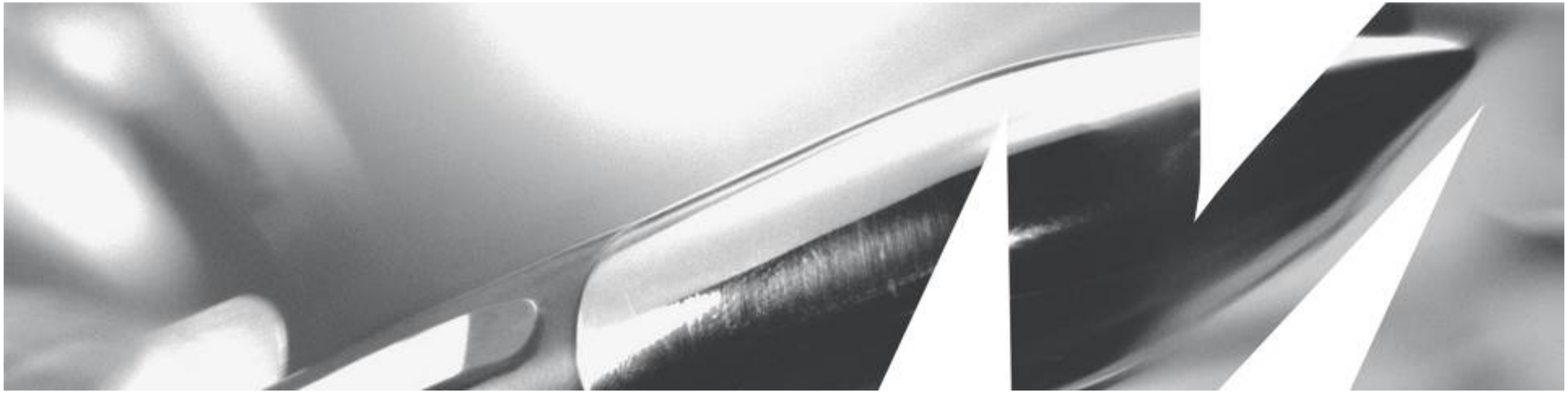

Hardware support for scheduling with Ada

Rod White

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Topics

- Context – the application domain
- Background and motivation
- Overall scheme
- What is a “Butler”
  - concept
  - hardware perspective
  - “instruction” set
- Integration with Ada
  - Zero-footprint
  - Ravenscar(-like)
- Cooperative vs. preemptive scheduling
- Results and observations
- Future developments
- Conclusions/questions

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Context – the application domain

- Real-time embedded systems
  - Constrained by
    - Available volume
    - Allowable mass
    - Power availability and dissipation
  - Harsh operational environment (temperature, vibration, shock etc)
    - COTS can not be used – few real technology choices available
- High integrity
  - Defstan 00-55/56 SIL3/4, DO-178B Level A/B
- Long lived products
  - Periodic updates – obsolescence and technology insertion
  - Evolving roles – requirements change and become more demanding over time
  - Moderate production volumes – limited opportunity for economy of scale

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Background and motivation

- Nature of the application is hard real-time
  - A large number of external stimuli which can be at a high rate (e.g. > 15 kHz)
  - Complex and wide ranging algorithmic requirements
    - e.g. control, navigation, and image/radar processing
    - Safety related/critical parts
  - Processing deadlines must be met
  - Can't afford to use all of the capacity on first delivery
    - Evolving roles require some usable processing margin
- Products can only be supplied with limited processing resources
  - The computer system is always being squeezed
    - Small volume and mass (fuel and payload are considered to be more "useful")
    - Aim to minimise cost in production

  → limited processing resources
- Need to maximise the potential capacity of processing platform
  - Dedicated hardware functions can be an efficient way of offloading tasks from the general purpose processor
  - Diverse tasks and a high rate of interrupts make scheduling decisions potentially costly
    - Can some of the scheduling "problem" be offloaded to hardware support?

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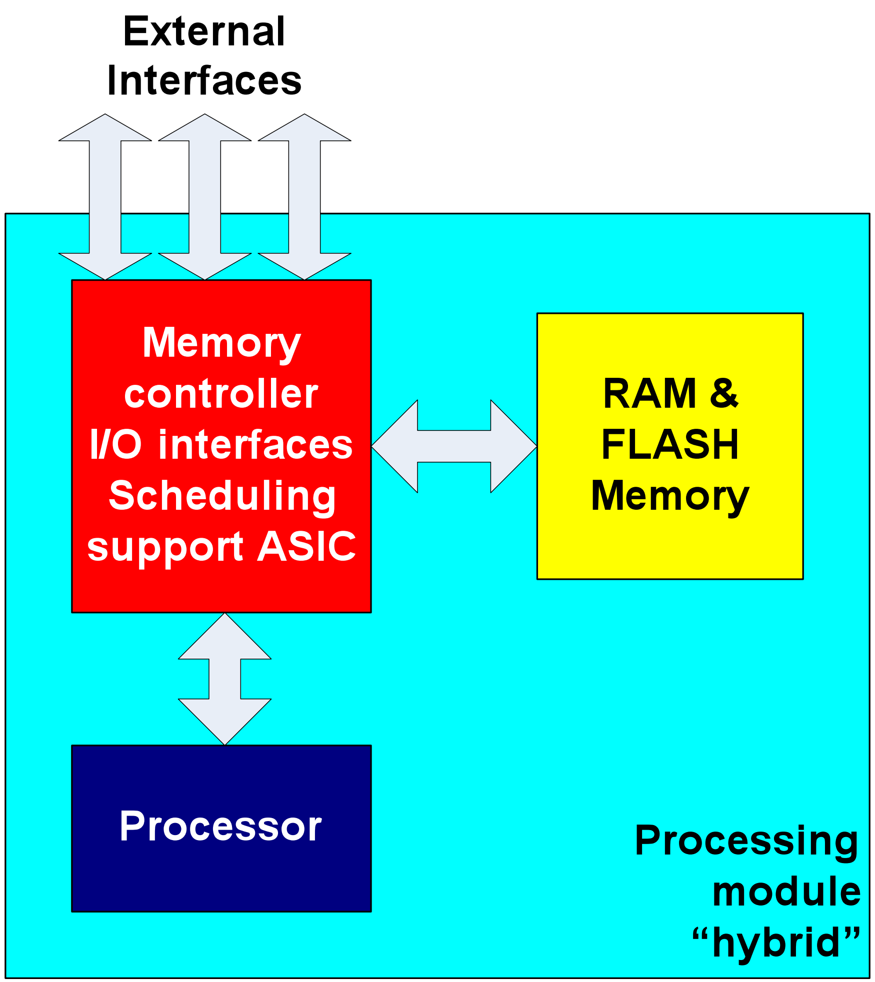
Overall scheme

- The goal is to offload the collection and organisation of information that is used to handle interrupts and schedule tasks in a unified manner
  - Minimal space and power footprint
  - Efficient coupling to the processor – low latency, simple access
  - High integrity – sufficiently deterministic for safety related applications

- COTS processors and memory parts in a custom package
  - ASIC is the glue that binds it all together



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What is a butler – the concept

- Why a Butler? Using the term in its traditional (British) sense:
  - the person who organises the smooth operation of the household whilst deferring to a higher "authority" for the important decisions
- The hardware Butler handles all of the interrupts and is the focus for all of the inter-task interactions, determining what is available to execute
  - Highly parallel hardware is good at handling a diverse range of asynchronous sources
  - The decision to execute what is suggested is taken by a simple software kernel
    - Controls and interacts with the Butler using a small number of simple instructions
- The fundamental "element" is the activity – something that may be scheduled
  - All of the other elements relate to the organisation and "control" of the activities – waiting, stimulating, delaying etc
- One idea but there have been several implementation variants depending on:
    - the platform
    - the technology
    - the production volumes
    - …
  - Range from a bespoke ASIC solution, through FPGA firmware, to software in a co-processor

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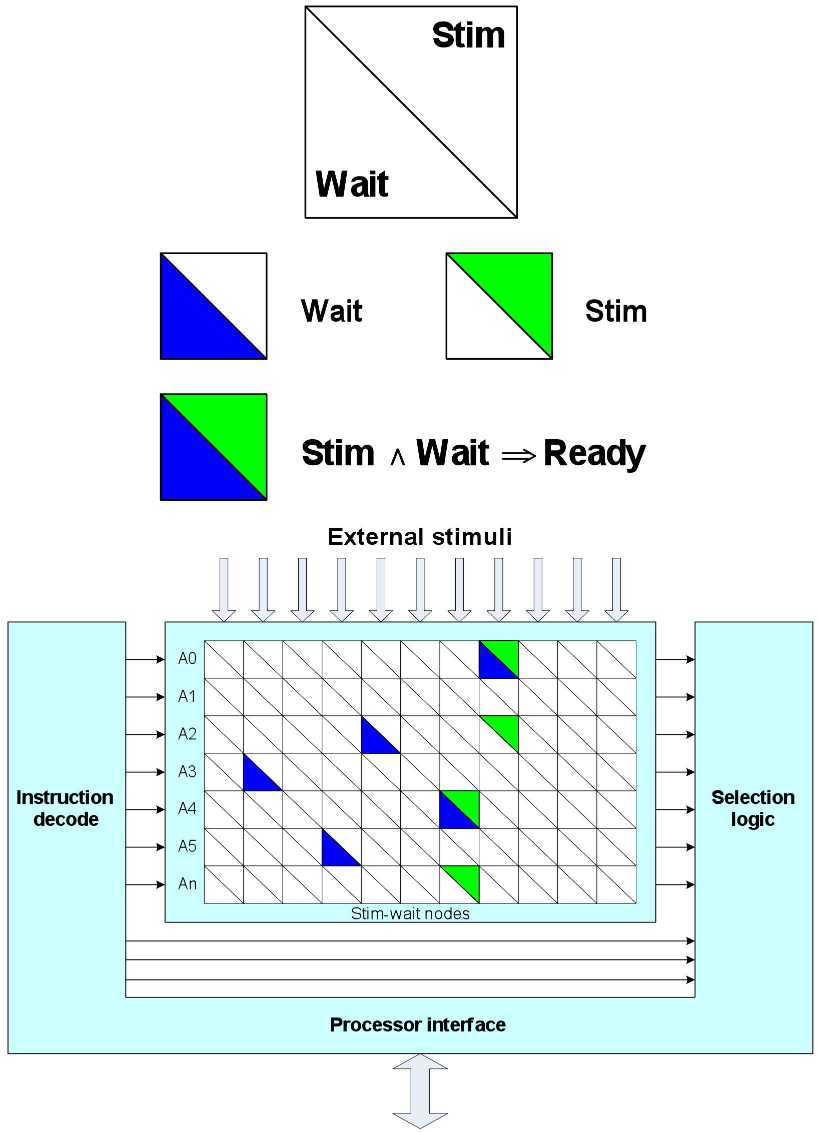
What is a “Butler” – hardware perspective

- Set of “resources” that relate to the activities and their grouping
  - The activities
  - Pollsets – groupings of activities considered to be at the same priority
  - Stim-wait nodes allowing activities to wait on, and be released by a particular event
  - A mechanism for the selection of the next activity to be executed
- Number of activities and width of the set of stim/wait nodes depends on the application
- Other (per activity) features include:
  - Watchdog timers to detect over-runs
  - Delay timers



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What is a Butler – instruction set

- Small number of instructions are use to control the activities operationally
  - `Suspend` – causes the current activity to release control and make itself schedulable, allows other ready activities at the same or higher priority to be run
  - `Wait <bit vector>` – causes the current activity to release control and set the wait bits defined in the <bit vector>. Becomes reschedulable once a corresponding stim bit has been set by an event or `stim` instruction
  - `Stim <activity, bit vector>` – sets the stim bits in the bit vector for the defined activity, if any stim matches a corresponding wait then the activity becomes schedulable (used for s/w-s/w interactions)
  - `Next_Activity <activity>` – causes the selection logic to complete the evaluation of the next activity to execute, the highest priority one is returned. [used in conjunction with the `suspend` and `wait` instructions]
  - `Curract <activity>` – return the number of the current activity
  - `AMI <boolean>` – the returned state of the boolean indicates if there is an activity of higher priority than the current one ready to be run (Anything More Important)

- … and a few other are used in their initialisation, organisation into pollsets, and general house-keeping functions

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Integration with Ada – general approach

- The general design approach follows that of a real-time network
  - Focus on threads and their interactions
  - Somewhat old-fashioned but well suited to these kinds of applications
- Implementation uses a restricted subset of the Ada language
  - Only requires a simple runtime
  - High integrity – lots of SPARK Ada (keeping the required runtime small)
- Two approaches:
  - A virtually runtime free environment (zero-footprint)
    - Butler activities are related to threads supplied by a simple kernel
    - Kernel supports a wide variety of inter-thread communication protocols
  - A runtime supporting Ravenscar-like tasking constructs
    - Butler activities are related to Ada tasks
    - … which in turn are implemented over the threads supplied by the simple kernel
    - Protected object are used for inter-task communication
- The latter has the advantages of application portability at the cost of some complexity in the kernel and runtime

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Integration with Ada – Zero-footprint runtime

- Main program creates all of the threads
  - Associates these with Butler activities
  - Organises them into pollsets

```
procedure Main is
begin
   Kernel.Initialise;  --  Ensures that the Butler is initialised
                       --  and that Activity'Last is the current activity

   Create_Thread (Activity_Ident   => Act_Id_1,
                  Pollset_Boundary => True,
                  Entry_Point      => Thread_1_Main'Access);
   Create_Thread (Activity_Ident   => Act_Id_2,
                  Pollset_Boundary => False,
                  Entry_Point      => Thread_2_Main'Access);
   Create_Thread (Activity_Ident   => Act_Id_3,
                  Pollset_Boundary => True,
                  Entry_Point      => Thread_3_Main'Access);

   --  All threads are now created but none have yet run
   --
   loop
      Yield_To_Higher; --  Allows the highest priority thread to
                       --  run, it will only return when there is
                       --  nothing else that is ready to run
   end loop;
end Main;
```

- Inside the inter-task communication protocols the Butler `Wait`, `Stim` and `Next_Activity` instructions are used to provide the desired behaviours

- Events are either handled by polling the `AMI` instruction periodically or as interrupts
  - Interrupts cause a full context switch to the thread mapped to the appropriate activity

```
if Butler.AMI then
   Butler.Suspend;
   Butler.Next_Activity (Next);
   Switch_To (Next);
end if;
```


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Integration with Ada – Ravenscar(-like) runtime

- All tasks are declared at library level in a single package
  - Simplifies activation management
  - Each task is associated with a Butler activity
  - Pollsets are are organised to group the tasks of equal priority
- Interrupts are mapped to protected procedures
  - Each “interrupt” is also associated with a particular Butler activity
- Delay until statements use dedicated timers within the Butler to stimulate the activity as necessary
- Protected entries are underpinned by the use of the `Wait` and `Stim` instructions

```
package body tasks is

    task A is
    begin
       Register;
       loop
          Perform_Application_A;
       end loop;
    end A;
…
    task C is
    begin
       Register;
       loop
          Perform_Application_C;
       end loop;
    end A;

end Tasks;
```

```
Suspend;
loop
   Next_Activity (Next);
   exit when Type_Of (Next) = Thread;
   Invoke (Next);  --  Protected operation executed in context
                   --  of the current task
end loop;
Switch_To (Next);  --  New task
```

Where the procedure `Invoke` is:

```
procedure Invoke (Act : Activity_Id) is
begin
   Entry_Points (Act).all;     -- Execute the protected procedur
   Wait (Release_Mask (Act));  -- Make the protected procedure's
                               -- activity ``sleep'' again
end Invoke;
```


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Cooperative vs. preemptive scheduling

- Cooperative – no interrupts, the possible task switching points are defined *a priori*
  - The assumed advantages of cooperative scheduling are better schedulability and lower processing overheads
  - Disadvantage in hard-real time system is ensuring an adequate response to external events
    - Application needs to be "seeded" with cooperation points
    - Not possible to automate (so far) – too many points swamp the benefits
- The support provided by the Butler makes the implementation of such a scheme efficient and simple
  - Especially the `AMI` instruction
- Two primitives used to seed application
  - `Yield` (same or higher priority)
  - `Yield_to_Higher` (strictly higher priority)

```
procedure Yield is
   Current, Next : Butler.Activity_Id;
begin
   Butler.Suspend;
   Butler.Curract (Current);
   Butler.Next_Activity (Next);
   if Next /= Current then
      Switch_To (Next);  --  Pointless switching to self..
   end if;
end Yield;
```

```
procedure Yield_To_Higher is
   Next : Butler.Activity_Id;
begin
   if Butler.AMI then
      Butler.Suspend;
      Butler.Next_Activity (Next);
      Switch_To (Next);  --  If the priority is higher
                         --  it cannot be self
   end if;
end Yield_To_Higher;
```


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Results and observations

- Using the Butler in a preemptive environment delivers only small gains
  - 1-2% (of processor capacity)
  - However not heavily loaded
- Cooperative savings were better
  - 5% (of processor capacity)
  - Again, not heavily loaded
- More recently, on a more heavily loaded system savings of ~10% have been observed, also the loading profiles are less variable with the cooperative approach
  - 10% is considered to be a very worthwhile saving

- The effort required to seed the application is not insignificant
  - Especially in the early phases of development where the rate of change is high
- Suggests that starting with a preemptive approach and migrating to a cooperative one once the solution is relatively stable is probably a good way to proceed
  - Of course tool support for seeding would make this transition unnecessary

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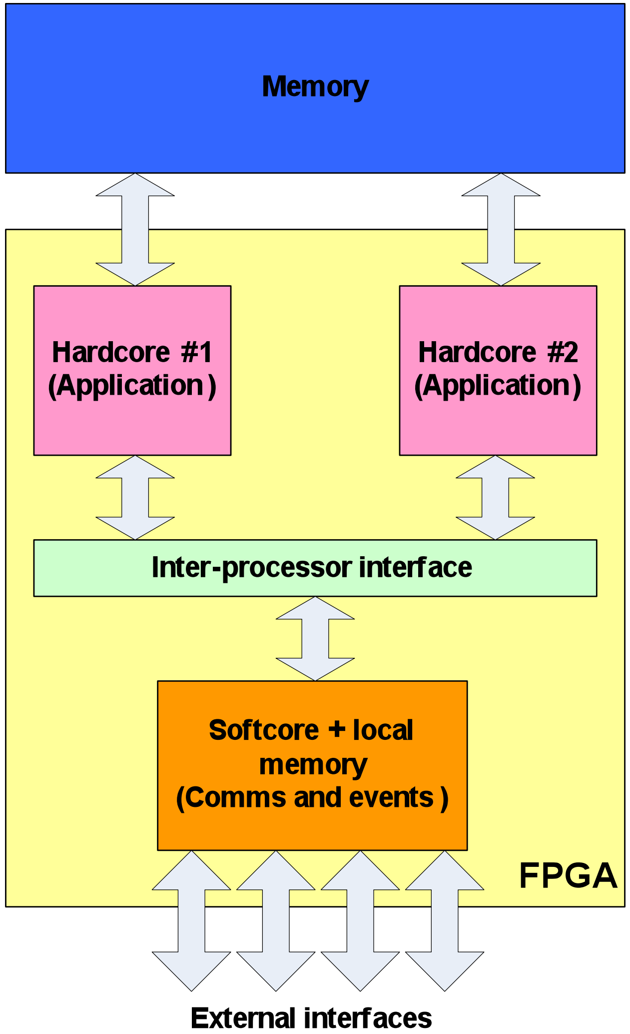
Future developments

- More powerful platforms based on FPGAs with embedded processing cores
  - Hardcores used for the application
  - Softcore use to manage interfaces and undertake the related Butler functions
  - …challenges of scheduling the application distributed across multiple cores with a single Butler device
- Integration with Ada 2005 features
  - Use of the Butler watchdog to support `Ada.Execution_Time.Timers` for overrun detection
  - Low overhead approach based on mapping the protected procedures in `Ada.Real_Time.Timing_Events` to Butler activities



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Conclusions

- Using hardware to support Ada scheduling has proven to be effective
  - Used across a number of fielded products
  - Has allowed “easy” migration as the processing platform has evolved
- Integration with the limited Ada runtime has not proven to be too problematic
  - Given the high-integrity domain there seems little point in extending support beyond Ravenscar to allow a more “complete” tasking model
  - … still some limited possibilities to explore (Ada 2005 timer related)
- Cooperative scheduling enhances the benefits
  - Larger margins and more stable execution profiles
  - Ada 2012(?) should have support for the concepts of `Yield_to_Higher` and `Yield` for non-preemptive dispatching

- However modern processors present difficult challenges
  - Very high speed
  - Multiple cores

  → … hardware scheduling coordination seems like a good idea – but how? (efficiently)

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Questions…

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