Elasticity of Workloads and Periods of Parallel Real-Time Tasks

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Why **Elastic** Parallel Real-Time Tasks?

Need to “re-size” either workloads or periods adaptively, e.g., in a 1000 degree-of-freedom simulation with **real-time** guarantees at periods down to millisecond time-scales, integrated **safely** with control, sensing, actuation.
Limitations of the Current State of the Art

- Scheduling theory and concurrency platforms for parallel real-time tasks are mainly static
  - Assume regular release intervals and workloads
  - Limited adaptation to run-time conditions (mixed criticality)

- Elastic scheduling techniques don’t address tasks with both internal parallelism and variable workloads
  - Uniprocessor scheduling of sequential variable-period tasks
  - Elastic scheduling of parallel tasks with variable periods (only)
Elastic Scheduling of Sequential Real-Time Tasks

- Buttazzo et al. introduced the elastic scheduling model
  - Increase tasks’ periods to compresses utilizations (RTSS ’98)
  - Analogous to elastic compression of physical springs

- Model was also extended to consider blocking terms for critical sections accessed via the Stack Resource Policy (IEEE ToC ’02)
Elastic Scheduling as Constrained Optimization

- Chantem et al. defined this as an optimization problem
  - Minimize a weighted sum of squares of the differences between the chosen utilization for each task and its maximum utilization
  - Subject to utilizations being between minimum and maximum values and the sum not exceeding the available utilization

\[
\text{minimize} \quad \sum_{i=1}^{n} \frac{1}{E_i} \left( U_i^{(\text{max})} - U_i \right)^2 \\
\text{such that} \quad \forall_i \left( U_i^{(\text{min})} \leq U_i \leq U_i^{(\text{max})} \right) \land U_d \geq \sum_{i=1}^{n} U_i
\]
Key Features of Parallel Real-Time DAG Tasks

- **DAG of subtasks and their dependences**
  - Predecessor nodes finish before successors start

- **Work (computation time) $C_i$**
  - Sequential execution time on 1 core

- **Span (critical path length) $L_i$**
  - Least parallel execution time on $\infty$ cores

- **Implicit deadline $D_i$ equals period $T_i$**
  - Task must finish execution before next release

\[
L_i = 1 + 4 + 15 + 11 + 1 = 32
\]
\[
C_i = L_i + 3 + 2 + 4 + 1 + 1 + 1 + 1 + 1 + 2 = 47
\]
Temporally Elastic Parallel Real-Time Tasks

- **Federated Scheduling**
  - Utilization of task $\tau_i$ is the ratio of its work $C_i$ to its period $T_i$
  - Number of (dedicated) cores $\tau_i$ needs also considers its span $L_i$
  - Schedulable if can dedicate sufficient cores for all tasks’ needs

- **Extending elastic scheduling to parallel real-time tasks**
  - Semantics of Buttazzo et al. model can be used directly
  - However, Chantem et al. model offers a more efficient approach based on Federated Scheduling of parallel real-time tasks
  - Paper submitted to a journal (currently under review)
Supporting Temporal or Computational Elasticity

- Contributions of this paper
  - Generalizations of algorithm and task model from LITES paper to support either computational or temporal elasticity
  - Empirical evaluations to gauge overheads, elastic equivalence

- Temporally elastic tasks
  - Minimum inter-arrival time (period) can be varied elastically
  - Task’s span and work are fixed

- Computationally elastic tasks
  - Sum of subtask execution times (work) can be varied elastically
  - Task’s span and period are fixed
Elastic Compression of Parallel Real-Time Tasks

\[ \text{minimize } \sum_{i=1}^{n} \frac{1}{E_i} \left( U_i^{(\text{max})} - U_i \right)^2 \]

such that \( \forall_i \left( U_i^{(\text{min})} \leq U_i \leq U_i^{(\text{max})} \right) \land m \geq \sum_{i=1}^{n} \left[ \frac{C_i - L_i}{T_i - L_i} \right] \)

- Updates optimization from Chantem et al. (RTSS 2006)
  - Uses utilization definition for parallel real-time tasks
  - Allows either period or work to be compressed elastically
  - Checks schedulability under Federated Scheduling on \( m \) cores
Concurrency Platform Design and Implementation

1. Task notifies scheduler of mode change
2. Scheduler performs reschedule, updates shared memory
3. Scheduler notifies tasks of completed reschedule
4. Tasks read shared memory, update which processors they use

Shared Memory

CPU 0
Scheduler

CPU 1
CPU 2
CPU 3
Task 1

CPU 4
CPU 5
Task 2

CPU 6
CPU 7
CPU 8
CPU 9
CPU 10
Task 3
Adaptation Mechanism Overheads are Acceptable

- Task notification via POSIX RT signals
  - Ranged from 11.23 µsec to 110.03 µsec, often around 18 µsec
- Thread priority change (and possible core migration)
  - Ranged from 2.67 µsec to 76.77 µsec, often around 30 µsec
Evaluation Experiments Demonstrate Equivalence

- Experiments compared varying a task’s $D_i$ vs. its $C_i$
- Comparable tasks compressed to the same utilization
  » Temporally vs. computationally elastic tasks reached same point
Conclusions and Future Work

- Contributions of this research
  - Scheduling of \textit{computationally elastic} parallel real-time tasks
  - Equivalence of utilization compression when tasks are computationally vs. temporally elastic
  - Efficient implementation using OpenMP atop Linux

- Future research directions
  - Allowing a task’s span and work and period to change at once
    - Schedulability analysis, optimization problem for elastic compression
    - Thread prioritization, core bindings, synchronization, notification
  - Elastic compression of tasks with only discrete utilization values
Thanks!

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In general, a parallel task requires \( \frac{C_i - L_i}{D_i - L_i} = A_i + \varepsilon_i \) (\( A_i \) is integer, \( 0 \leq \varepsilon_i < 1 \)) CPUs to guarantee completion.

Federated scheduling allocates

\[
\left\lfloor \frac{C_i - L_i}{D_i - L_i} \right\rfloor = \begin{cases} 
A_i & \varepsilon_i = 0 \\
1 + \frac{A_i}{A_i} & \varepsilon_i > 0
\end{cases}
\]

CPUs

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In general a parallel task requires \( \frac{C_i - L_i}{D_i - L_i} = A_i + \varepsilon_i \) (\( A_i \) is integer, \( 0 \leq \varepsilon_i < 1 \)) CPUs to guarantee completion.

Semi-federated scheduling first allocates \( \left\lfloor \frac{C_i - L_i}{D_i - L_i} \right\rfloor = A_i \) CPUs

- Remaining \( \varepsilon_i \) scheduled as sequential tasks on remaining CPUs (e.g. via partitioned EDF)

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**Backup Slide: Semi-Federated Scheduling**