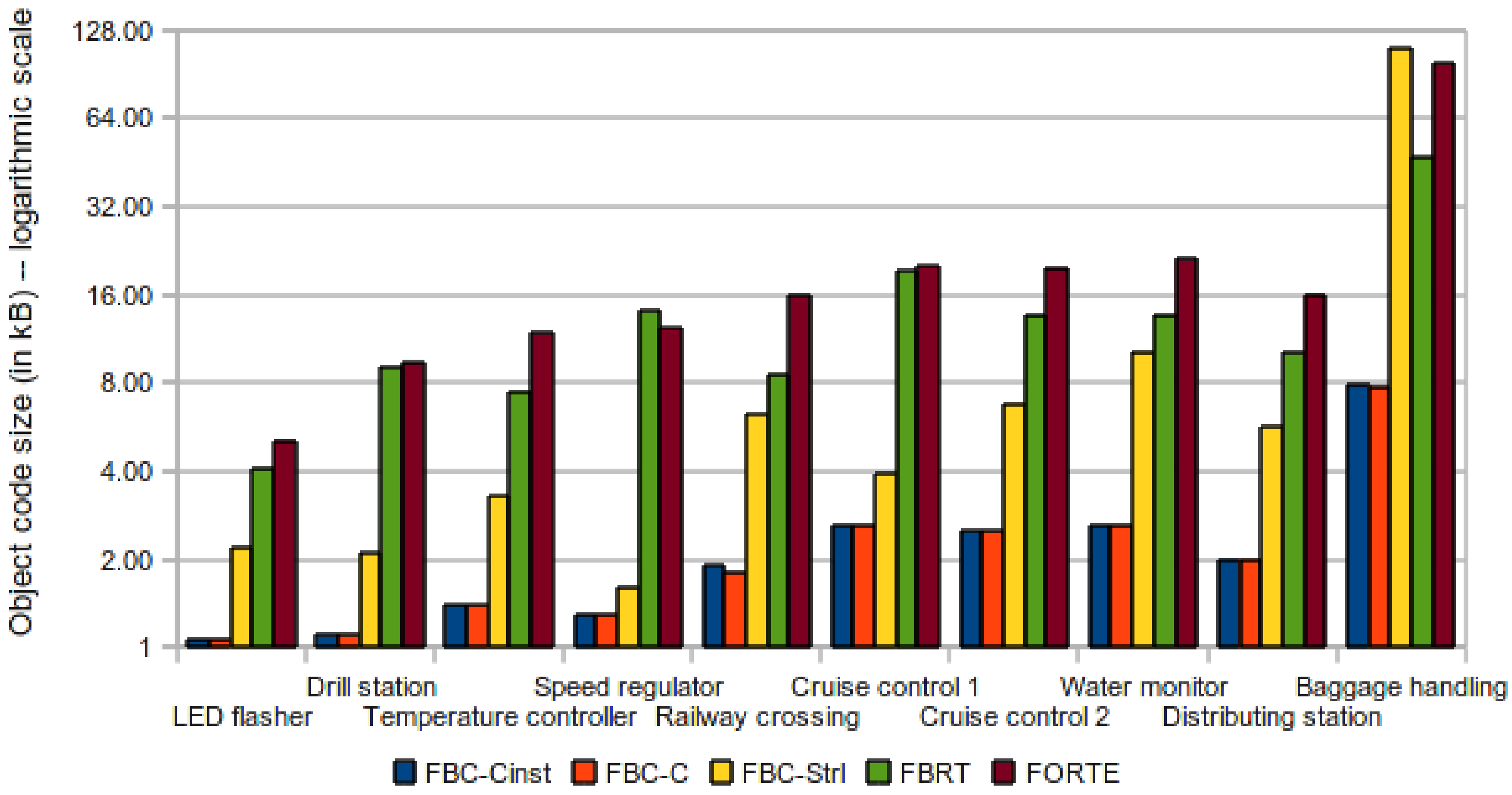
Experimental results – speed



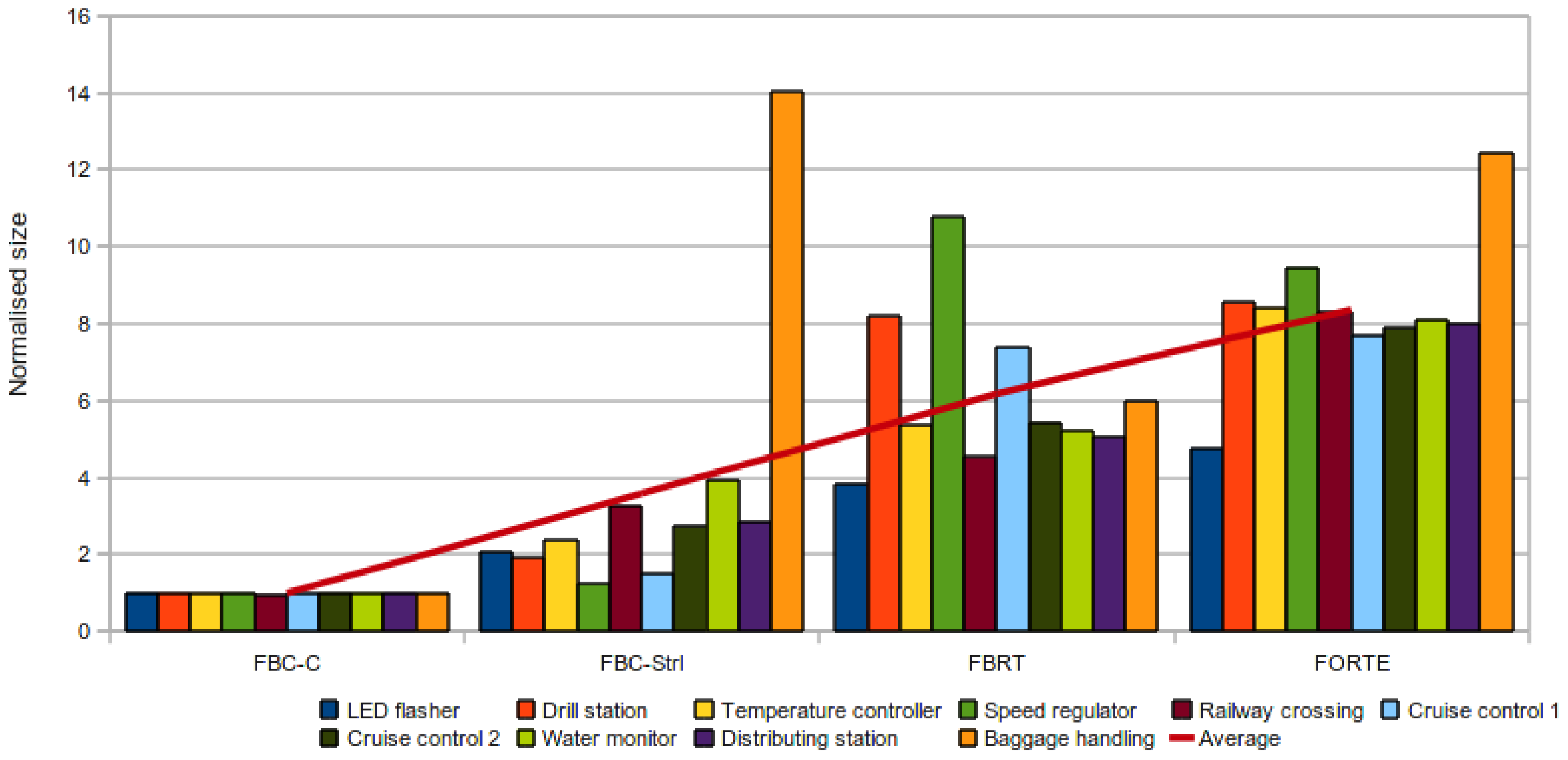
Experimental results – normalized speed



Experimental results – size



Experimental results – normalized size



Towards a multi-rate framework

- Multi-rate framework is based on the *synchronous approach*. Consists of several clocks derived as a rational multiple of some base clock.
- Why multi-rate?
  - Multi-rate systems ensure determinism and facilitates verification of global behaviour.
  - Amenable to static timing analysis – *real-time systems*.
  - When used with time-triggered networks, deterministic distributed real-time systems can be achieved.

Basic idea to ensure timing determinism

- Assume execution platform to be always fast enough:
  - Language provides semantics to express timing constraints of environment (reactivity).
  - Compiler ensures that timing constraints are met on platform (schedulability).
- Similar abstraction to synchronous approach, but for multi-rate systems, every module requires timing-deterministic I/O operations.

Proposed approach for multi-rate software

- Goals:
  - Facilitate analysis of global behaviour, e.g., by simulation of formal verification.
  - Implementable using a simple static priority preemptive scheduler.
  - Efficient use of computing resources, while ensuring equivalence with single-task approach.

Proposed approach for multi-rate software

- Scheduling:
  - Rate monotonic preemptive scheduling will be used.
  - All task periods are multiples of the base period. The base period must be a common factor of all task periods.
  - Timing constraints:

$$\mathrm{WCET}(P_0) + other_0 < T_0$$

$$\sum_{i=0}^{n-1} \left[N_i \times \left(\mathrm{WCET}(P_i) + other_i \right) \right] + \mathrm{WCET}(P_n) + other_n < T_n$$

$$\text{where } N_i = \left\lceil \frac{T_n}{T_i} \right\rceil$$

Proposed approach for multi-rate software

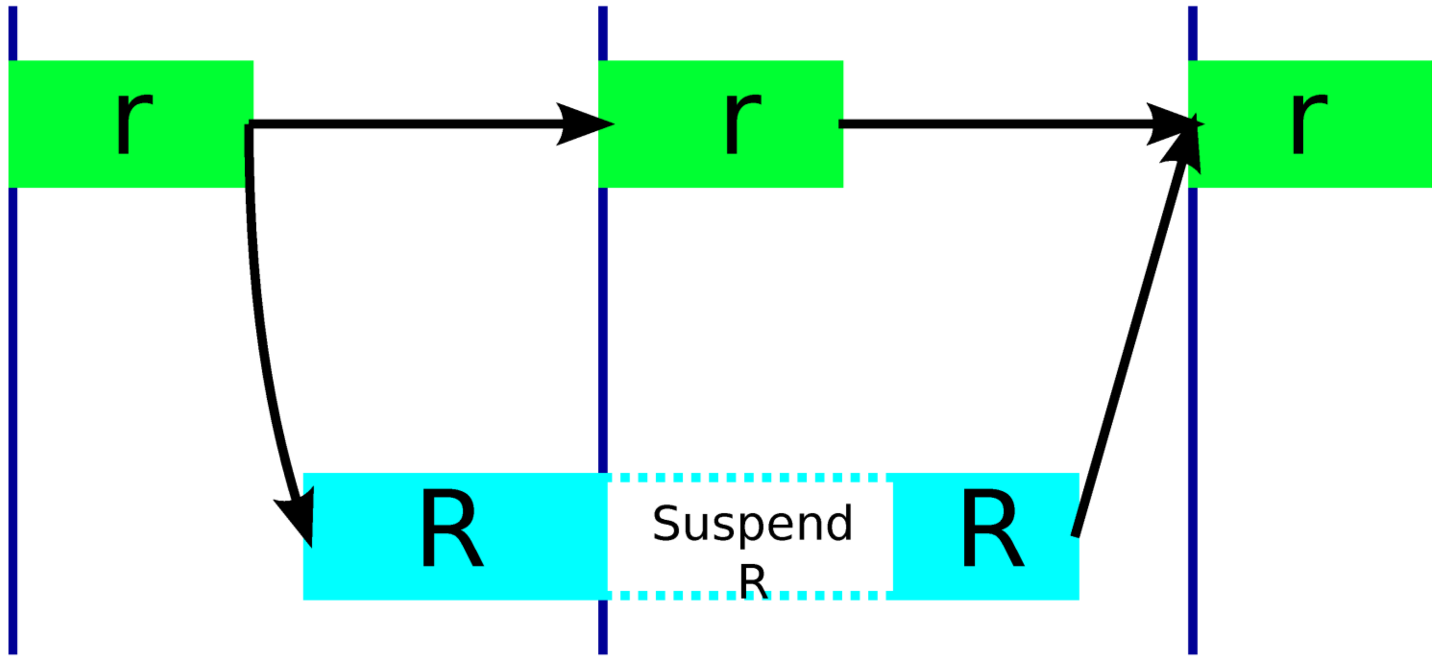
- Issues:
  - Determinism means producing the same output sequence for a given input sequence at specific instants of time.
  - For synchronous programs, execution time may vary as long as:

$$\mathrm{WCET}(P) + other < T$$

  - For multi-rate programs in a multi-tasking scheme, I/O operations must remain timing-deterministic even with variations in execution time.

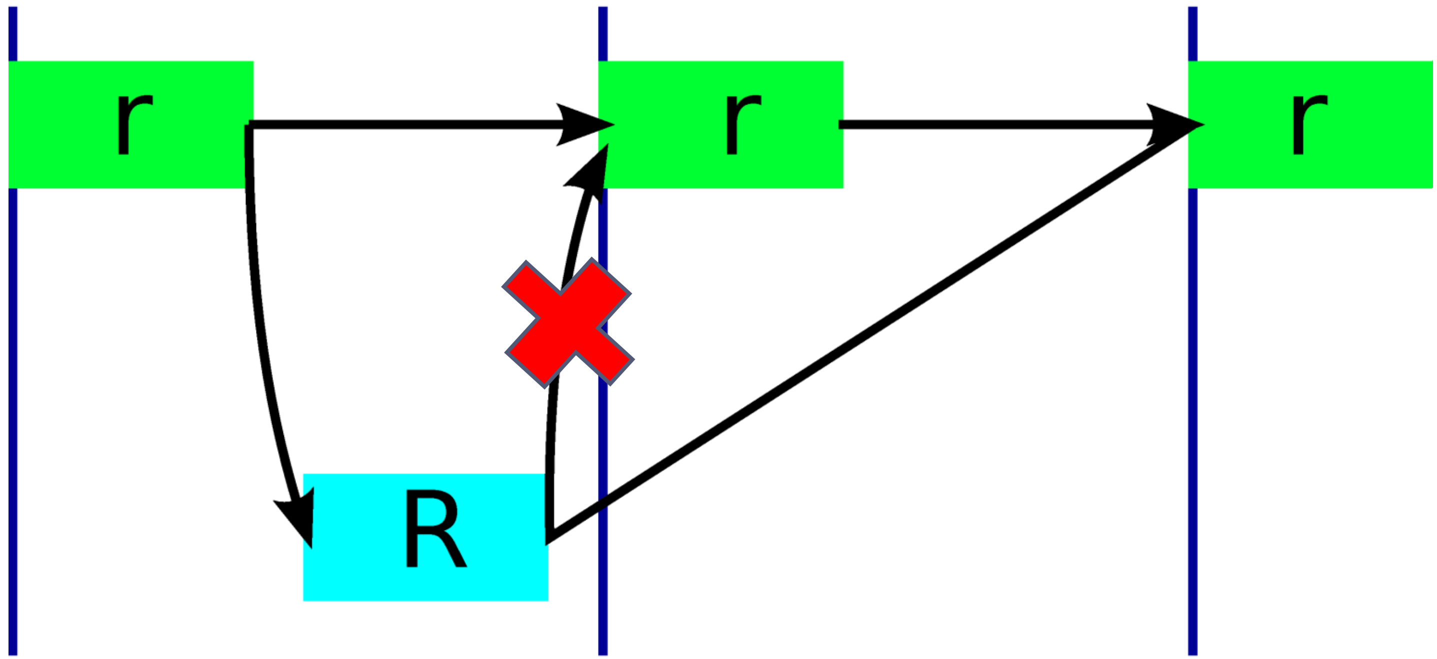
Slow-to-fast resource communication

- Illustration: assume $T_R = 2T_r$
- Case 1: R computes slowly



Slow-to-fast resource communication

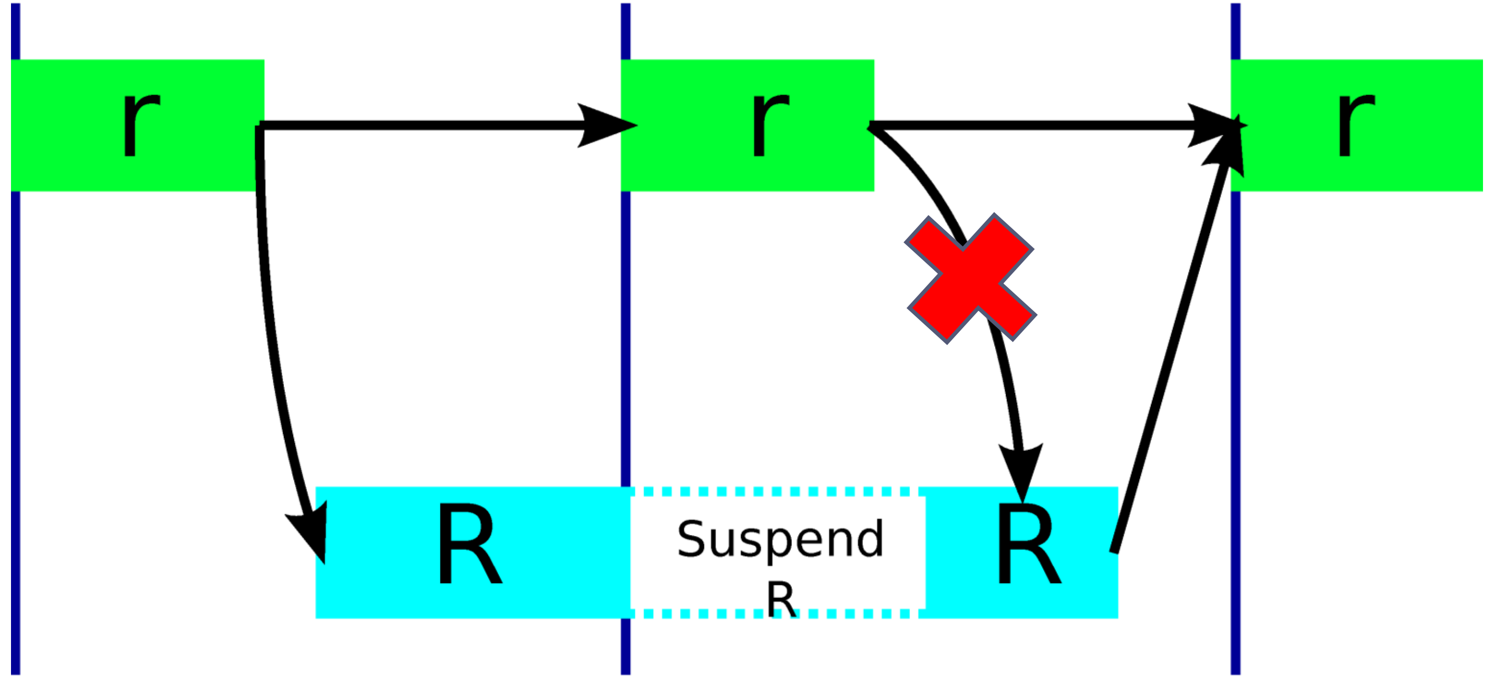
- Case 2: R computes faster than usual



- To maintain determinism, R must communicate to r at the beginning of the next fast cycle, where R starts its next slow cycle.

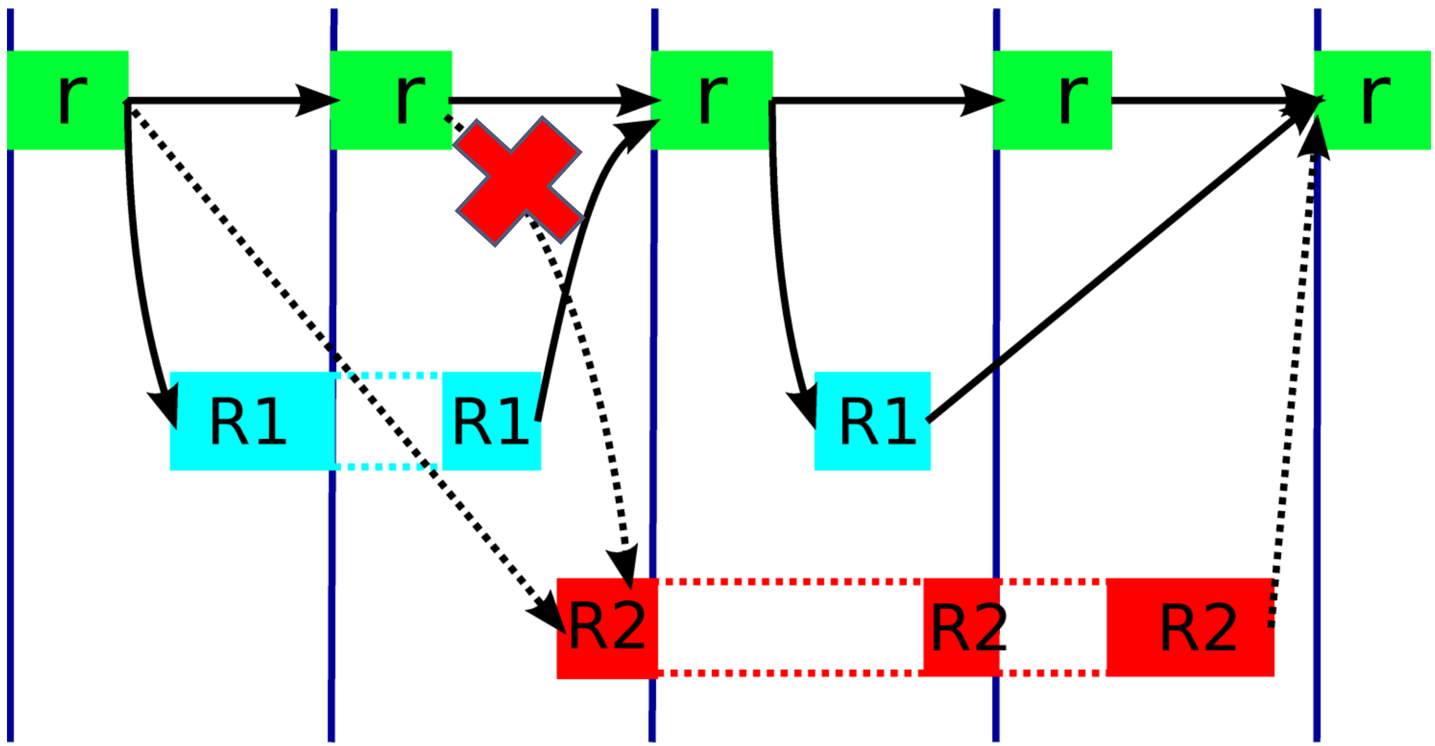
Fast-to-slow resource communication

- Communication from the fast to slow resource can occur instantly after the completion of the fast resource.
- But, communication must not happen *during* the computation of the slow resource.



Fast-to-slow resource communication

- If the slow resource gets delayed by an intermediate resource, the original data from the fast resource must not get overwritten.



General rule for communication

- From slow to fast: use delayed communication
- From fast to slow: sample and hold communication
- For modules of same speed: use delayed communication
- Implications for implementation:
  - Outputs must be scheduled as separate non-preemptible tasks.

Extensions to distributed systems

- Similar determinism is achievable using time-triggered networks.
- TDMA cycle is divided into separate communication slots.
- Order of slots will be the same as priority derived using rate-monotonic scheduling.

Industrial impact

- Glidepath (airport baggage handling system)
- Powerplants (greenhouse controller)
- Integration with nxtControl Studio (commercial IDE)
- Auckland UniServices (IDE – editor, compiler, timing analyzer, and module checker for function blocks)