

# Challenges for Time-Critical Transportation Cyber-Physical Systems

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## Society and Automobiles

- More than 1 million people die every year in automotive accidents globally
  - Largest global killer of ages 10-24
  - Tens of millions of injuries
  - Global annual cost of road injuries in medical care, disability and property damage is \$518 billion.
- Traffic delays are expensive.
  - The average US driver spends a week stuck in traffic per year.
  - In the EU, € 80 billion wasted per year due to traffic congestion.
- Loss of independence and self-esteem of senior and disabled citizens

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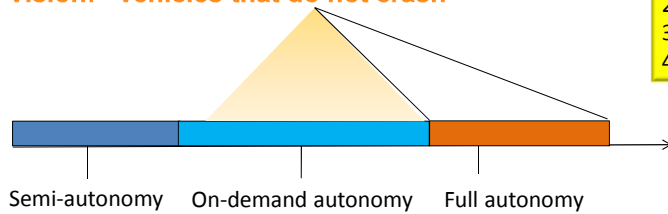
# Transportation Vision

## Grand Challenge: Zero fatalities

- Fewer accidents and injuries
- Higher throughput and much lower delays
- Smart traffic infrastructure
- Real-time information delivery and system-level feedback



Vision: "Vehicles that do not crash"



### Metrics

1. Safety
2. Throughput
3. Environmental Impact
4. Quality of Life

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# What must Intelligent Vehicles do?

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## Sensors

**Velodyne multi-plane lidar**  
3° x 26° FOV, 60m

**Continental ISF 172 lidar**  
14°, 150m

**Ma/Com proximity radar**  
80°, 27m

**Continental ARS 300 radar**  
60/17°, 60/200m

**Applanix GPS/INS**

**High dynamic range camera**  
90° FOV

**SICK Scanning Lidar**  
90/180° FOV, 40m

**Vehicle Tracking 1**

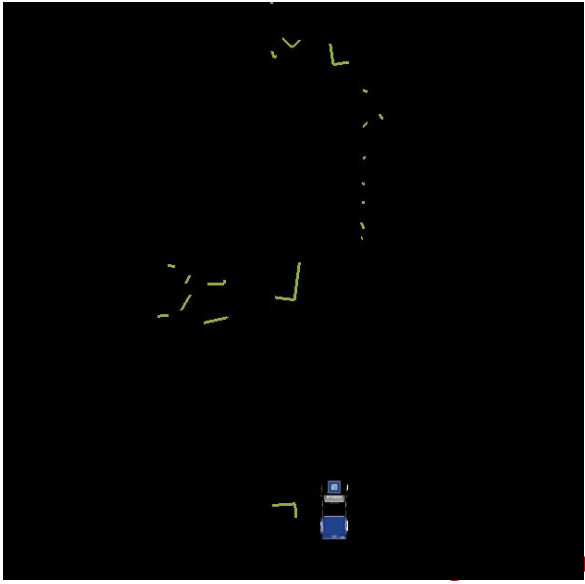
## Vehicle Tracking

- Raw Data

**Raw Data (13 Sensors)**  
15.4 fps

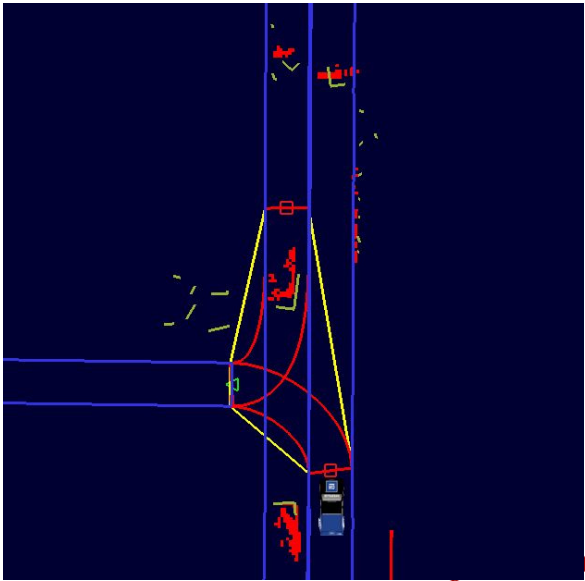
### Vehicle Tracking

- Raw Data
- Feature Extraction

A top-down view of a vehicle on a road. The vehicle is a small blue car at the bottom center. The road is dark, and there are several green dashed lines scattered around, representing detected features or points of interest. The lines are mostly in the upper half of the image, forming a large, irregular shape.

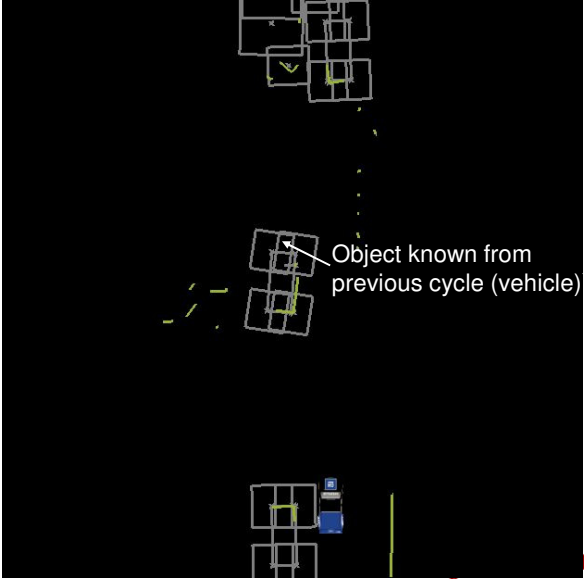
### Vehicle Tracking

- Raw Data
- Feature Extraction
- Measurement Validation

A top-down view of a vehicle on a road. The vehicle is a small blue car at the bottom center. The road is dark, and there are several red and yellow lines scattered around, representing measurement validation. The lines are mostly in the upper half of the image, forming a large, irregular shape. There are also some blue lines and a red square on the road.

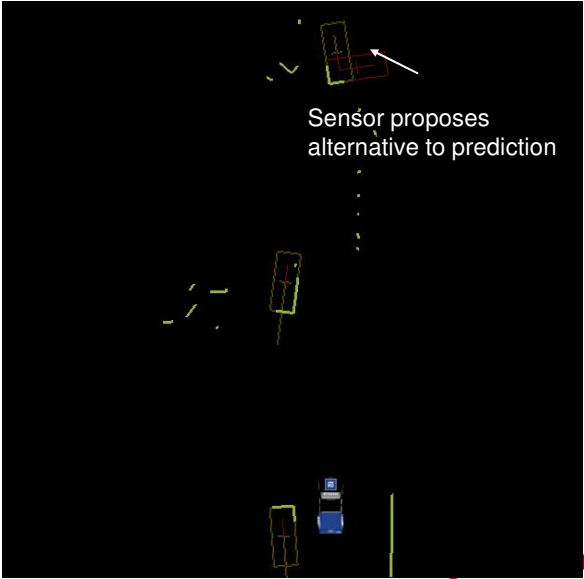
### Vehicle Tracking

- Raw Data
- Feature Extraction
- Measurement Validation
- **Data Association**



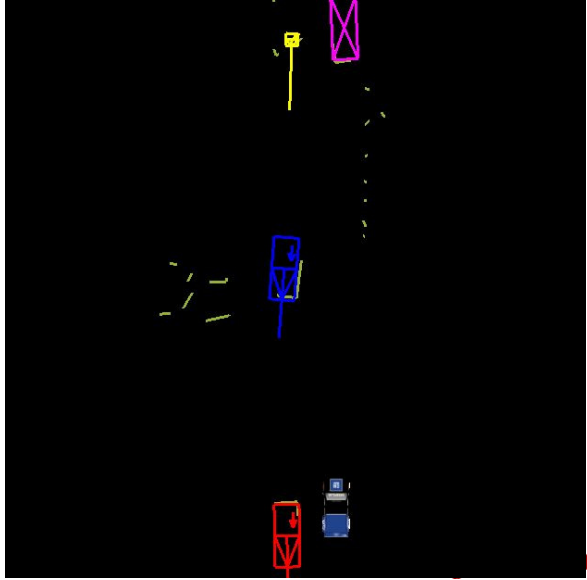
### Vehicle Tracking

- Raw Data
- Feature Extraction
- Measurement Validation
- Data Association
- **Proposals & Observation**



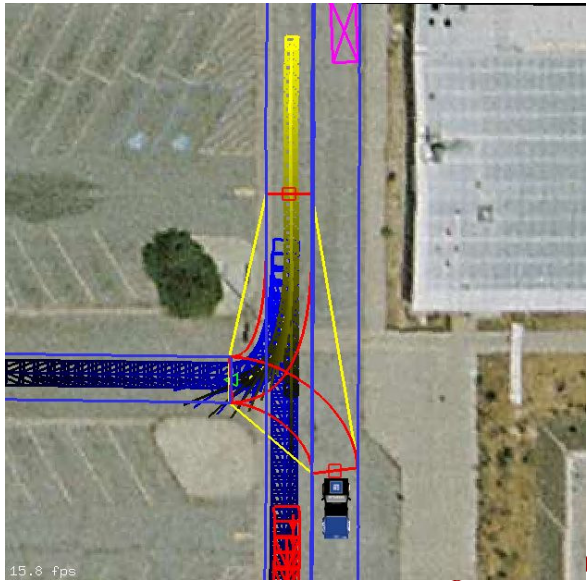
### Vehicle Tracking

- Raw Data
- Feature Extraction
- Measurement Validation
- Data Association
- Proposals & Observation
- **Model Voting**
- **Estimation**
- **Statistics**

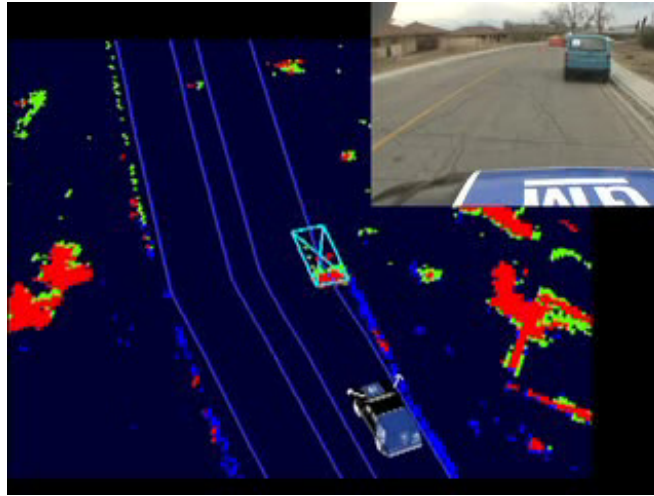


### Vehicle Tracking

- Raw Data
- Feature Extraction
- Measurement Validation
- Data Association
- Proposals & Observation
- Model Voting
- Estimation
- Statistics
- **Prediction**

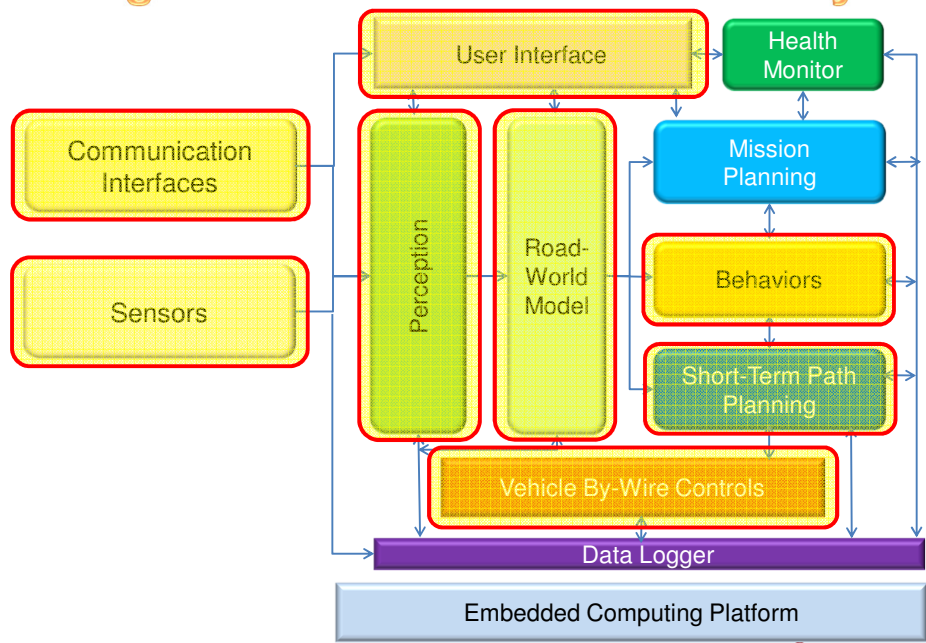


## Operating in the Real World



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## Logical Architecture for Autonomy



# No Scarcity of Problems

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## Sensor Fusion & Perception

**Tracking cars at intersections**

**Tracking cars on roadways**

**Moving Obstacles**

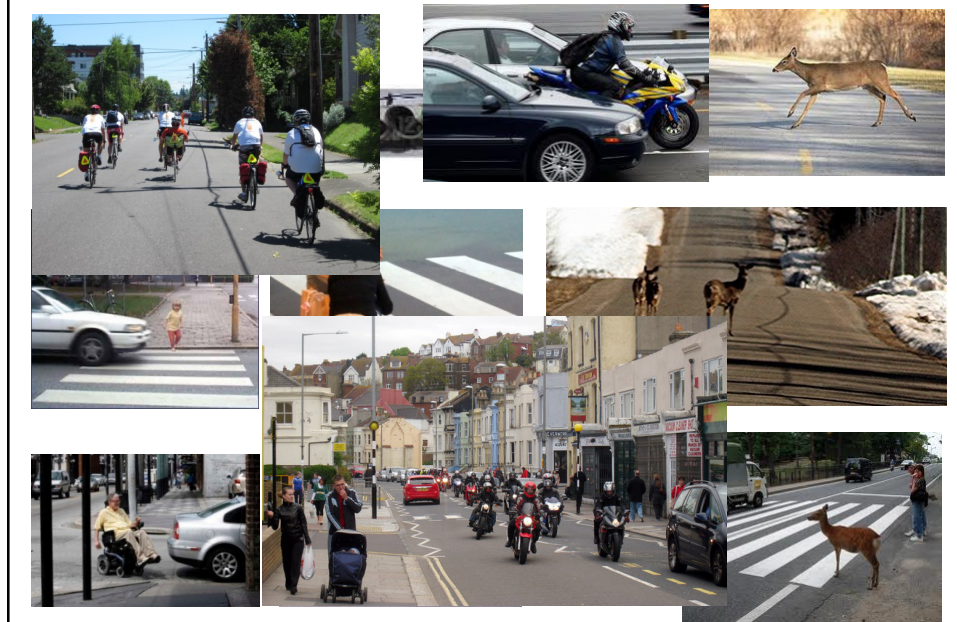
**Static Obstacles**



## Encounters of the *Daily Kind*



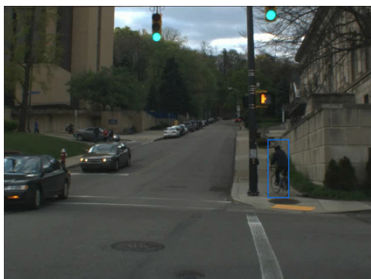
## More Encounters



## Solutions?

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## Pedestrian & Bicycle Detection



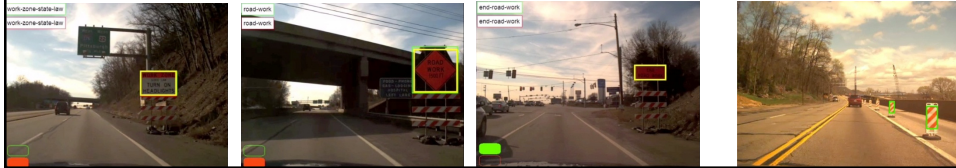
Dr. Paul Rybski

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## Workzone Detection



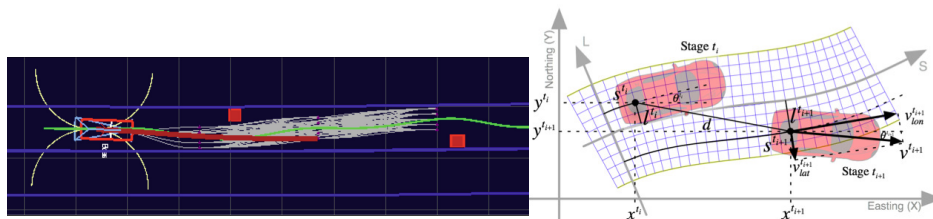
Prof. David Wettergreen



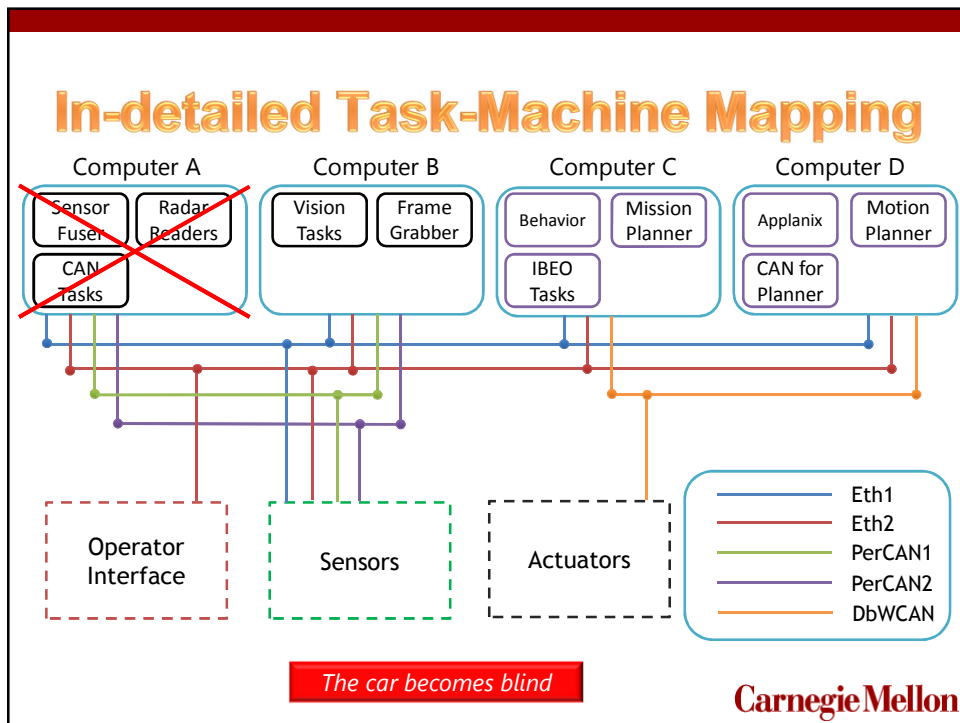
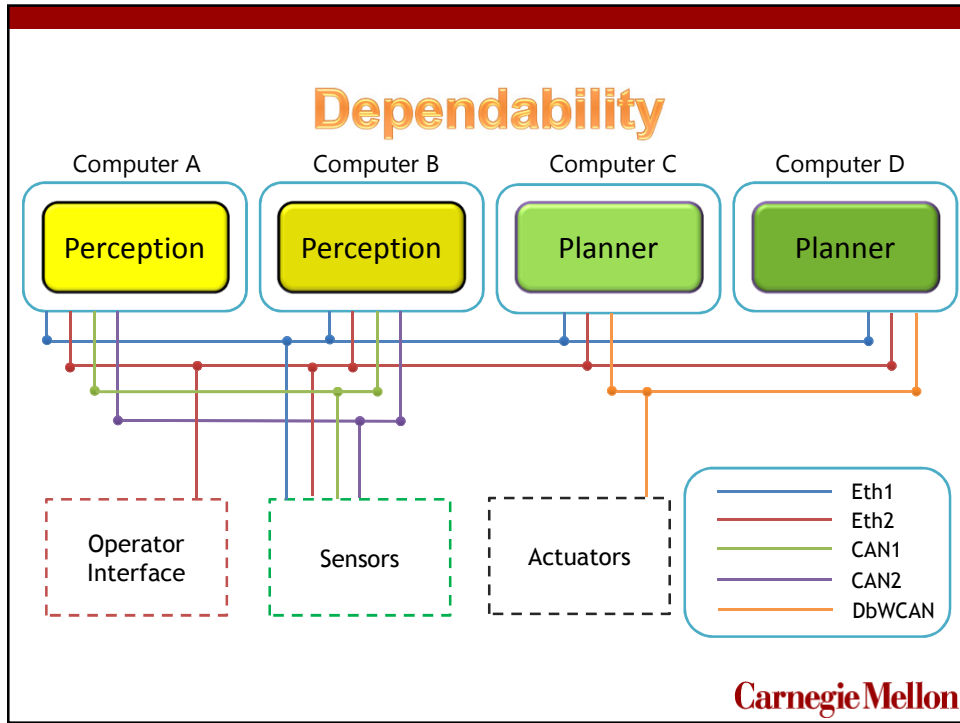
## Planning

Dr. John Dolan

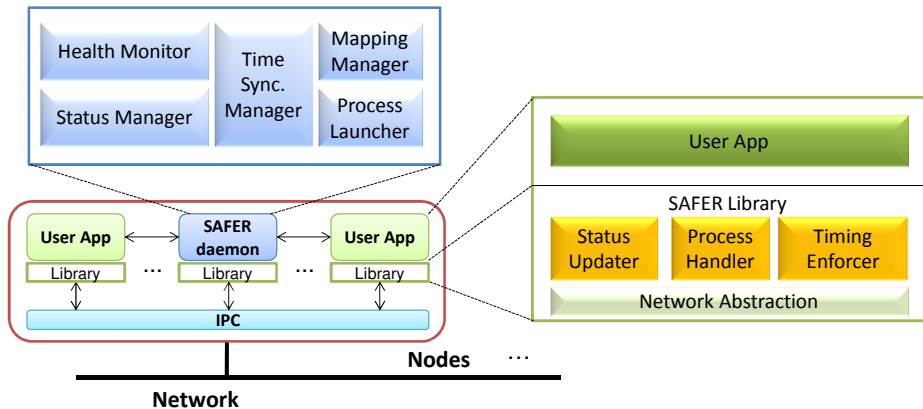
- Need a **planner for avoiding obstacles, over-steering/under-steering on curves, and roadside structures.**
- Computationally efficient (CPU) high-performance planner



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# Real-Time Dependability Architecture



How/what do we gracefully degrade?  
 How do we re-deploy existing resources?

# Coordination and Cooperation

## V2V Protocols

With Traffic Lights

Using V2V

## If all vehicles could communicate...

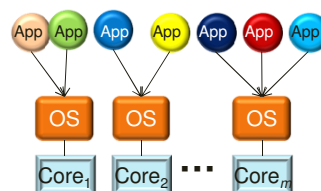
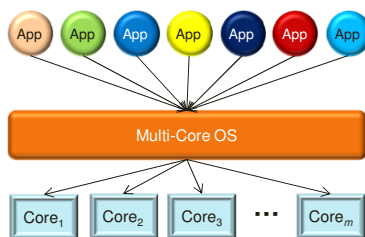
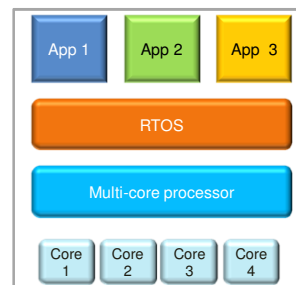
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## Challenges for Time-Critical Cyber-Physical Systems

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## Real-time Processing Challenges

- Worst-case execution time? May not be characterizable at all.
- Resource allocation and multicore allocation on multiple cores
- Parallel processing of multiple real-time tasks
- Coordination of hardware accelerators and CPUs



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## Cores, Cores, Everywhere

The diagram illustrates a multi-core system architecture. It features a central grid of cores. Surrounding the grid are four Memory Controllers (two at the top and two at the bottom). On the left side, there are two MICA blocks, each containing UART x2, USB x2, JTAG, PC, and SPI interfaces. Below these are 3 PCIe interfaces and Flexible I/O. On the right side, there is a Network I/O block with mPIPE, offering configurations of Eight 10Gb, 32 1Gb, or Two 40Gb. Bidirectional arrows indicate data flow between the cores and the external components.

### Issues

- Allocation
- Synchronization
- Communication
- Shared physical resources
- Timing predictability?
- Adaptation

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## Impact of Inter-Core Cache Interference

The diagram shows a 4-core system. Each core (C1, C2, C3, C4) has its own private L1 and L2 caches. All four cores share a common L3 cache. A large green arrow points from this diagram towards the right, indicating the impact of cache interference.

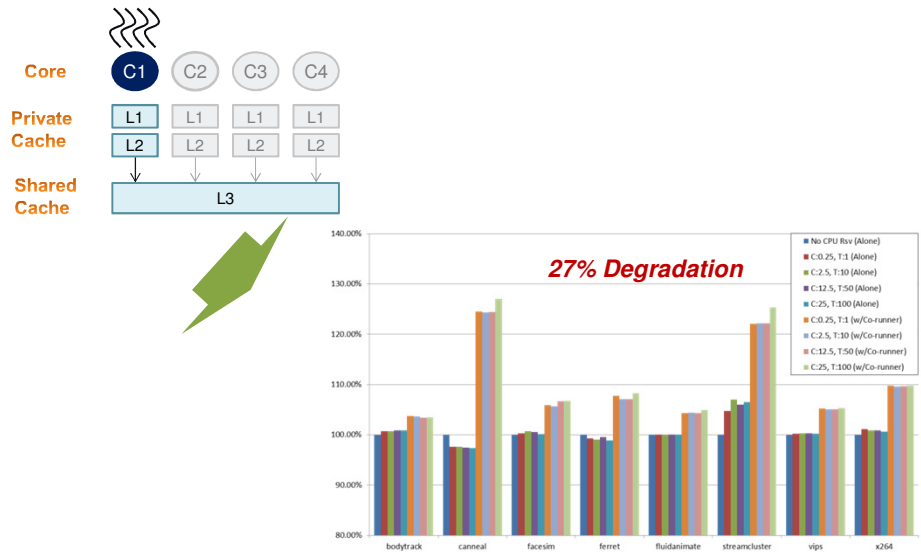
*PARSEC benchmarks*

The bar chart displays execution time as a percentage of the 1-core baseline for various benchmarks. The y-axis is 'Execution Time' (80% to 150%). The x-axis lists benchmarks: blackholes, bodytrack, canonical, dbshop, facsim, ferret, fullanemite, freemove, mvtface, streamcluster, swaption, vips, and x264. A legend indicates four series: 1core(alone) (blue), 2cores (red), 3cores (green), and 4cores (purple). A red text overlay states: **43% Degradation (C:2.5ms, T:10ms)**.

Benchmark	1core(alone)	2cores	3cores	4cores
blackholes	100	100	100	100
bodytrack	100	100	100	100
canonical	100	120	130	140
dbshop	100	100	100	100
facsim	100	100	100	100
ferret	100	100	100	100
fullanemite	100	100	100	100
freemove	100	100	100	100
mvtface	100	100	100	100
streamcluster	100	120	130	140
swaption	100	100	100	100
vips	100	100	100	100
x264	100	100	100	100



## Impact of Intra-core Interference

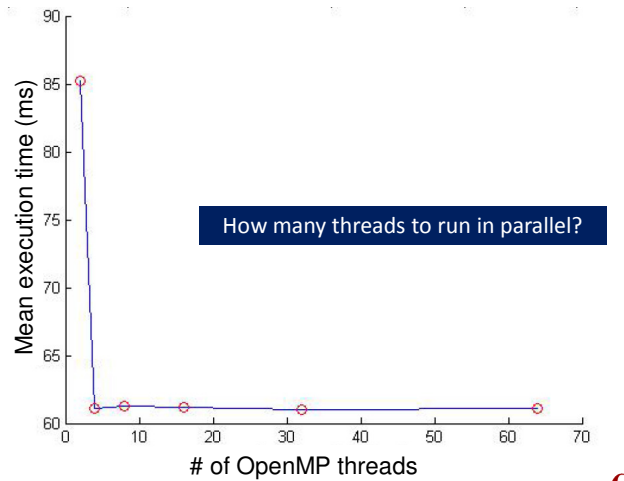


## Real-Time Parallel Processing

- **OpenMP:**
  - Parallel processing on multicores and multiprocessors
- **CUDA:**
  - for nVidia GPUs

# OpenMP

Performance comparison for path cost calculation as a function of the # of OpenMP threads



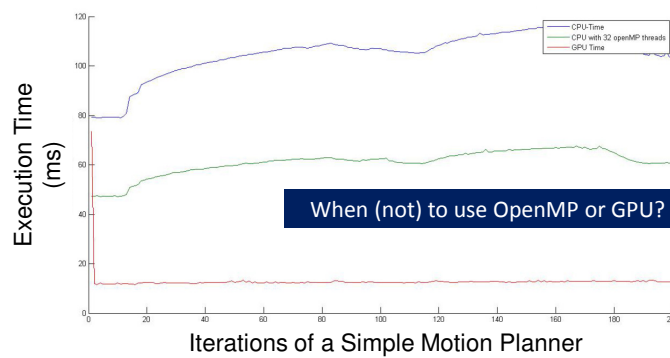
On a 4-core platform

How many threads to run in parallel?

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# CUDA vs OpenMP

Comparison of performance for path cost calculation among only CPU, OpenMP and only GPU

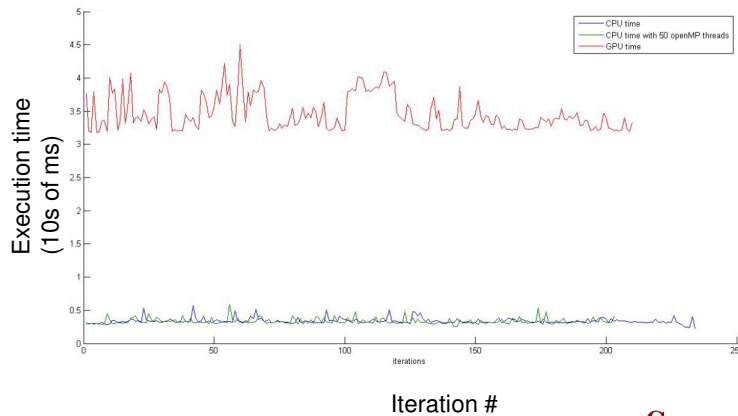


When (not) to use OpenMP or GPU?

- GPU gives a 10x improvement over the original CPU code
- GPU gives a 5x improvement over the optimal OpenMP code

## GPU Parallelism does not always pay

Performance comparison for path velocity calculation with little parallelism



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## Multiple QoS Dimensions

- Timeliness
- Dependability
- Secure V2V and V2I communications
  - 10Hz Basic Safety Messages
  - Each message is likely to be encrypted and signed
  - About 750 messages per second must be authenticated and acted upon on a regular and timely basis
  - New hardware platforms required
  - New solutions required

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## Humans in the Loop

- Real-time monitoring of the driver's status
- When to take over control from the human driver?
  - Transition of control
  - Additional workloads



## Mode Changes

- What happens **when GPS fails** (or is corrupted)?
  - What other mechanisms can kick in?
  - How to reallocate?
  - How to meet the new timing constraints during transition?
- **Graceful degradation**
  - Actuator adaptation
  - Can differential braking be used to steer in case of steering control failure?
  - Cut down fuel in case of brake failure?

## Challenges Revisited

- **Real-time processing, communication and coordination challenges**
  - Resource allocation and multicore allocation on multiple cores
  - Parallel processing of multiple real-time tasks
  - Coordination of hardware accelerators and CPUs
  - Widely varying worst-case execution times (potentially even unbounded)
- **Multiple QoS dimensions**
  - Timeliness
  - Dependability
  - Security & Privacy
- **Humans in the loop**
  - Real-time monitoring of operator status
  - When to take over control from the human operator?
- **Unexpected conditions**
  - Graceful degradation and actuator adaptation
  - What happens when localization fails?

Modeling, Analysis and Synthesis of Highly Dynamic CPS in Uncertain Environments.

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## Summary

Timing requirements are dramatically different for dynamic CPS operating in unpredictable environments.

Dependability, privacy and security constraints must be satisfied simultaneously.

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