Surviving Peripheral Failures in Embedded Systems

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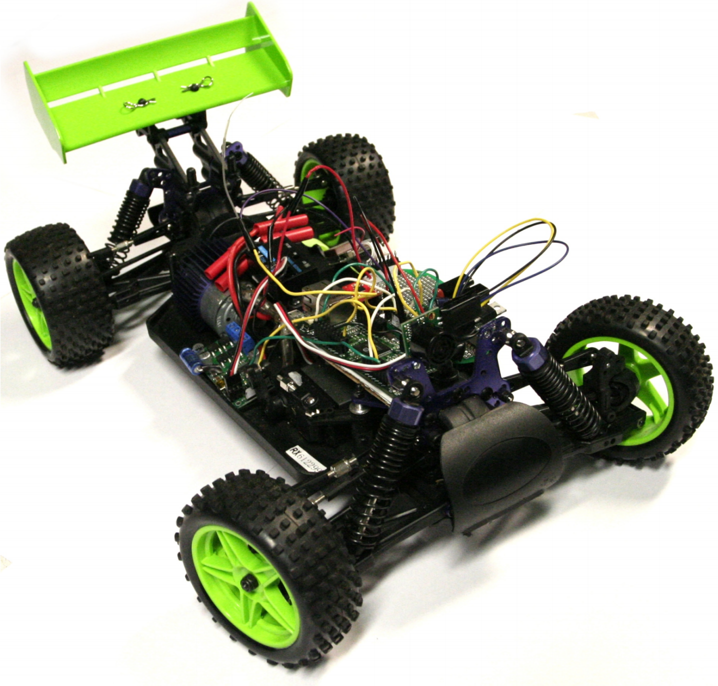
RICE

Motivation

- Embedded systems are ubiquitous
- They interact with the real world via sensors and actuators
- These peripherals can fail asynchronously



Contributions & Outline

- Phoenix Peripheral Recovery System
    1. **Insights** into embedded system recovery
    2. **Procedure** for recovering from peripheral failures
    3. **Mechanisms** implementing this procedure
    4. **Evaluation** on microbenchmarks and applications

Owl

- An embedded run-time system and development toolchain which provides:
    - **Productivity:** Python interpreter, interactive prompt
    - **Hardware access:** two native function interfaces
- Available at embeddedpython.org

Insights: Embedded Systems

1. External Peripheral State
   - External state must be restored
   - Phoenix logs all peripheral accesses and handles each one individually during recovery
2. Space Constraints
   - Microcontrollers have extremely limited memory
   - Phoenix only logs memory that has been changed
3. Time Constraints
   - Embedded systems are event-driven
   - Phoenix minimizes the latency of recovery

Insights: Peripherals

1. Peripherals affect the external state in four different ways
    - **Stateless:** no state
    - **Ephemeral:** temporary state
    - **Persistent:** state determined by a single write
    - **Historical:** state determined by multiple writes

Insights: Peripherals

2. Peripherals do not operate in isolation
    a. P1 **depends on** P2 if P2 failing results in P1 not having its intended effect on the external state
        - e.g. autonomous car: motor and servo

Insights: Peripherals

3. Not all peripheral accesses can be replayed
    a. Re-executing accesses to peripherals that depended on the failed peripheral is mandatory
    b. Re-executing accesses to other peripherals may be incorrect
        - **Rematerialize** = skip during re-execution, restoring the old value instead

Insights: Peripherals

4. Restoring persistent state takes extra steps
   A. Put P in a safe state during recovery

   B. Restore P’s last state during re-execution
      - If P is in the redo set, restore:

        what: initial state at point of failed access

        when: before re-execution

      - Otherwise, restore:

        what: final re-materialized state
        when: after re-execution

Recovery Procedure

1. Rollback to the point of failure
   - **Goal**: Restore the internal program state
2. Recovery of the failed peripheral
   - **Goal**: Restore system functionality
3. Redo mode execution
   - **Goal**: Restore the external peripheral state

Example

```
# Run the motor
speed = 100
motor.run(speed)
SD.write("set motor to 100")
speed += 100

# Turn the wheels
servo.set_servo(-1)
...
```

Example

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# Run the motor
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...
```

detect motor failure ←

Example

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detect motor failure ←

put motor, servo in safe state

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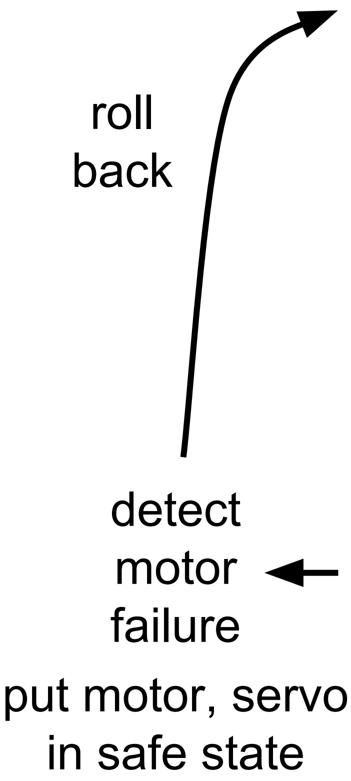


roll back

detect motor failure

put motor, servo in safe state

Example

recover motor →

```
# Run the motor
speed = 100
motor.run(speed)
SD.write("set motor to 100")
speed += 100

# Turn the wheels
servo.set_servo(-1)
...
```

Example

(no last states) →

```
# Run the motor
speed = 100
motor.run(speed)
SD.write("set motor to 100")
speed += 100

# Turn the wheels
servo.set_servo(-1)
...
```

Example

```
        # Run the motor
        speed = 100
redo →  motor.run(speed)
        SD.write("set motor to 100")
        speed += 100

        # Turn the wheels
        servo.set_servo(-1)
        ...
```

Example

```
                1  # Run the motor
                2  speed = 100
                3  motor.run(speed)
rematerialize → 4  SD.write("set motor to 100")
                5  speed += 100
                6
                7  # Turn the wheels
                8  servo.set_servo(-1)
                9  ...
```

Example

```
        # Run the motor
        speed = 100
        motor.run(speed)
        SD.write("set motor to 100")
redo →  speed += 100

        # Turn the wheels
        servo.set_servo(-1)
        ...
```

Example

```
        1  # Run the motor
        2  speed = 100
        3  motor.run(speed)
        4  SD.write("set motor to 100")
        5  speed += 100
        6
        7  # Turn the wheels
redo →  8  servo.set_servo(-1)
        9  ...
```

Example

```
# Run the motor
speed = 100
motor.run(speed)
SD.write("set motor to 100")
speed += 100

# Turn the wheels
servo.set_servo(-1)
...
```

exit redo mode →

Mechanisms

- Run-time system:
  - Enables and disables checkpointing
  - Logs the internal and external state when checkpointing is enabled
  - Detects success and failure of peripheral accesses
  - Executes the recovery procedure
- Compiler:
  - Injects code to enable checkpointing
  - Injects code to track outstanding peripheral accesses

Checkpointing Structures

- **Goal:** Log the internal and external state
  - Store multiple simultaneous checkpoints efficiently
- Stored on a second heap to persist past rollback of the Python heap
- Only used when checkpointing is enabled
  - Populated incrementally as state is changed
  - Freed incrementally as accesses are acked

Journal

- **Goal:** Log the internal program state
- One entry per store to the Python heap
    - Heap is set read-only by the MPU
    - Faults are handled by journaling the (memory address, old contents) prior to executing the store
- Implemented in software; could be implemented in hardware for efficiency

Rematerialization Queues

- **Goal:** Log the external peripheral state

- One queue per peripheral
- One entry per access, which stores:
  1. **Rollback point:** current index into the journal
  2. **Rematerialization info:** arguments and return value

Control Flow Queue

- **Goal:** Drive redo mode execution

- Logs control flow during normal execution
- One entry per bytecode

- Exit redo mode if:
    1. Control flow diverges from the original path, *or*
    2. The point of failure detection is reached again

Example

```
speed = 100
motor.run(speed)
speed += 100
servo.set_servo(-1)
...
```

Example

```
→ speed = 100
  motor.run(speed)
  speed += 100
  servo.set_servo(-1)
  ...
```

Journal:

FIRST SLOT: -1
NEXT SLOT: 0

ENTRIES:

0		
1	...	...

Example

```
  speed = 100
→ motor.run(speed)
  speed += 100
  servo.set_servo(-1)
  ...
```

Journal:

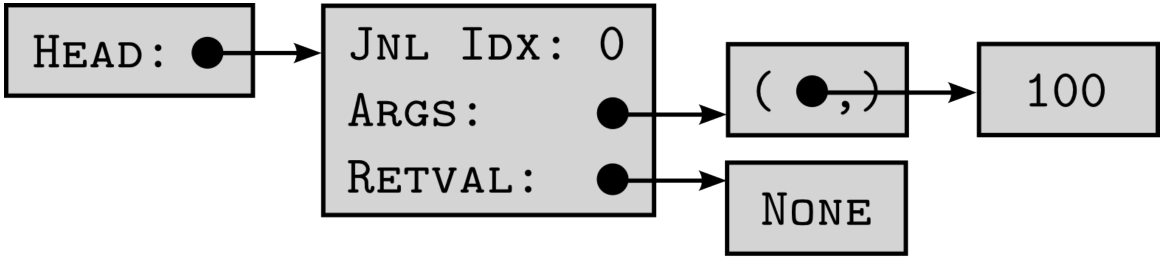
First Slot: -1
Next Slot: 0

Entries:

0		
1	...	...

Rematerialization Queues:

(Motor)



Example

```
speed = 100
motor.run(speed)
speed += 100
servo.set_servo(-1)
...
```

Journal:

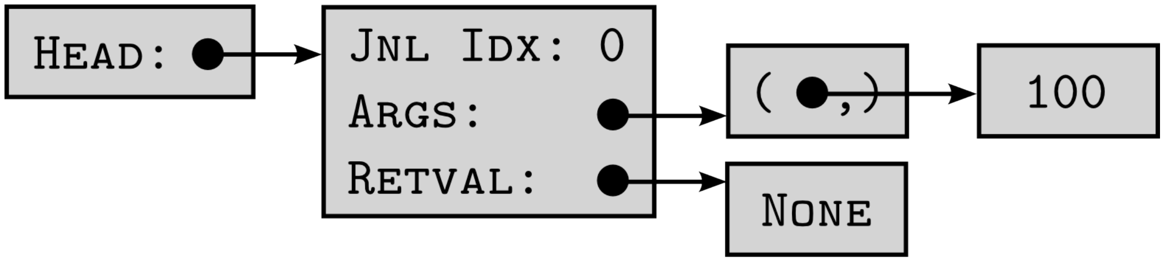
FIRST SLOT: 0
NEXT SLOT: 1

ENTRIES:

0	&speed	100
1	...	...

Rematerialization Queues:

(Motor)



HEAD: ●

JNL IDX: 0
ARGS: ●
RETVAL: ●

(●,)

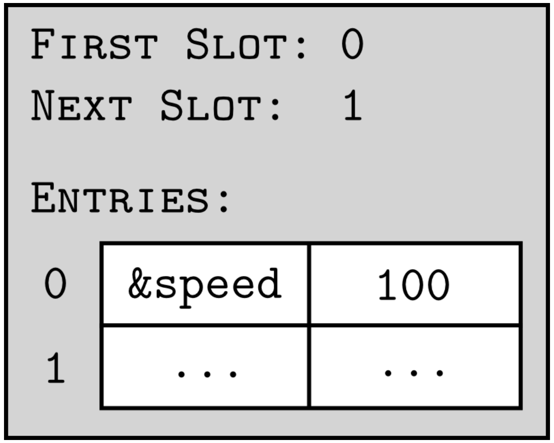
100

NONE

Example

```
  speed = 100
  motor.run(speed)
  speed += 100
→ servo.set_servo(-1)
  ...
```

Journal:

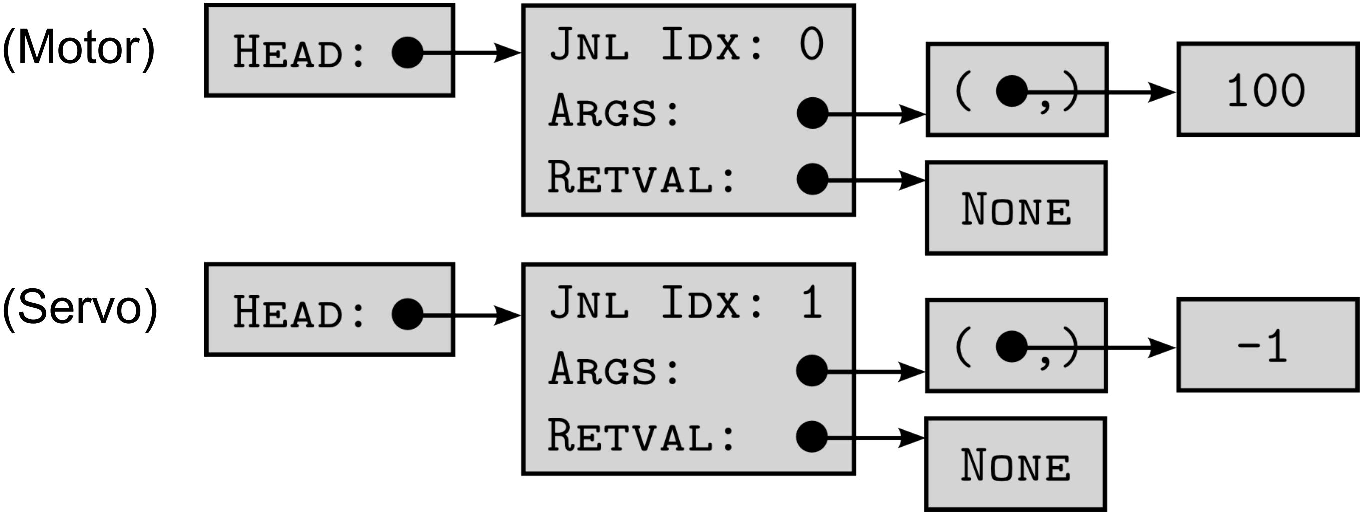


First Slot: 0
Next Slot: 1

Entries:

0	&speed	100
1	...	...

Rematerialization Queues:



(Motor)
Head: ● → Jnl Idx: 0
Args: ● → (●,) → 100
Retval: ● → None

(Servo)
Head: ● → Jnl Idx: 1
Args: ● → (●,) → -1
Retval: ● → None

Example

```
  1  speed = 100
  2  motor.run(speed)
  3  speed += 100
  4  servo.set_servo(-1)
→ 5  ...
```

Journal:

FIRST SLOT: -1

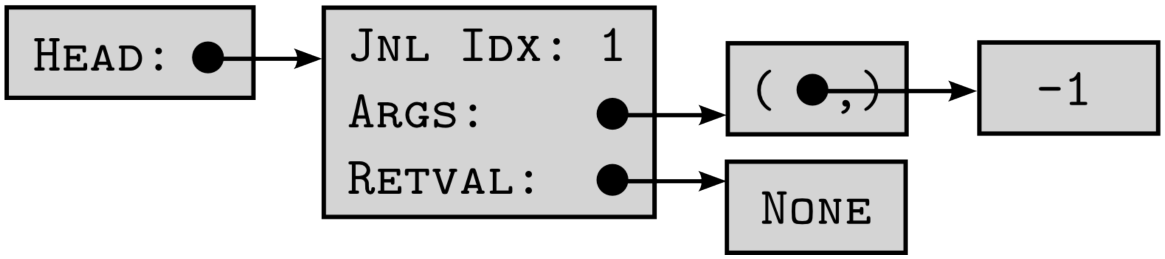
NEXT SLOT: 1

ENTRIES:

0	&speed	100
1	...	...

Rematerialization Queues:

(Servo)



Interrupt Handlers

- **Goal:** Detect failure, acknowledge success

- On **success**, decrement the count of outstanding peripheral accesses
- On **failure**, throw an exception to the interpreter requesting rollback

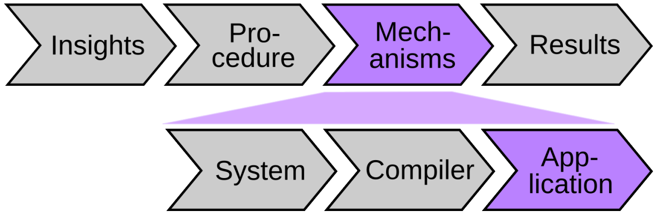
Compile-time Support

- **Goal:** Identify rollback points
  - New `JOURNAL_STORE` bytecode enables checkpointing
  - Inserted just before loading arguments to peripheral access function calls
- **Goal:** Track outstanding peripheral accesses
  - After each access, code is added to increment the number of outstanding accesses

Application Development

- **Goal:** disentangle peripheral recovery code from application-specific code

- Programmer must follow two simple rules:
    1. Define a Python class for each peripheral
    2. Provide a config file including peripheral metadata



Peripheral Class

- **Goal:** Specify peripheral recovery behavior
- Each peripheral extends one of four classes
  - `StatelessPeripheral`
  - `EphemeralPeripheral`
  - `PersistentPeripheral`
  - `HistoricalPeripheral`
- Programmer defines functions to support:
  - **Access**: the only C code the programmer must write
  - **Recovery** & **Restoration**: programmer determines how; system determines when

Example

```
class Motor(PersistentPeripheral):
    def __init__(self):
        # Initialize primary device
        self.init(PRIMARY)

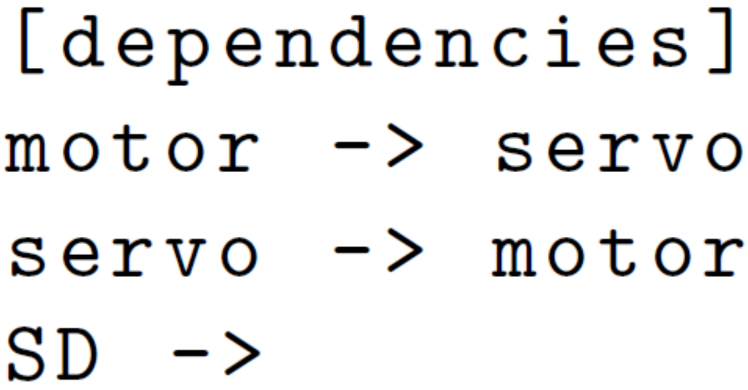
    def recover(self):
        # Switch to backup device
        self.init(BACKUP)

    def safe_state(self):
        # Stop the motor
        self.set_speed(0)

    def last_state(self, *args):
        # For use by Phoenix only
        native_write(*args)
```

Configuration File

- **Goal:** Specify peripheral metadata
  1. Number of interrupts per peripheral access
  2. Dependencies between peripherals



```
[dependencies]
motor -> servo
servo -> motor
SD ->
```

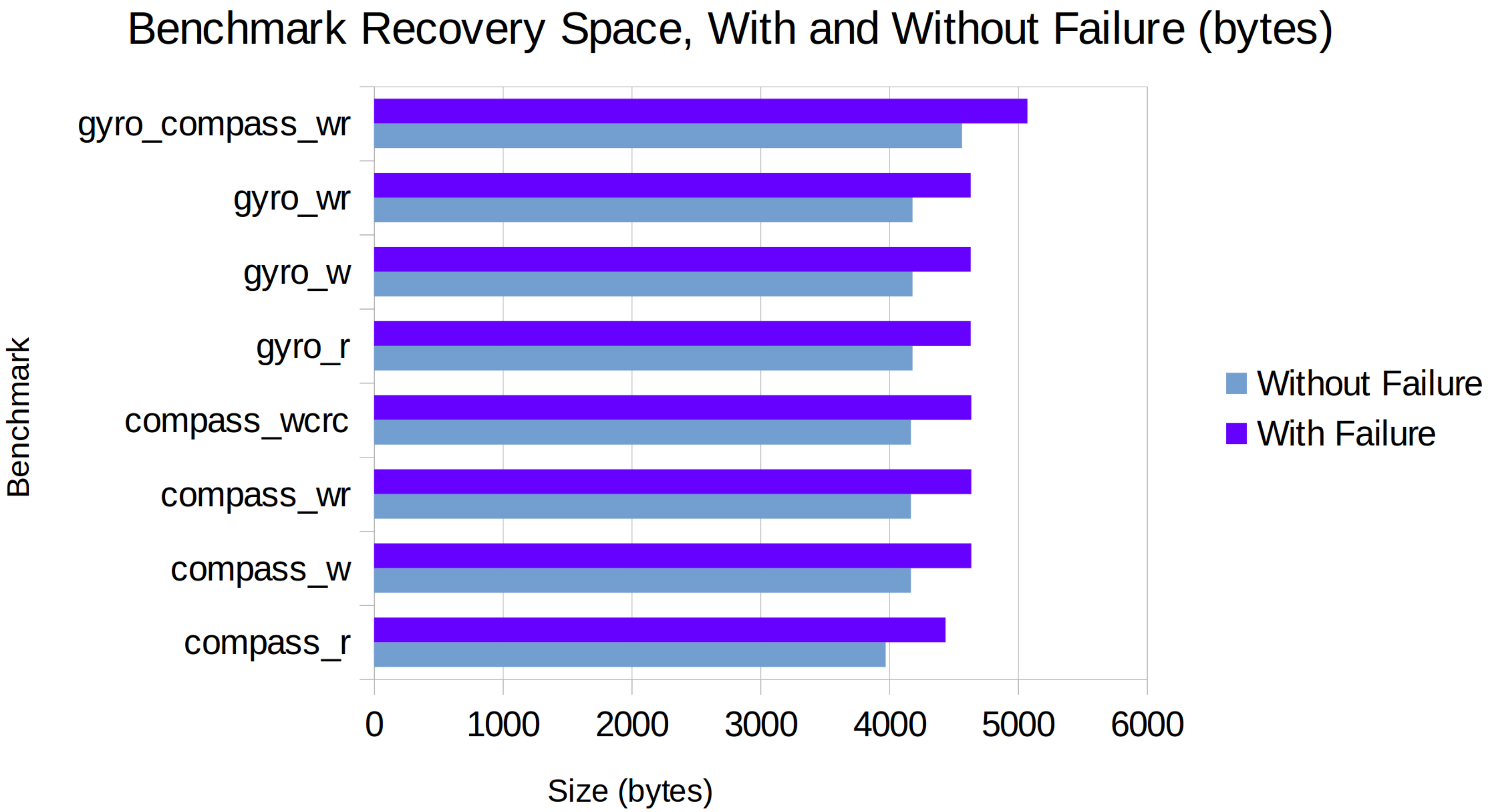
Evaluation

- Used the Stellaris LM3S9B92 for evaluation
  - 96 KB SRAM, 256 KB flash, 50 MHz

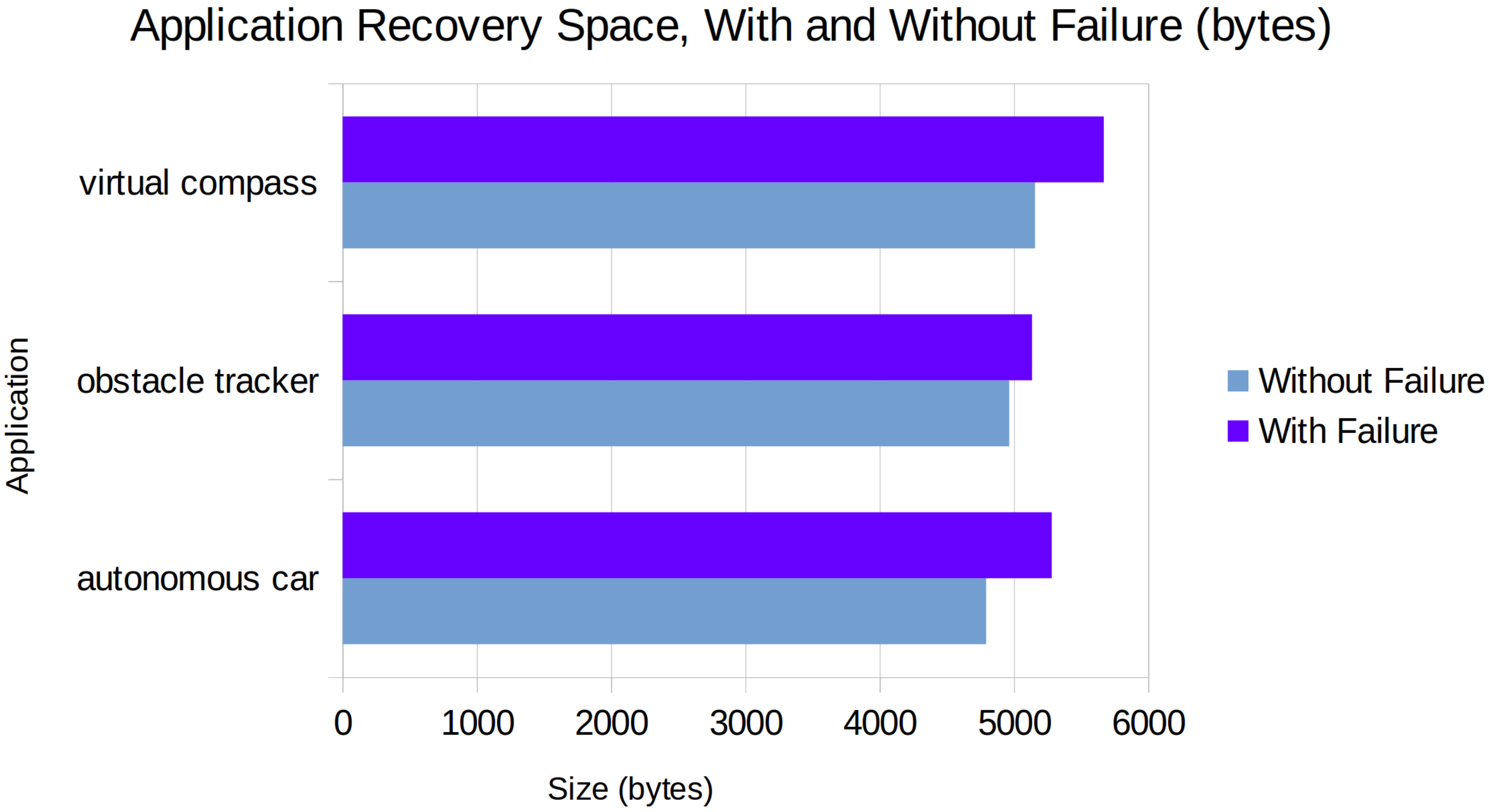
- Microbenchmarks:
  - Named in the form <peripherals>_<actions>
    - <peripherals> $\subseteq$ {gyro, compass}
    - <actions> $\subseteq$ {r, w, c} for {read, write, compute}

- Applications:
  - Autonomous RC car (motor, servo, gyro)
  - Obstacle tracker (display, range finder)
  - Virtual compass (display, compass)

Evaluation: Space



Evaluation: Space



Evaluation: Time

- Overhead of a single failure: 12–143 ms
- Overhead of a journaled store: 6.2 µs
  - Projected 40.2 ns with hardware journal
- No discernible slowdown on ⅔ applications
  - Virtual compass **(intensive accesses)**
  - Autonomous RC car **(periodic accesses)**
  - Obstacle tracker **(fixed sleep between accesses)**

Conclusions

- Hardware peripherals introduce complex failure scenarios
  - External state impacts the real world
  - Failures occur asynchronously
- Phoenix simplifies handling these failures
  - Incremental checkpointing
  - Precise rollback to the source of the failure
  - Correct recovery of both the internal program state and the external peripheral state