Online Teaching

- Lectures are delivered live over Zoom at class time.
  - Also recorded for offline viewing after class.
  - Time to become a Zoom master 😊

- Project demos will be done live in class (preferred if possible), or through prerecorded videos to be played in class.
  - Prepare a prerecorded video as backup even if you plan a live demo.
  - Send your video and slides to Ruixuan by 11am on demo day.
    - Use YouTube or WU Box.
  - Feel free to adapt your projects.

- Your feedbacks are welcome!
  - We will work together to optimize online learning.
Coming Up

- Demo II: 3/31 (next Tuesday)
  - 10 min per team.
  - Email Ruixuan your slides and videos by 11am.
  - Gearing up for the final demo.

- Critique #3: 4/7
Parallel Real-Time Systems for Latency-Critical Applications

Chenyang Lu
CSE 520S
Cyber-Physical Systems (CPS)

Since the application interacts with the physical world, its computation must be completed under a time constraint.

NSF Cyber-Physical Systems Program Solicitation:
CPS are built from, and depend upon, the seamless integration of computational algorithms and physical components.

^ Robert L. and Terry L. Bowen Large Scale Structures Laboratory at Purdue University
Cyber-Physical Systems (CPS)
Interactive Cloud Services (ICS)

Need to respond within 100ms for users to find responsive*.

* Jeff Dean et al. (Google) "The tail at scale." Communications of the ACM 56.2 (2013)
Interactive Cloud Services (ICS)

Need to respond within 100ms for users to find responsive*. E.g., web search, online gaming, stock trading etc.

* Jeff Dean et al. (Google) "The tail at scale." Communications of the ACM 56.2 (2013)
Real-Time Systems

The performance of the systems depends not only upon their functional aspects, but also upon their temporal aspects.

Real-time performance:
1) Provide hard guarantee of meeting jobs’ deadlines (e.g. CPS)
2) Optimize latency-related objectives for jobs (e.g. ICS)
New Generation of Real-Time Systems

Characteristics:

- New classes of applications with complex functionalities
- Increasing computational demand of each application
- Consolidating multiple applications onto a shared platform
- Rapid increase in the number of cores per chip

**Demand**: leverage parallelism within the applications, to improve real-time performance and system efficiency
Parallelism Improves RTHS Accuracy

A RTHS simulates a nine stories building, with first story damper

- Previously, sequential processing power limits a rate of 575Hz
- Parallel execution now allows a rate of 3000Hz
Parallelism Improves RTHS Accuracy

A RTHS simulates a nine stories building, with first story damper

- Previously, sequential processing power limits a rate of 575Hz
- Parallel execution now allows a rate of 3000Hz

- Reduction in error for acceleration and displacement
- Parallelism increases accuracy via faster actuation and sensing
State of the Art

- **Real-time systems**
  - Schedule multiple sequential jobs on a single core
  - Schedule multiple sequential jobs on multiple cores

- **Parallel runtime systems**
  - Schedule a single parallel job
  - Schedule multiple parallel jobs to optimize fairness or throughput

- New: parallel real-time systems for latency-critical applications
## Challenges for Parallel Real-Time Systems

<table>
<thead>
<tr>
<th>Theory</th>
<th>Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>How to provide real-time performance for multiple parallel jobs?</td>
<td>How to build parallel real-time systems that are efficient and scalable?</td>
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</tbody>
</table>

*Develop provably good and practically efficient real-time systems for parallel applications*
Parallel Job – Directed Acyclic Graph (DAG)

Naturally captures programs generated by parallel languages such as Cilk Plus, Thread Building Blocks and OpenMP.

**Node**: sequential computation

**Edge**: dependence between nodes

**Work** $C_i$: execution time on one core
Parallel Job – Directed Acyclic Graph (DAG)

Naturally captures programs generated by parallel languages such as Cilk Plus, Thread Building Blocks and OpenMP.

**Node**: sequential computation

**Edge**: dependence between nodes

**Work** $C_i$: execution time on one core

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

$C_i = 18$

$L_i = 9$
Parallel Real-Time Task Model

A task periodically releases DAG jobs with deadlines.

Task 1: Deadline $D_i = 12$

Job 1

Job 2

Deadline $D_i = \text{period}$
Parallel Real-Time Task Model

A task periodically releases DAG jobs with deadlines.

Deadline $D_i = \text{period}$

Worst-case span $L_i$

Worst-case work $C_i$
Parallel Real-Time Task Model

A task periodically releases DAG jobs with deadlines. Multiple tasks scheduled on multi-core system.

Goal of system: guarantee all tasks can meet all their deadlines.
Federated Scheduling

For parallel tasks, FS has the best bound in term of schedulability.

FS assigns $n_i$ dedicated cores to each parallel task

$$n_i = \left\lfloor \frac{C_i - L_i}{D_i - L_i} \right\rfloor$$

- deadline $D_i = \text{period}$
- worst-case span $L_i$
- worst-case work $C_i$

$n_i$ – the minimum #cores needed for a task to meet its deadline
Empirical Comparison

FS platform

- Middleware platform providing FS service in Linux
- Work with GNU OpenMP runtime system
- Run OpenMP programs with minimum modification

Compare with our Global Earliest Deadline First platform (GEDF)

- Linux kernel 3.10.5 with LITMUS$^{RT}$ patch
- 16-core machine with 2 Intel Xeon E5-2687W processors
- GCC version 4.6.3. with OpenMP
- Each data point has 100 task sets
- Each task is randomly generated with parallel for-loops
Empirical Comparison

- Linux kernel 3.10.5 with LITMUS$^{RT}$ patch
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- Each task is randomly generated with parallel for-loops

Fraction of Task Sets Missing Deadlines

\[
\text{normalized system utilization} = \frac{\sum_{i} \frac{C_i}{D_i}}{m}
\]

m: #cores

Better performance

Harder to schedule

Normalized System Utilization

GEDF

FS
Empirical Comparison

- Linux kernel 3.10.5 with LITMUS$^\text{RT}$ patch
- 16-core machine with 2 Intel Xeon E5-2687W processors
- GCC version 4.6.3. with OpenMP
- Each data point has 100 task sets
- Each task is randomly generated with parallel for-loops

**Better performance**

52% tasks sets become schedulable under FS

Fraction of Task Sets Missing Deadlines

Normalized System Utilization

Harder to schedule
Summary of Federated Scheduling

For parallel real-time systems with guarantee of meeting deadlines, Federated Scheduling has:

- the best theoretical bound in term of schedulability
- better empirical performance compared to GEDF

RTHS has used FS platform to improve system performance

The End?
Issue with the Classic System Model

The classic system model uses the worst-case work for analysis. The worst-case work is significantly larger than the average work. The average system utilization is very low in practice. To guarantee that all tasks can meet all deadlines at all cases.

Most cases
Work 10ms

Very rare cases
Work 100ms
Mixed-Criticality in Cars

Features with different criticality levels:

- Safety-critical features
- Infotainment features

Display system with Car Navigation and Infotainment
**Toy Example of MC System**

**High criticality task** deadline 40ms

- Most-case work 10ms
- Most cases

**Low criticality task** deadline 40ms

- Most-case work 80ms
Most-Case vs. Worst-Case Scenarios

Single-criticality systems: need to model **worst-case scenario**

**Most cases**
- core 1: 10ms
- core 2: 80ms
- core 3
- core 4
- core 5

**Very rare cases**
- core 1
- core 2
- core 3: 100ms
- core 4
- core 5: 80ms
MC Model Improves Resource Efficiency

**Mixed-criticality system:**

Provide different levels of real-time guarantees

---

**Most cases:**

- guarantee that both high and low-criticality tasks meet deadlines

**Very rare cases:**

- only guarantee that high-criticality tasks meet deadlines
MCFS Algorithm at a High Level

For each parallel task, calculate and assign:

(1) dedicated cores in typical-state
MCFS Algorithm at a High Level

For each *parallel* task, calculate and assign:

1. dedicated cores in typical-state
2. dedicated cores in critical-state

**Typical-state (most cases)**

- High-Criticality
- Low-Criticality

**Critical-state (rare case)**

- High-Criticality
- High-Criticality

$m$ cores
MCFS Algorithm at a High Level

For each parallel task, calculate and assign:
(0) virtual deadline
(1) dedicated cores in typical state
(2) dedicated cores in critical state

If a job has not completed by its virtual deadline, it transitions to critical-state.

$m$ cores
MCFS Algorithm at a High Level

**MCFS jointly assigns virtual deadlines and cores to maximize utilization while guaranteeing task deadlines.**

1. Dedicated cores in typical state
2. Dedicated cores in critical state

If a job has not completed by its virtual deadline, it transitions to critical-state.

$m$ cores
MCFS Implementation

In typical-state, MCFS assigns dedicated cores to all tasks.

High-Criticality

Low-Criticality

High-Criticality

OpenMP Runtime

OpenMP Runtime

OpenMP Runtime

HC thread

LC thread

cores

Linux

MCFS
MCFS Implementation

In critical-state, MCFS increases cores assigned to high-crit. tasks.

High-Criticality

Low-Criticality

High-Criticality

OpenMP Runtime

OpenMP Runtime

OpenMP Runtime

HC thread

cores

more HC thread

MCFS

Linux
MCFS Implementation

Put additional HC threads to sleep on higher priority

High-Criticality

Low-Criticality

High-Criticality

OpenMP Runtime

OpenMP Runtime

OpenMP Runtime

HC thread

MCFS

Linux

cores

Sleeping HC thread

LC thread
Empirical Evaluations

Fraction of tasks with no deadline miss (per criticality)

- Linux with RT_PREEMPT patch version 4.1.7-rt8
- 16-core machine with 2 Intel Xeon E5-2687W processors
- GCC version 4.6.3. with OpenMP
- Each data point has 100 task sets
- Each task is randomly generated with parallel for-loops
Empirical Evaluations

Fraction of tasks with no deadline miss (per criticality)

- Linux with RT_PREEMPT patch version 4.1.7-rt8
- 16-core machine with 2 Intel Xeon E5-2687W processors
- GCC version 4.6.3. with OpenMP
- Each data point has 100 task sets
- Each task is randomly generated with parallel for-loops
Issue with the Analysis of Parallel Jobs

Centralized greedy scheduler

- Threads get work (nodes) from a centralized queue

Implicit assumption of parallel real-time scheduling theory: when a thread (core) is allowed to work on a job, it must be able to find the available nodes *immediately* (within bounded time).
Issue with the Analysis of Parallel Jobs

Centralized greedy scheduler
- Threads get work (nodes) from a centralized queue

Randomized work-stealing
- Threads usually get work locally;
- If local queue is empty, it steals randomly from another queue

<table>
<thead>
<tr>
<th>Predictable</th>
<th>Bounded worst-case</th>
<th>Unbounded worst-case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalable</td>
<td>Does not scale well</td>
<td>Good scalability</td>
</tr>
</tbody>
</table>
Empirical Comparisons

Randomized work-stealing for *large-scale soft* real-time system?

- FS Implementations (with scheduling overheads incorporated):
  - FSCG with centralized greedy scheduler in GNU OpenMP
  - FSWS with randomized work-stealing in GNU Cilk Plus

- Linux with RT_PREEMPT patch version r14
- 32-core machine with 4 Intel Xeon E5-4620 processors
- GCC 5.1 with OpenMP, Cilk Plus
- Each data point is one task set
- Each task is randomly generated using benchmark program Heat
Empirical Comparisons

Randomized work-stealing for *large-scale soft* real-time system?

FSCG and FSWS
- Same computation
- Same resources
- Only difference: *internal scheduling* of parallel tasks
Empirical Comparisons

Randomized work-stealing for *large-scale soft* real-time system?

FSCG and FSWS

- Same computation
- Same resources

- Only difference: *internal scheduling* of parallel tasks
Empirical Comparisons

Randomized work-stealing for *large-scale soft* real-time system?

The benefit of scalability in work-stealing dominates the increased variation in parallel execution times.

FSCG and FSWS

- Same computation
- Same resources
- Only difference: *internal scheduling* of parallel tasks
Outline

- Contributions

- System Guaranteed to Meet Deadlines for Parallel Jobs in CPS

- System Optimized to Meet Target Latency for ICS

- Future Work
System for Interactive Cloud Services

**Online system:** do not know when jobs arrive

**Objective:** optimize latency-related objectives for the service
  e.g., average latency, max latency
System for Interactive Cloud Services

**Online system:** do not know when jobs arrive

**Objective:**

maximize the number of jobs that meet a target latency $T$
Workload Distribution Has a Long Tail

- Large jobs must run in parallel to meet target latency
- Always run large jobs in full parallelism?

Bing search workload

Target latency

Job Sequential Execution Time (ms) (work)
Parallelize Large Jobs According to Load

**Tail-Control Strategy:** when load is low, run all jobs in parallel; when load is high, run large jobs sequentially.

Latency = Processing Time + Waiting time

**At low load:**
processing time dominates latency

**At high load:**
waiting time dominates latency
The Inner Workings of Tail-Control

We implement tail-control algorithm in the runtime system of Intel Thread Building Block and evaluate on Bing search workload.
The Inner Workings of Tail-Control

We implement tail-control algorithm in the runtime system of Intel Thread Building Block and evaluate on Bing search workload.
The Inner Workings of Tail-Control

We implement tail-control algorithm in the runtime system of Intel Thread Building Block and evaluate on Bing search workload.

![Graph showing request latency over time for default work-stealing and tail-control algorithms, with target latency indicated.](image-url)
The Inner Workings of Tail-Control

We implement tail-control algorithm in the runtime system of Intel Thread Building Block and evaluate on Bing search workload.
Conclusion

Exploit the untapped efficiency in parallel computing platforms and drastically improve the real-time performance of applications.

- System Guaranteed to Meet Deadlines for CPS
  - Develop provably good schedulers for parallel applications
  - Incorporate real-time scheduling into parallel runtime system
  - Improve system efficiency by dealing with uncertainty in jobs
  - Address system scalability issue due to internal scheduling

- System Optimized to Meet Target Latency for ICS
  - Design and implement strategy to optimize real-time performance
References

- J. Li, D. Ferry, S. Ahuja, K. Agrawal, C. Gill and C. Lu, Mixed-Criticality Federated Scheduling for Parallel Real-Time Tasks, RTAS’16. Outstanding Paper Award