Towards Introducing Asynchronous Tasks to an FRP Language for Small-Scale Embedded Systems

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Overview

Objective

- Support for the **heavy task** execution in an FRP language for small scale embedded systems
  - **Heavy tasks**: tasks that may degrade the responsiveness of the systems

Proposed Method

- A simple asynchronous task execution mechanism that supports mutual exclusions of computational resources
  - Future types
  - Tasknodes: special time-varying values for heavy tasks
  - Task resources: abstractions of computational resources for heavy tasks

Contribution

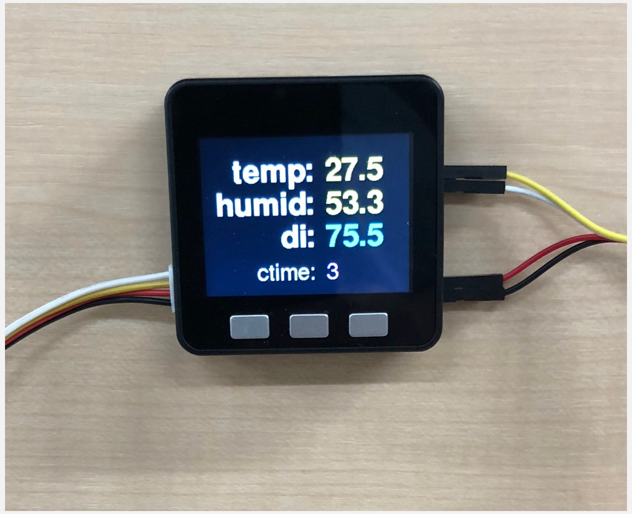
- Embedding heavy task executions to reactive programs naturally.

Emfrp [Sawada et al. 2016]

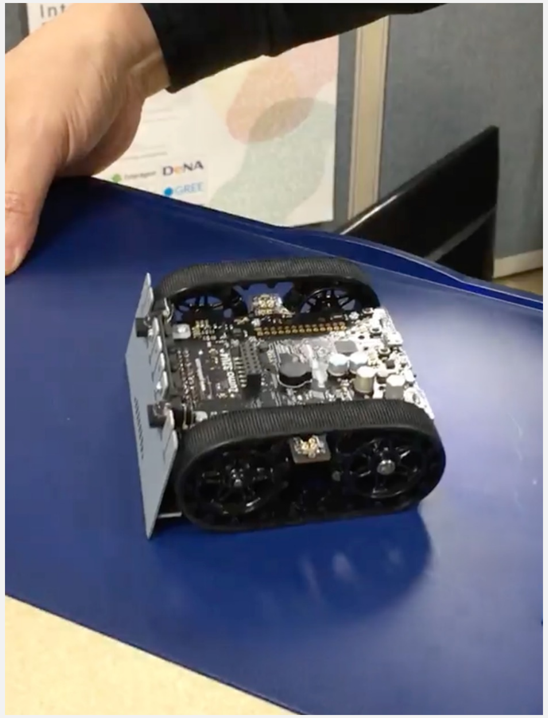
- Statically-Typed Pure FRP Language
  - Designed for small-scale (resource-constrained) embedded systems
    - Ex) AVR, STM32, ESP32 etc.
  - Statically-determined runtime memory size
  - Nodes represent time-varying values.
  - The values in the previous moment can be referred by **@last** operator

```
module FunController
in  tmp: Float, hmd: Float
out fan: Bool
use Std

node di = 0.81 * tmp +
          0.01 * hmd * (0.99 * tmp - 14.3) + 46.3
node init[False] fan = di >= th
node th = 75.0 + if fan@last then -0.5 else 0.5
```

Emfrp module to control a fan by discomfort index



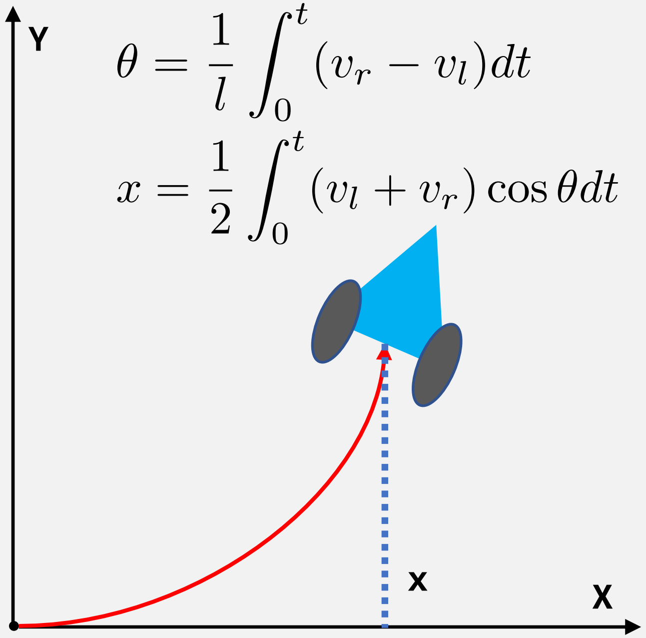
M5 Stack (CPU: ESP32 240MHz, Flash: 16MB, RAM: 520KB)


Zumo (CPU: ATmega328p 16MHz, Flash: 32KB, RAM: 2KB)

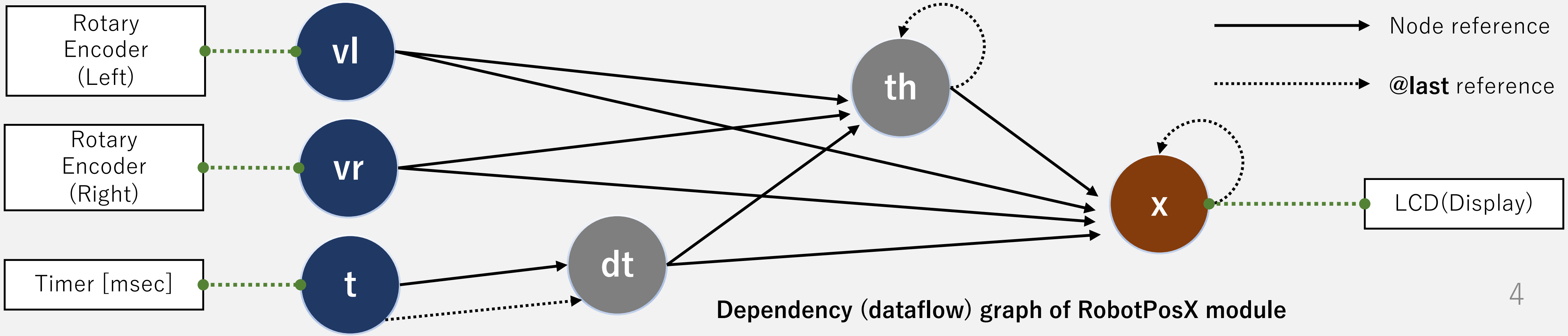
Example: Position of a Robot in Emfrp

$$\theta = \frac{1}{l}\int_0^t (v_r - v_l)dt$$

$$x = \frac{1}{2}\int_0^t (v_l + v_r)\cos\theta dt$$

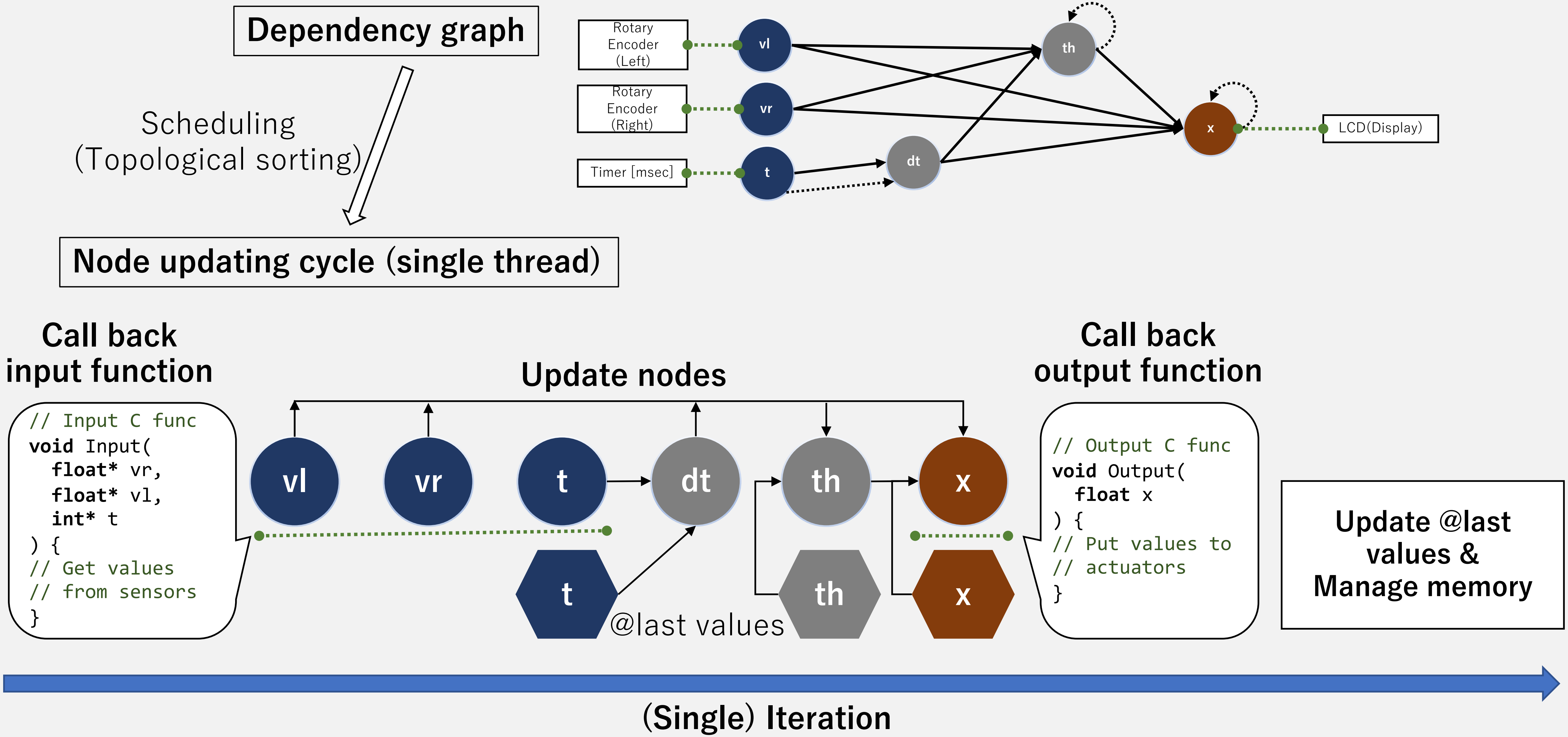



```
# RobotPosX.mfrp
module RobotPosX   # Module Name
in   vl : Float,   # Left velocity [m/sec]
     vr : Float,   # Right velocity [m/sec]
     t(0) : Int    # Elapsed time [msec]
out x : Float,     # X-coordinates [m]
use Std, Params    # Import library

# Intermediate nodes
node dt = (t - t@last) / 1000.0
node init[0.0] theta = theta@last + (vr - vl) * dt / l

# Output node (X-coordinates)
node init[0.0] x = x@last + (vr + vl) * cos(theta) * dt / 2.0
```



Dependency (dataflow) graph of RobotPosX module

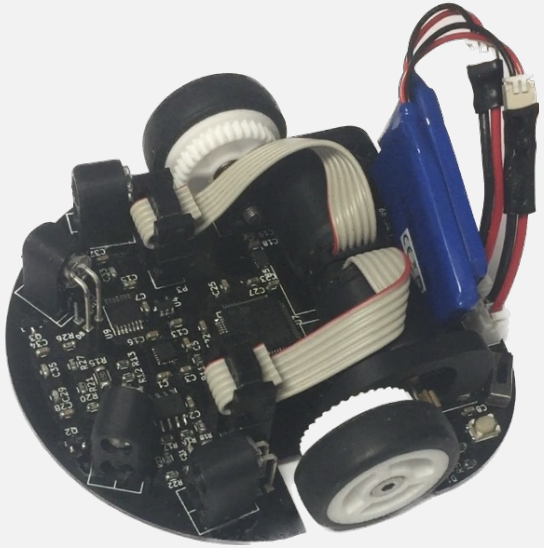
Execution Model of Emfrp

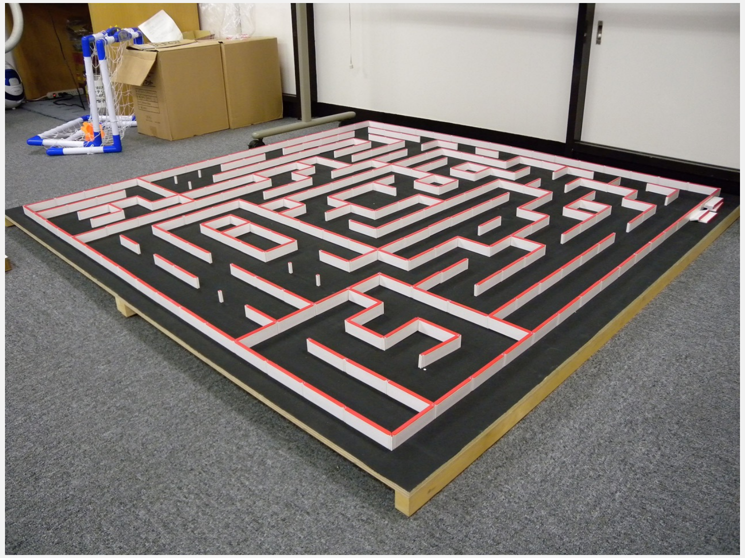


Motivating Example: Exploration Robot

Micromouse

- A robot competition
- Small-scale embedded systems
  - Microcontroller (STM32 etc.)
  - Sensors
    - Infrared sensors
    - Rotary encoders
    - IMU (accelerometer, gyro sensor)
  - Actuators
    - Motors
    - LEDs
- Computation on **graph structures**



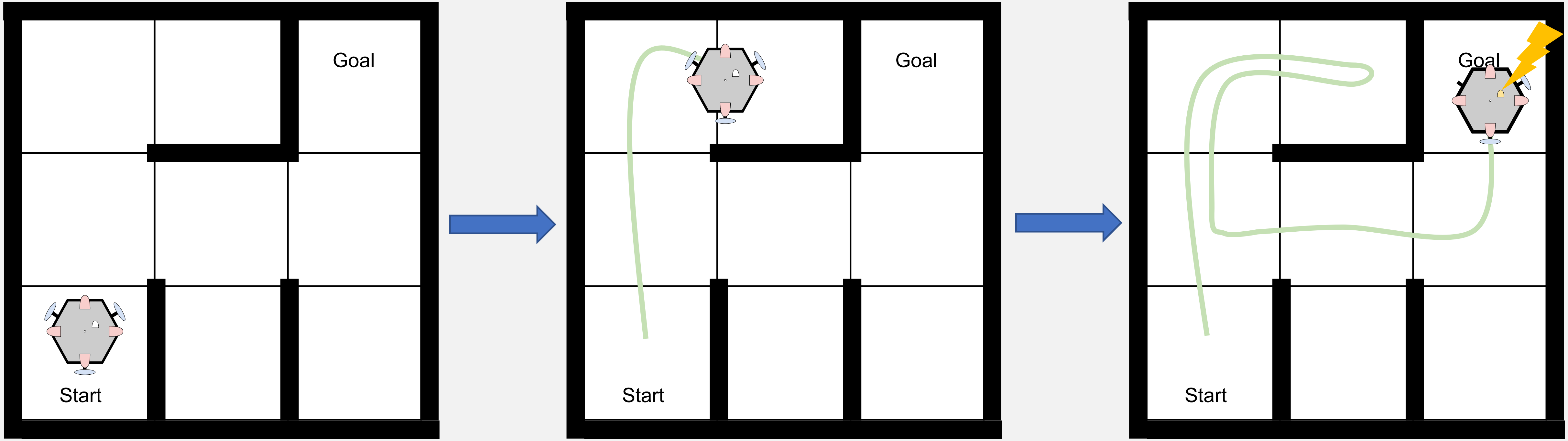


https://en.wikipedia.org/wiki/Micromouse

Motivating Example: Exploration Robot

Problem Setting

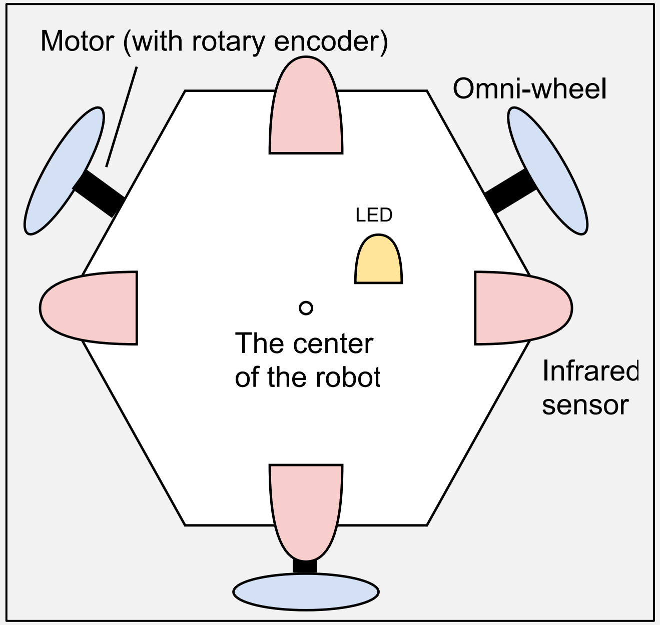
- Simplified version of micromouse.
- Starting from the start, the robot explores the maze autonomously and turns on the LED when it reaches the goal.



Motivating Example: Exploration Robot

Hardware Specifications of the Exploration Robot

- Omni-directional mobile vehicle
- Sensors
  - Wall sensor: Infrared sensor x4
  - Velocity sensor: rotary encoder x3
- Actuators
  - Motor with omni-wheel x3
  - LED x1



https://en.wikipedia.org/wiki/Omni_wheel

Motivating Example: Exploration Robot

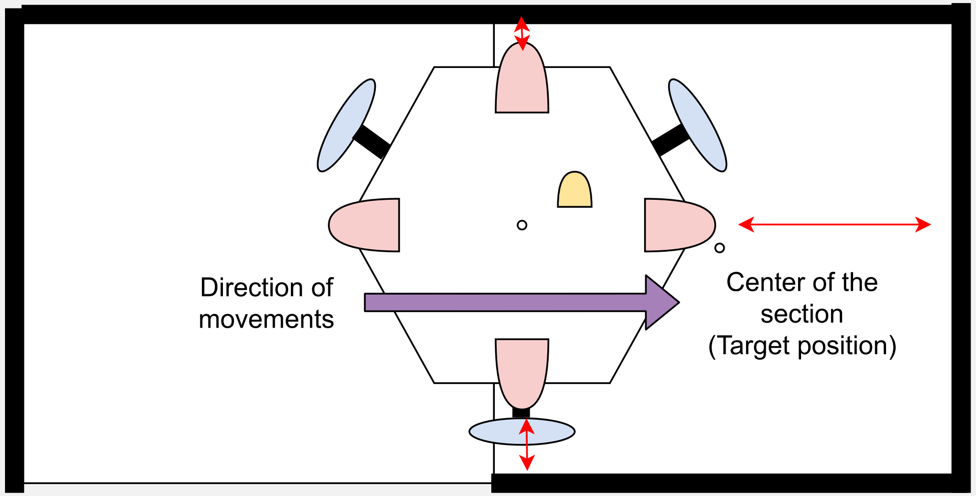
Naive (Standard) Exploration

- Repeat the following actions until reaching the goal.
  - A: Moving the robot to the target section and Stop.
  - B: Recording the wall information.
  - C: Calculating the next destination by a graph algorithm (e.g., A*).

Improved Exploration

- Wall information can be obtained before reaching the target position.

→ If A and (B, C) can be executed concurrently, the latency for exploring is reduced.



Heavy Tasks

Heavy tasks

- Computations not required to be executed every iteration, but are relatively **time-consuming**
  - Heavy task execution during iterations degrades responsiveness of the whole system.
- Heavy tasks are assumed to be operations on somewhat complex data structures.
  - E.g., graph algorithms, parsing, etc.
  - Updating or searching “maze” in the exploration robot example.

Task resources

- The objects handled by the heavy task
  - E.g., the data structures representing “maze”

Restrictions in Emfrp

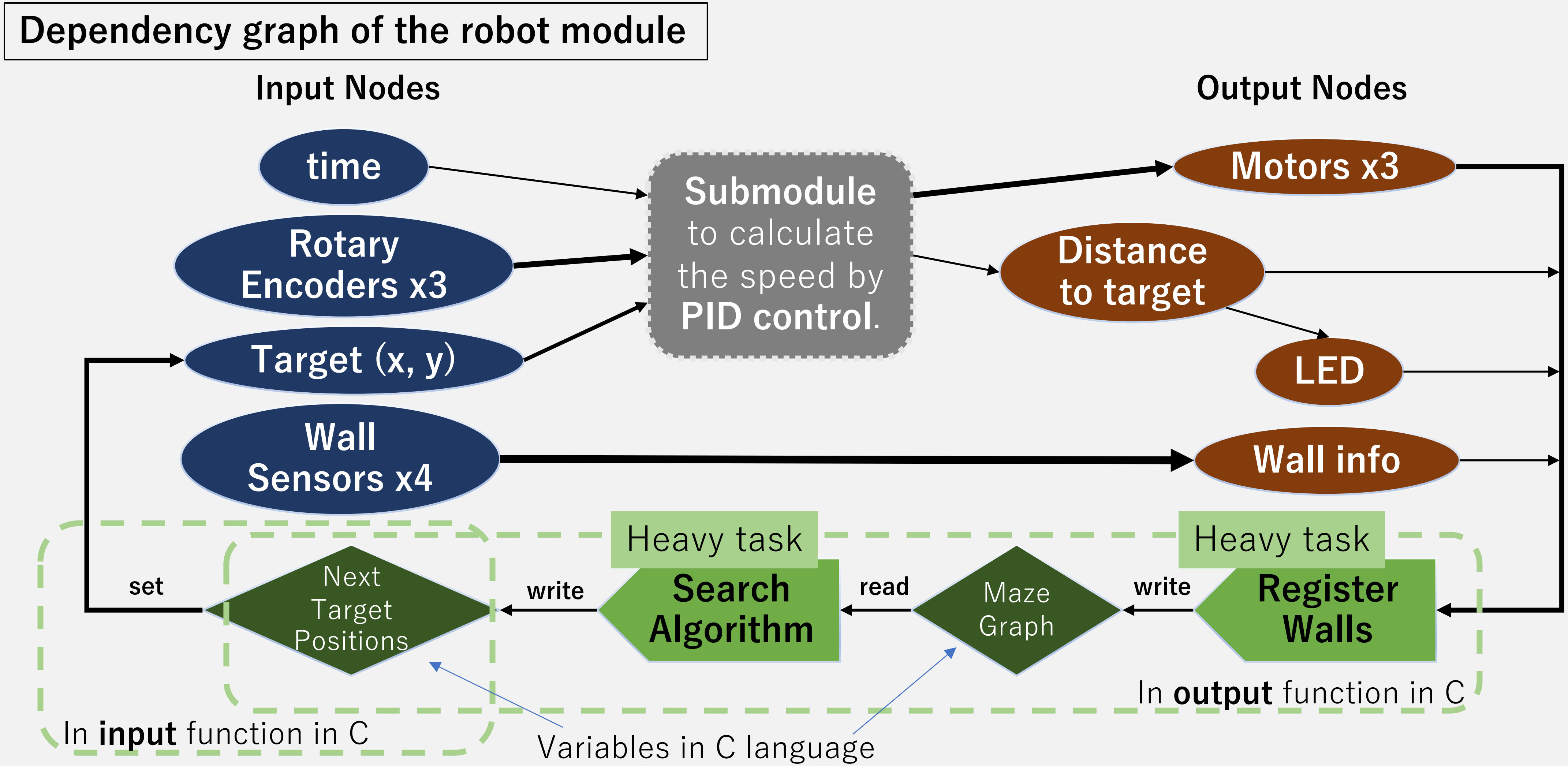
- Time-varying values are not first-class
  → Preventing space / time leak

- Recursive data types and recursive functions are prohibited.
  → Determination of memory used at runtime

- The data structures representing “maze” and related operations cannot be written in Emfrp.
  → Requires foreign (C language) function calls.

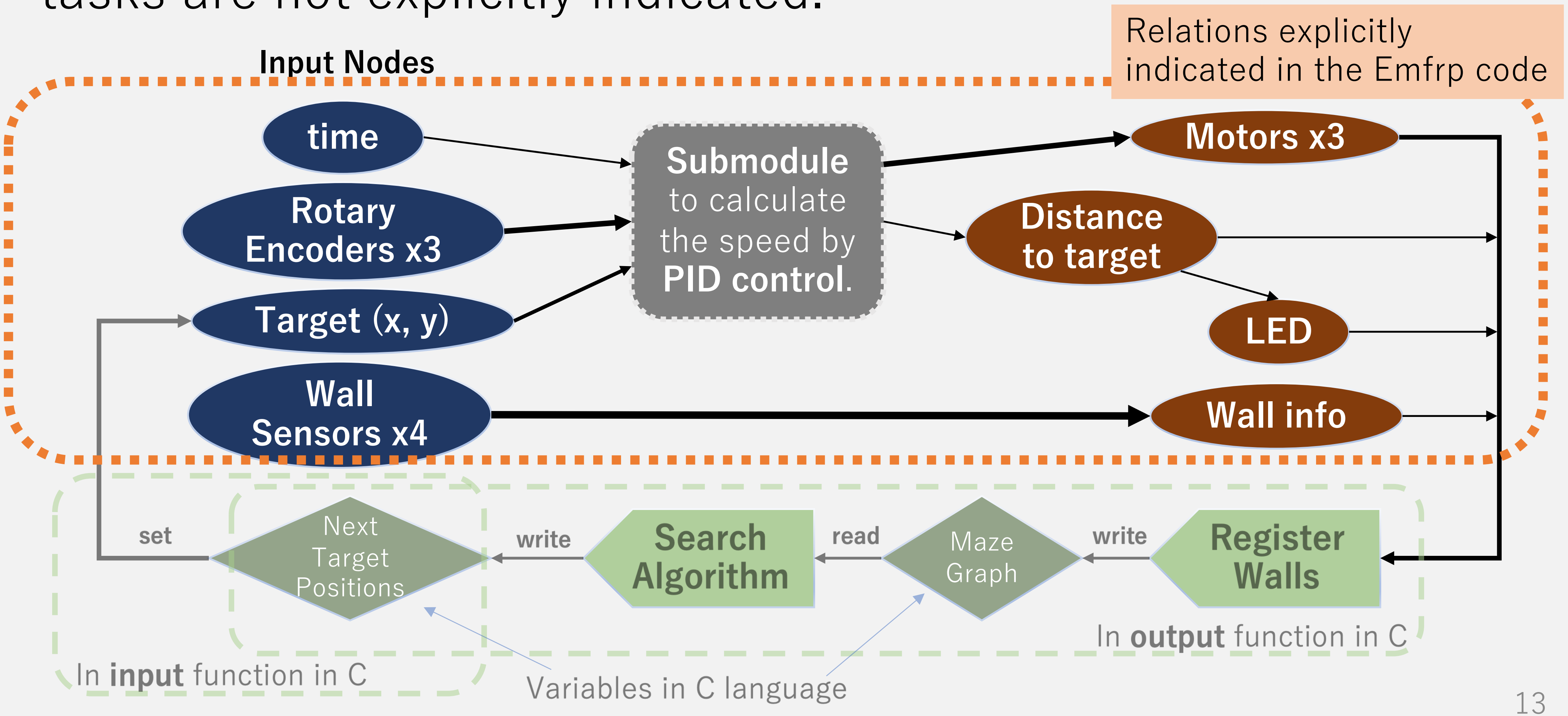
Design of the robot in original Emfrp

Heavy-task execution during feedback from output to input.



Problem (P2 in the paper) of the robot module

The dependencies and/or the data structures subject to heavy tasks are not explicitly indicated.



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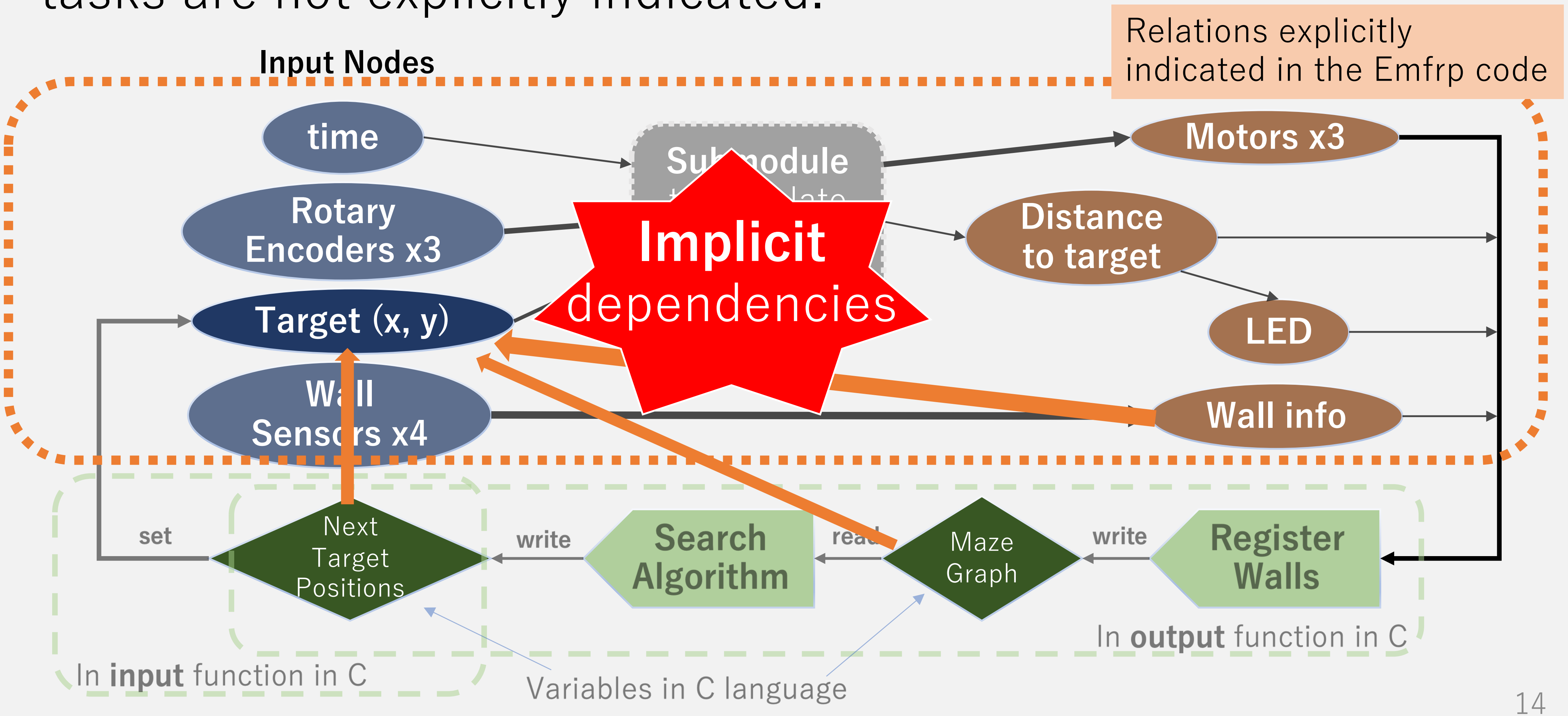
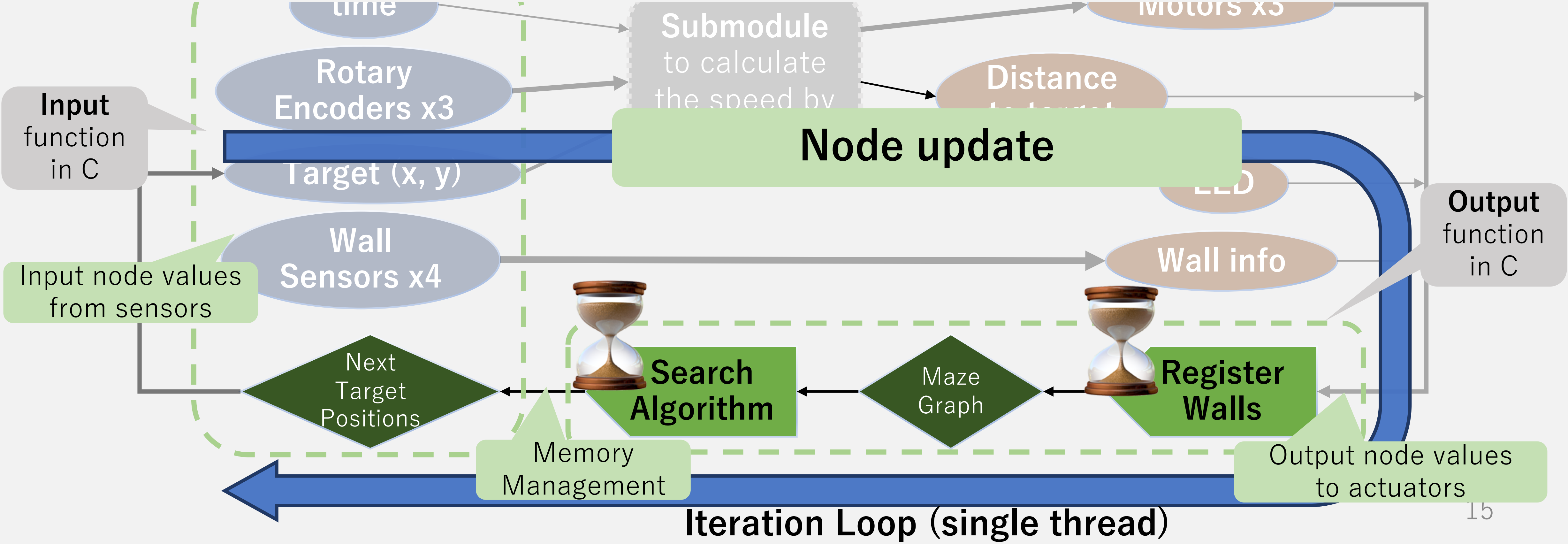


Problem (P1 in the paper) of the robot module

The sequential execution of heavy tasks in the output function makes other reactive behaviors less responsive.

- Due to execution model of original Emfrp.
- **Reactive Thread Hijacking Problem (RTHP)** [Van den Vonder et al. 2020]



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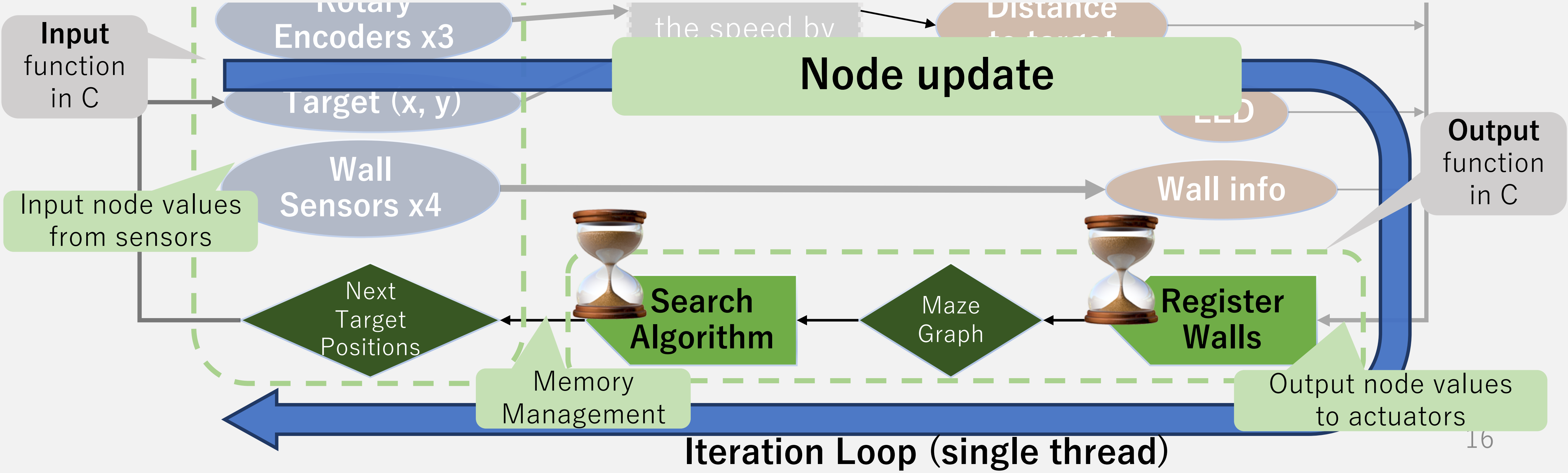
The sequential execution of heavy tasks in the output function makes other reactive behaviors less responsive.

- Due to execution model of original Emfrp.
- **Reactive Thread Hijacking Problem (RTHP)** [Van den Vonder et al. 2020]

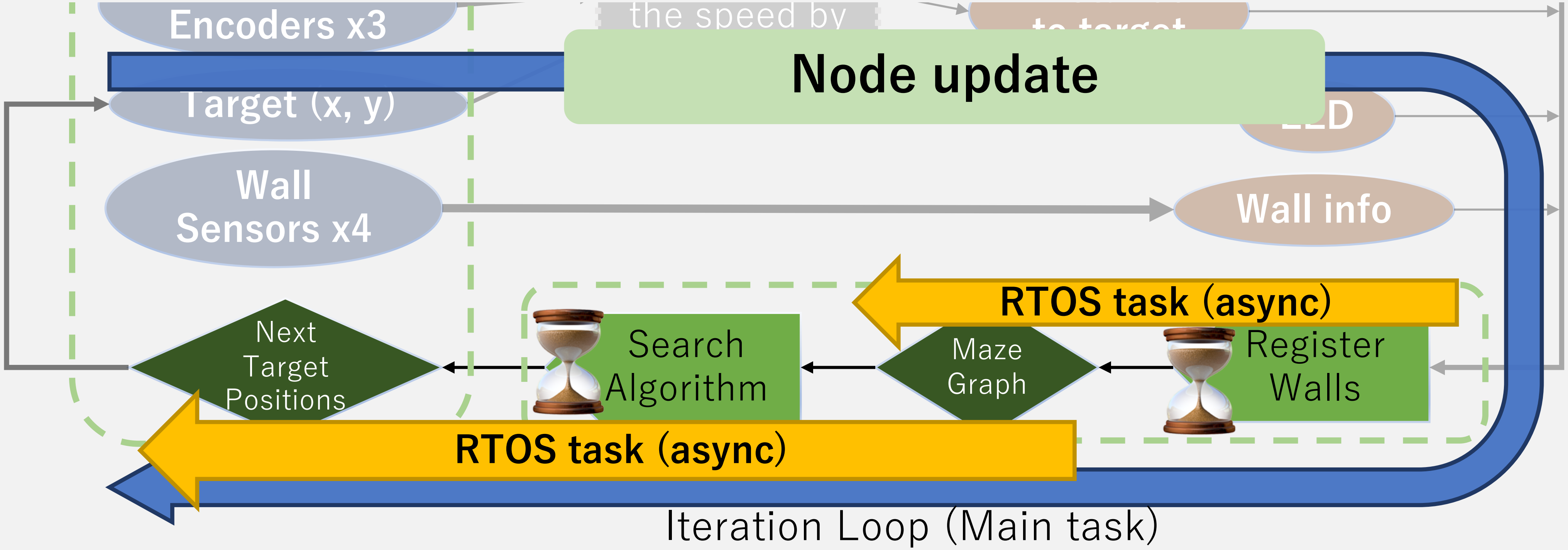
→ **Cannot implement the improved search.**



Problem (P3 in the paper) of the robot module

Solution? of P1: Cooperation with concurrent execution libraries.

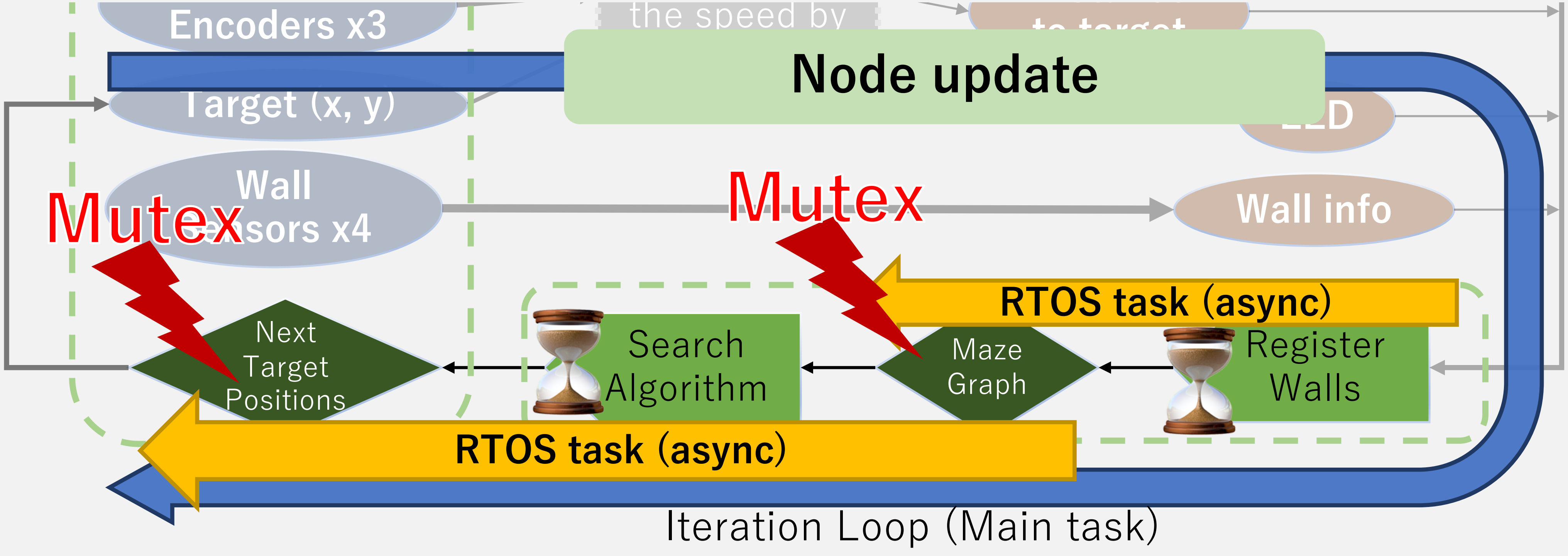
- E.g., FreeRTOS's tasks
- Reactive computations (iteration loop) and heavy tasks can be executed concurrently.



Problem (P3 in the paper) of the robot module

Solution? of P1: Cooperation with concurrent execution libraries.

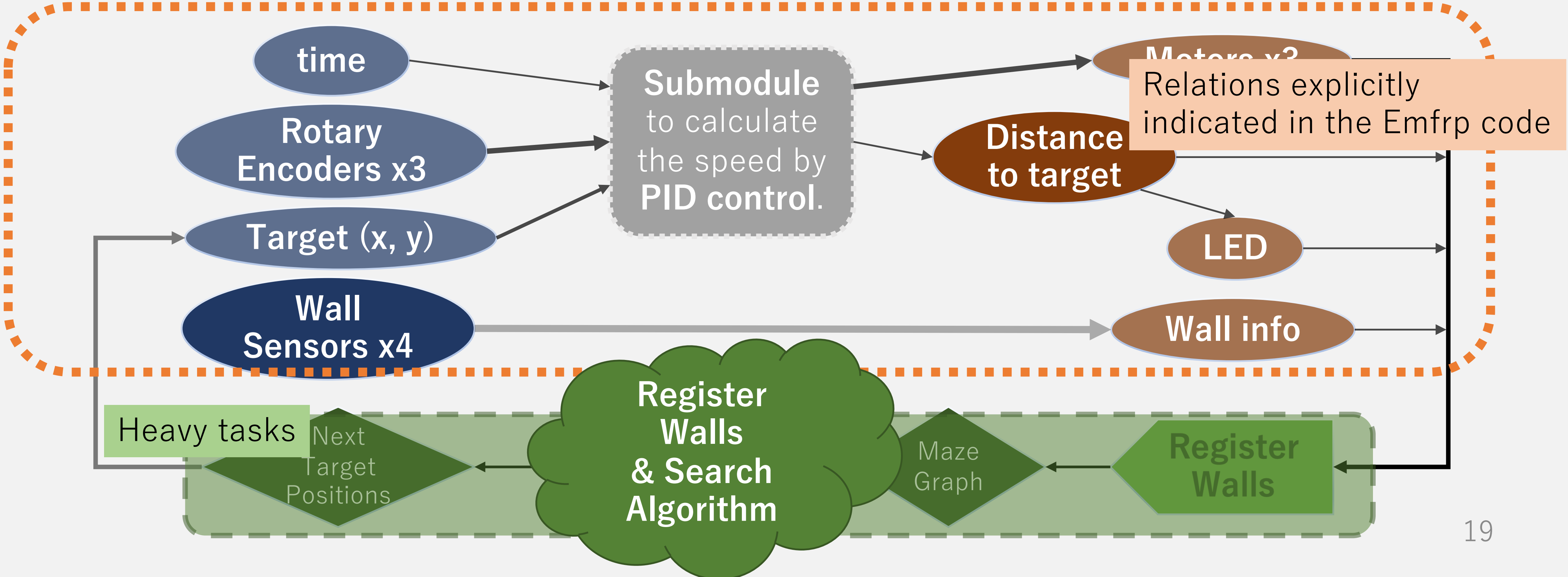
- E.g., FreeRTOS's tasks
- Reactive computations (iteration loop) and heavy tasks can be executed concurrently.
- **(P3) Mutual exclusions** for task resources (shared variables) is required.
  → The advantage of Emfrp (or FRP) is lost.



Our Approach

We want to make heavy tasks and task resources **explicit** in the scope of Emfrp.

- Enhance **readability** and **maintainability**.



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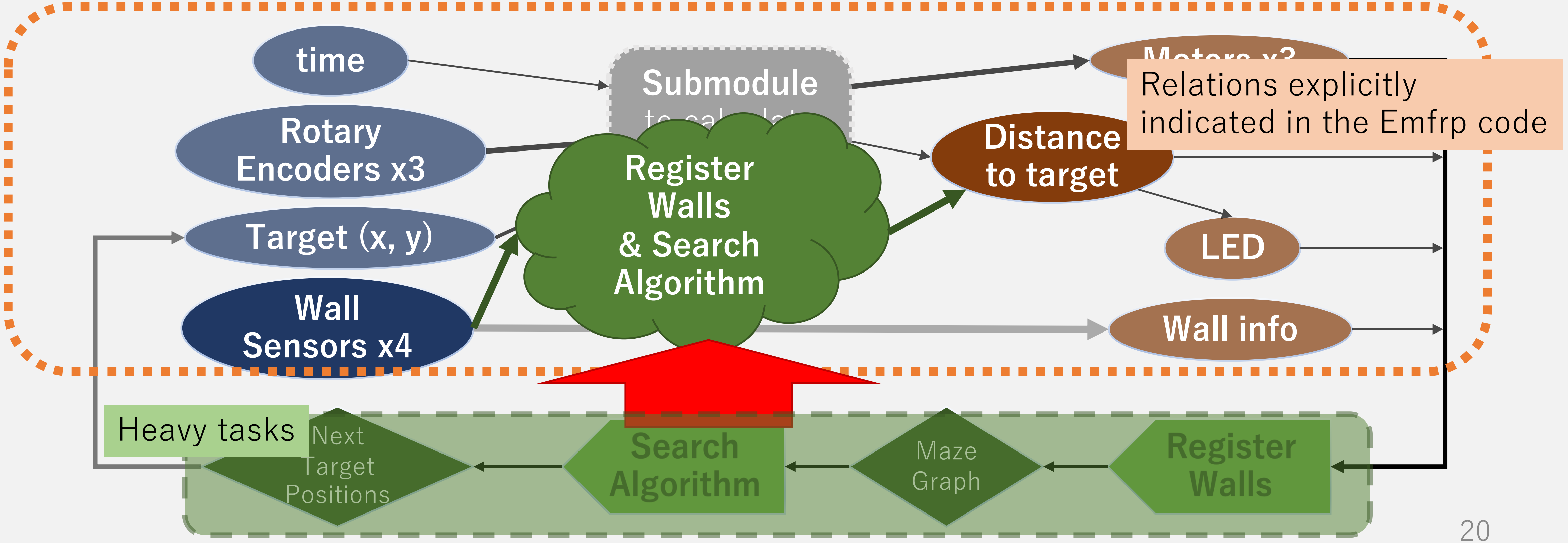
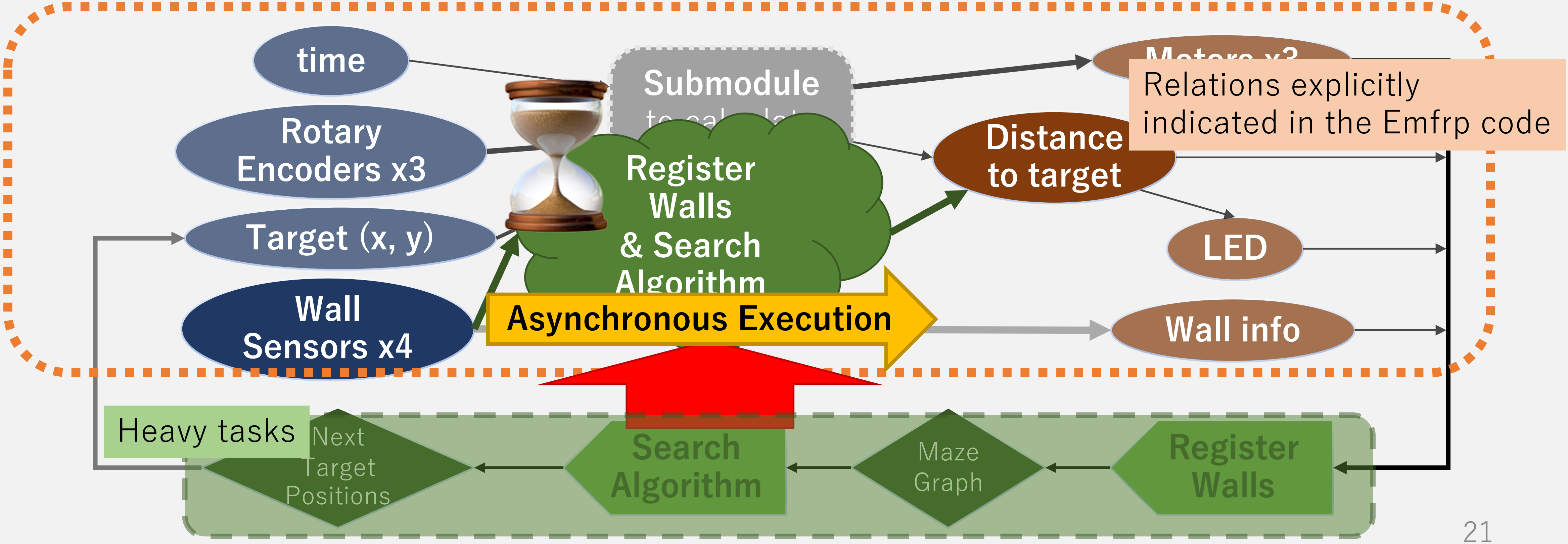


Our Approach

We want to execute heavy tasks **asynchronously** to prevent RTHP.

- **Responsiveness** of the whole system is not degraded.

→ **Asynchronous executions** and **Future types**



Proposed method

- Language Extensions
  - Future types
  - Definitions of tasks and task resources
  - Tasknodes: special nodes invoking heavy tasks

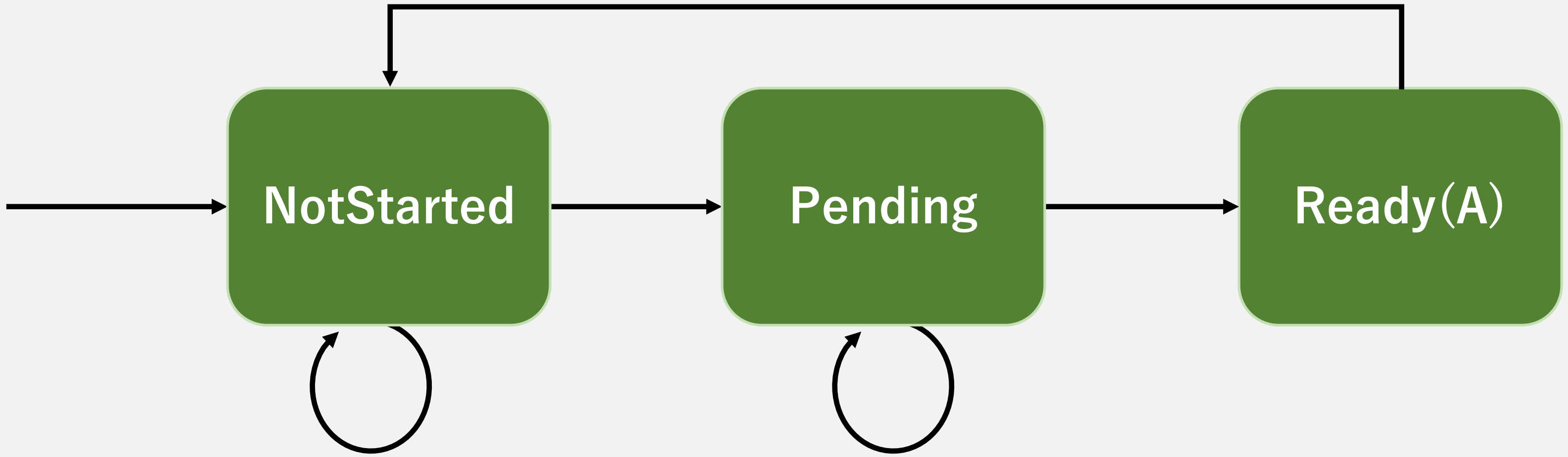
- Runtime Extensions
  - Inserting an asynchronous execution phase of a task into each iteration
  - Simple task scheduler for resource-constrained environments with mutual exclusion of task resources

Language Extensions: Future types

- Future types represent the state of the task computation.

```
type Future[A] =
  | Ready(A)     # Just after the task is completed.
  | Pending      # Waiting for the task completion
  | NotStarted   # The task is not issued.
```

State transitions of the value of future types



Language Extensions: Tasks and Task resources

- Definitions of task resources and tasks
  - Task resources are compiled to skeleton codes of C structure
  - Tasks are compiled to skeleton codes of C function

Name of task resources

Result of the task

```
resource MazeGraph {
  # Task to record wall information of section (u, v) in a MazeGraph instance
  task RegisterSection :
    (u: Int, v: Int,
     n: Bool, e: Bool, s: Bool, w: Bool) -> (h: Unit) / write

  # Task to compute the next section (next_u,next_v) to go from (u,v) to the goal
  task CalcNextSection :
    (u: Int, v: Int, goal_u: Int, goal_v: Int)
        -> (next_u: Int, next_v: Int) / read
}
```

Hint for mutual exclusion

Input parameters of the task

Language Extensions: Tasks and Task resources

- Definitions of task resources and tasks
  - Task resource instance

```
resource MazeGraph {
  # Task to record wall information of section (u, v) in a MazeGraph instance
  task RegisterSection :
    (u: Int, v: Int,
     n: Bool, e: Bool, s:

  # Task to compute the n                                                          oal
  task CalcNextSection :
    (u: Int, v: Int, goal
        -> (next_u: Int,
}
```

```
# Toplevel module
module MazeRunner
in mg : resource MazeGraph
   sn: Int, se: Int, … time(0): Int
out duty1:Int, …
use Std, Resources

node move_dir = …
…
```

Passing the task resource instance from C code (activation function)

Language Extensions: Tasknodes

Tasknode

- Special node that ties the heavy task to the future type node.
  - Issue the task when the condition is satisfied.
    - Required that state of the task is NotStarted.
  - The parameters of the issued task are snapshots of node values.

Node name

Future type

Task name

```
tasknode next : Future[(Int, Int)] =
  CalcNextSection(to_u, to_v, G_U, G_V)
    with mg at wait(finish_register)
```

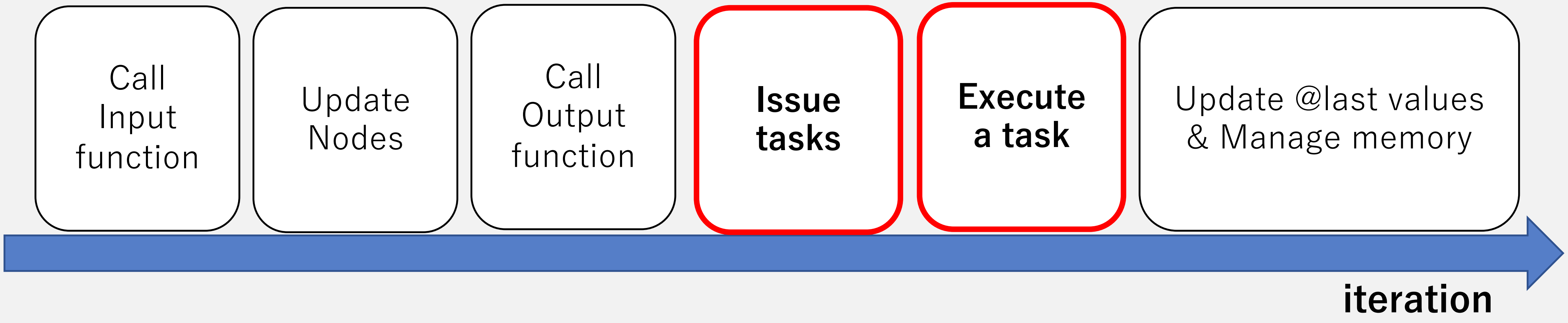
Instance of the task resource

The condition (timing) for issuing tasks

Parameter
(snapshots of node values)

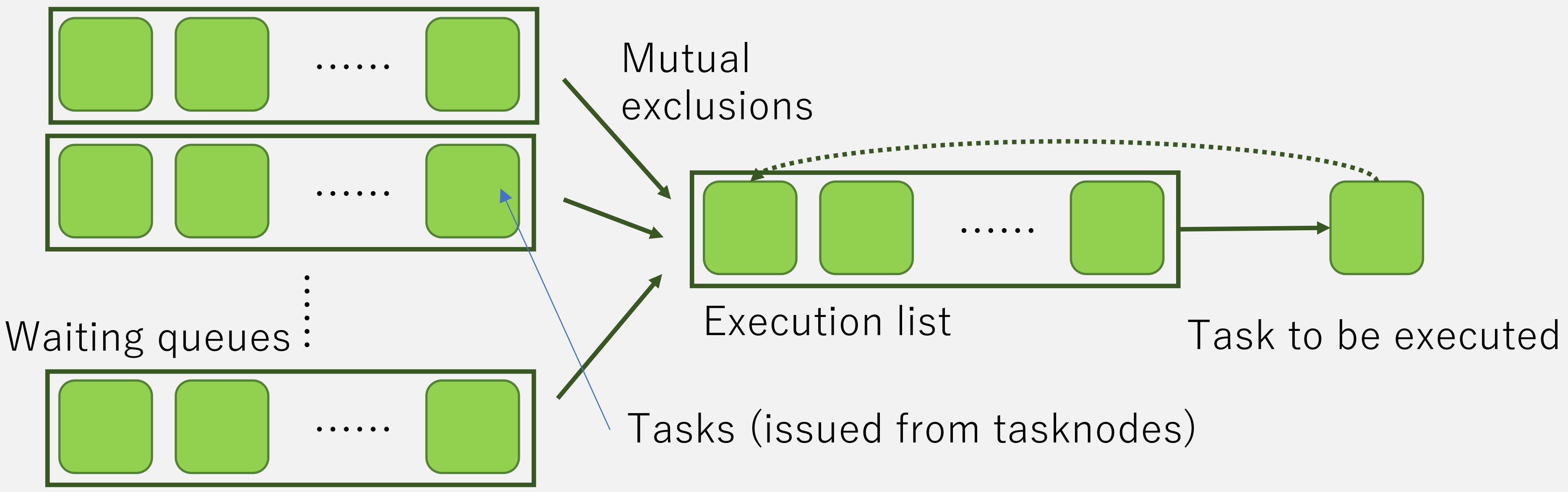
Runtime Extension: Iteration Loop

- Add phases related heavy tasks to iteration loop
  - Issuing tasks
  - Executing a task for N (milli)seconds
    - N is specified at compile time
    - One task execution per iteration (Round-robin scheduling)
    - Preemptive task execute using timer interrupts or RTOS tasks
      - Traditinal context switch techniques



Runtime Extension: Task Scheduling

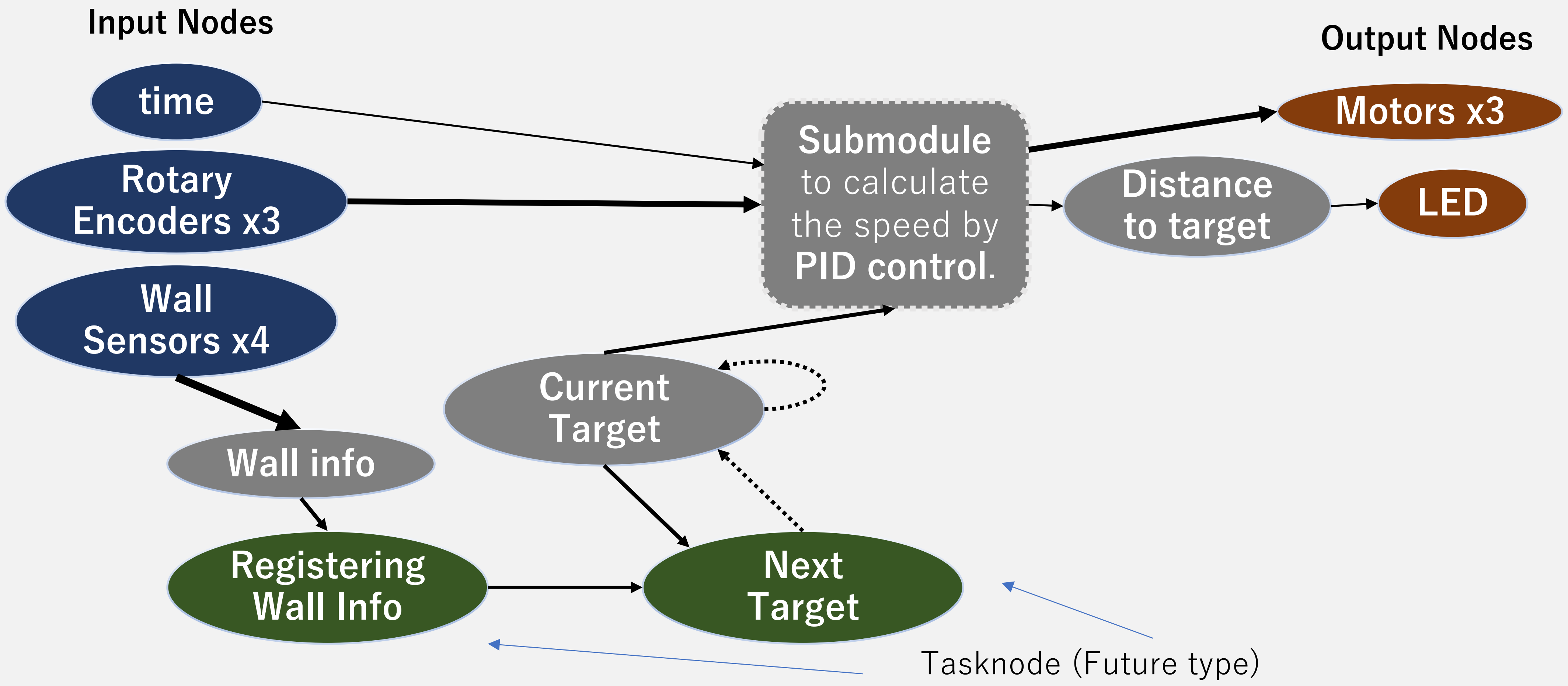
- Round-robin scheduling
- Simple task execution management algorithm
  - Designed for single-core microcontrollers
  - Mutual exclusion of task resources using **`read`**/**`write`** on tasks
  - Execution list, Waiting queues (per task resource instance)
    - Maximum queue length can be conservatively estimated.



Design of the robot in Extended Emfrp

Heavy-task execution with future nodes.

Dependency graph of the robot module



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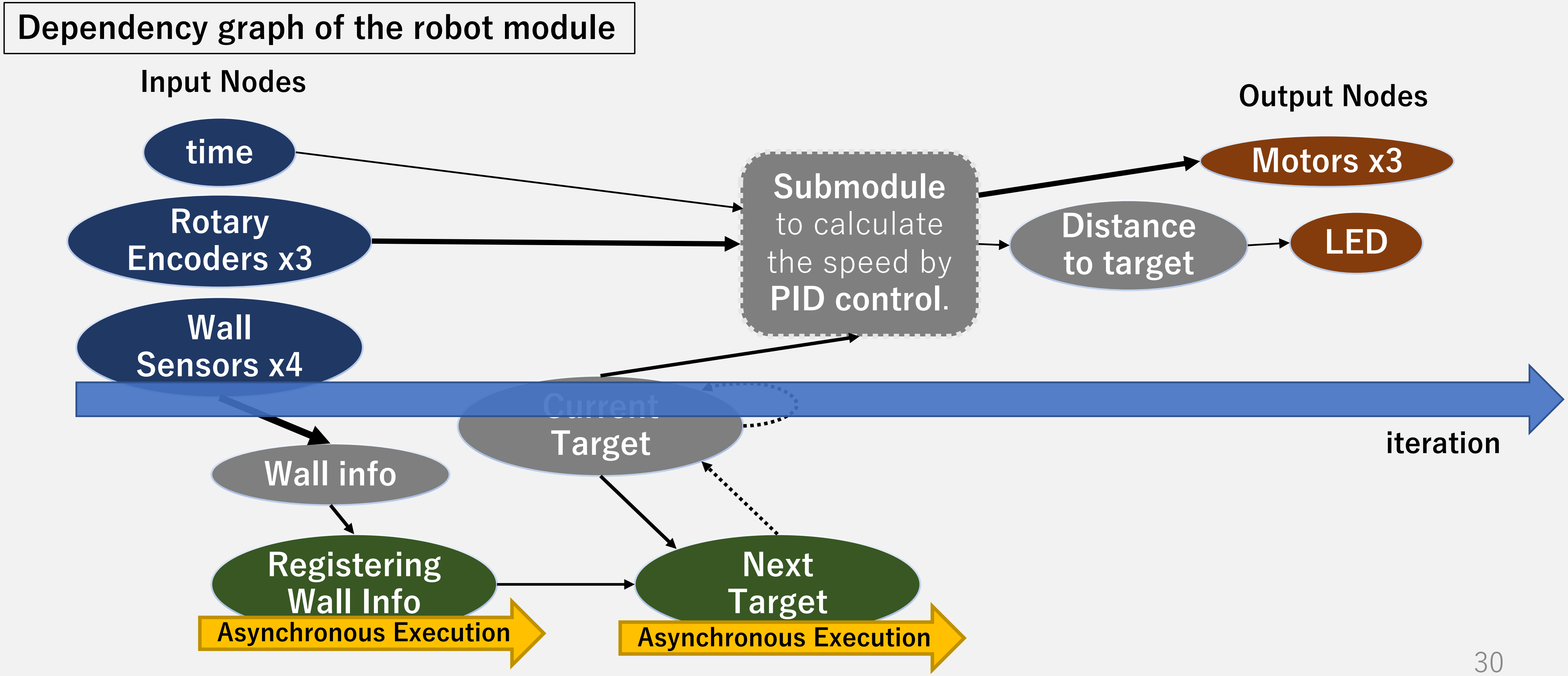

Related works

- Actor-Reactor model [Van den Vonder et al. 2020]
  - A method to separate and modularize reactive (reactor) and procedural (actor) behavior descriptions.
  - Actors (heavy tasks) and reactors are in single language (Stella).
    - Dependencies are explicitly defined in the single language.
  - They also advocated Reactive Thread Hijacking Problem.

- Lustre with Futures [Cohen et al. 2012]
  - Lustre: a synchronous dataflow language
  - Their future types enables concurrency, pipelining and jitter control.
    - Compiled into Java's threads.
  - Not for heavy tasks defined as foreign (C language) functions.

Future Tasks

- Implementation and evaluation of Emfrp compiler with proposed methods.

- Design of abstractions for task resources
  - Coarse-grained task resources are sufficient for current examples.
    - Heavy tasks are **computationally bound heavy tasks** in this presentation.

  - We need more fine-grained resource abstractions for I/O devices.
    - **I/O bound heavy tasks** will handle network or serial ports.

Conclusion

- We proposed an asynchronous task execution mechanism for Emfrp, an FRP language for small embedded systems.
- The mechanism enables the heavy task executions while keeping sufficient responsiveness.
- We showed the usefulness of the mechanism through the explanation of an non-trivial example.