A Document-Oriented Robot Memory for Knowledge Sharing and Hybrid Reasoning on Mobile Robots

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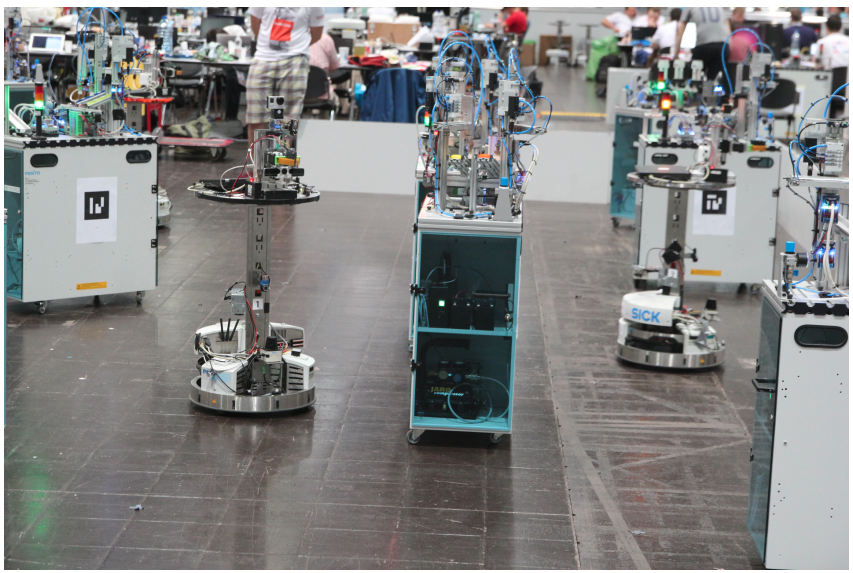
Robot Memory at a Glance

Database to store information of a robot about its environment

- **Domain:** Logistics and domestic service robots
- **Purpose:** Scalable storage and rich querying
- **Focus:** Knowledge sharing and hybrid reasoning for knowledge-based systems

Why do robots need a memory?



- Store and reason about world state
- Share information in multi-robot system

- Remember object sights
- Persistent storage
- Consistent information base for different components

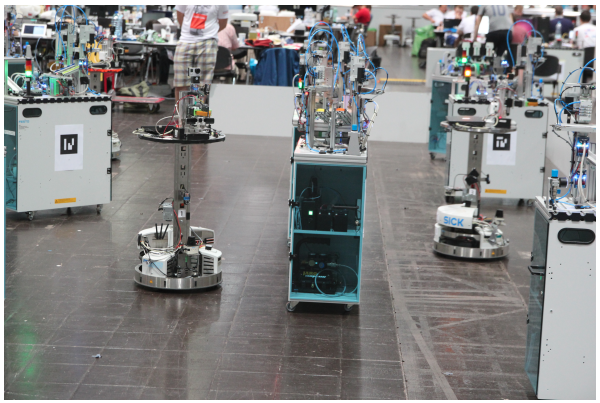
Robot Memory Goals

- Flexible storage and retrieval
- Spatio-temporal grounding
- Persistent storage

- Memory sharing between knowledge-based systems
- Distributed memory for multi-robot systems

- Computation on demand (*Computables*)
- Notification about updates (*Triggers*)

Application Domains



RoboCup Logistics League

- Production logistics in smart factory
- Share world model
  - between robots
  - between global planner and reasoner executive

RoboCup@Home

- Domestic service robots
- Collect knowledge about concrete environment
- Hybrid reasoning with spatio-temporal knowledge
- Persistent storage

Planners and Reasoners in Fawkes

CLIPS Rules Engine

- First-Order Logic forward chaining system
- Fact base and condition-action rules

$\Rightarrow$ Used for world model reasoning and execution monitoring

Planning Domain Definition Language (PDDL)

- Standardized language for planning problems
- Find action sequence through heuristic search

$\Rightarrow$ Used for finding global plans

Motion Planners

- Robot arm and locomotion collision avoidance
- Depend on geometric data

Robot Information Storage Systems

KnowRob [Tenorth and Beetz, 2013]

- Common sense reasoning with ontologies
- Based on Prolog
- Virtual knowledge base to interface perception

OpenRobots Ontology [Lemaignan et al., 2010]

- Common sense reasoning with ontologies
- Based on Java
- Events notifying about changes

- Not applicable for multi-robot systems
- Scalability, efficiency concerns
- Missing events / computation on demand

Document Orientation

- Documents: Sets of key-value pairs
- Java Script Object Notation (JSON)

```
{
  "key": "value",
  "subdocument": {"x":3, "y":1},
  "array": [{"n":0.1},{"n":2}]
}
```

- Denormalized (information bundled in documents)
- Schema free

$\Rightarrow$ Allows generic, flexible, and distributable robot memory

MongoDB Database System

- Scalable and widely used
- Query language with aggregation, MapReduce, JavaScript

```
db.environment.find(
  { object: "cup", color: {$ne: "red"}})
```

- Indexing for fast querying
- Distributable with Replica Sets
  Operations Log (Oplog) to forward changes
- Comparable good performance and scalability
  [Oliveira and del Val Cura, 2016, Li and Manoharan, 2013]

Related Work with MongoDB

Robot Database with MongoDB [Niemueller et al., 2012]

- Data logging for evaluation and fault analysis
- Generic and scalable storage with MongoDB
- Integration in Fawkes and ROS

Extensions of MongoDB

- Triggers with replication Oplog [Dwivedi and Dubey, 2016]

Terminology

Documents

$$\{(\text{"}object\text{"}, \text{"}cup\text{"}), (\text{"}position\text{"}, \{(\text{"}x\text{"}, 8), (\text{"}y\text{"}, 4)\})\}$$

- Sets of key-value pairs (unique keys)
- Finitely nested sub-documents

Robot Memory

- Composed of database and computables
- Database: Set of documents
- Computables: Functions yielding sets of documents

Computables

Perception

(at cup kitchen_counter)

PDDL-based Planner

Computables

Perception

{ object: ”cup”, position: {x: 8, y:4} }

(at cup kitchen_counter)

PDDL-based Planner

Computables

Perception

{ object: ”cup”, position: {x: 8, y:4} }

{ relation: “at”, object: ”cup”, place: “kitchen_counter” }

(at cup kitchen_counter)

PDDL-based Planner

Computables

Perception

{ object: ”cup”, position: {x: 8, y:4} }

Computable

Function
Query x State → Set of docs

Specification:
{ relation: “at”,
object: {$exists: true}}

{ relation: “at”, object: ”cup”, place: “kitchen_counter” }

(at cup kitchen_counter)

PDDL-based Planner

Computables

Perception

{ object: ”cup”, position: {x: 8, y:4} }

Computable

Function
Query x State → Set of docs

Specification:
{ relation: “at”,
object: {$exists: true}}

{ relation: “at”, object: ”cup”, place: “kitchen_counter” }

Mapping
Documents - Predicates

(at cup kitchen_counter)

PDDL-based Planner

Triggers

Perception

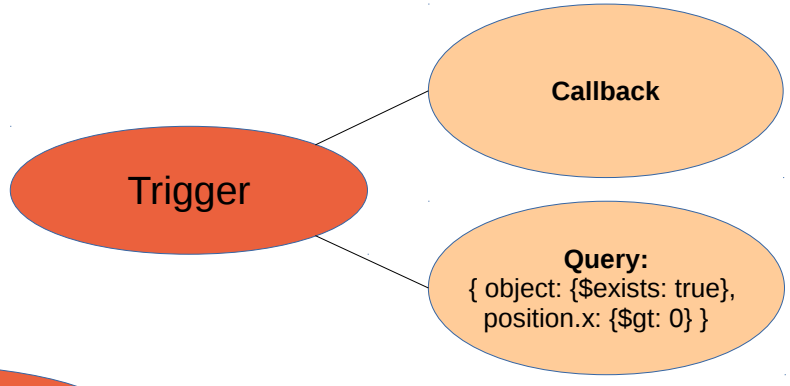
{ object: ”cup”, position: {x: 8, y:4} }

Motion Planner

Triggers

Perception

{ object: ”cup”, position: {x: 8, y:4} }

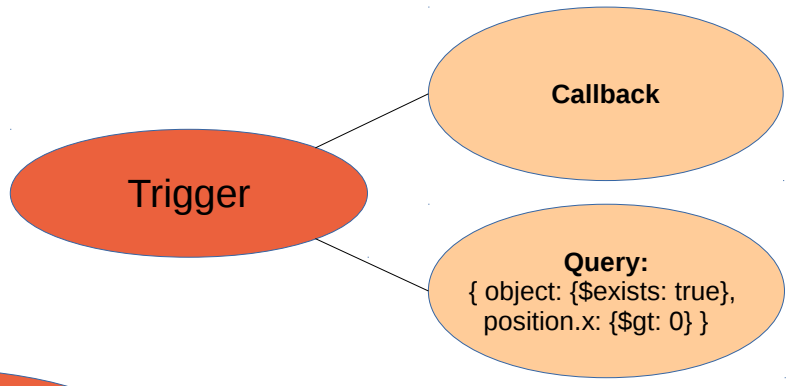


Motion Planner

Triggers

Perception

{ object: ”cup”, position: {x: 8, y:4} }
{ object: ”cereal”, position: {x: 8, y:3} }



Motion Planner

Triggers

Perception

{ object: ”cup”, position: {x: 8, y:4} }
{ object: ”cereal”, position: {x: 8, y:3} }

Oplog

{ op: "insert", ts: Timestamp(1485369072, 5),
o: {object: ”cereal”, position: {x: 7, y:4}} }

Trigger

Callback

Query:
{ object: {$exists: true},
position.x: {$gt: 0} }

Motion Planner

Triggers

Perception

{ object: ”cup”, position: {x: 8, y:4} }
{ object: ”cereal”, position: {x: 8, y:3} }

Oplog

{ op: "insert", ts: Timestamp(1485369072, 5),
o: {object: ”cereal”, position: {x: 7, y:4}} }

Trigger

Callback

Query:
{ object: {$exists: true},
position.x: {$gt: 0} }

Motion Planner

Triggers

Perception

{ object: ”cup”, position: {x: 8, y:4} }
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Oplog

{ op: "insert", ts: Timestamp(1485369072, 5),
o: {object: ”cereal”, position: {x: 7, y:4}} }

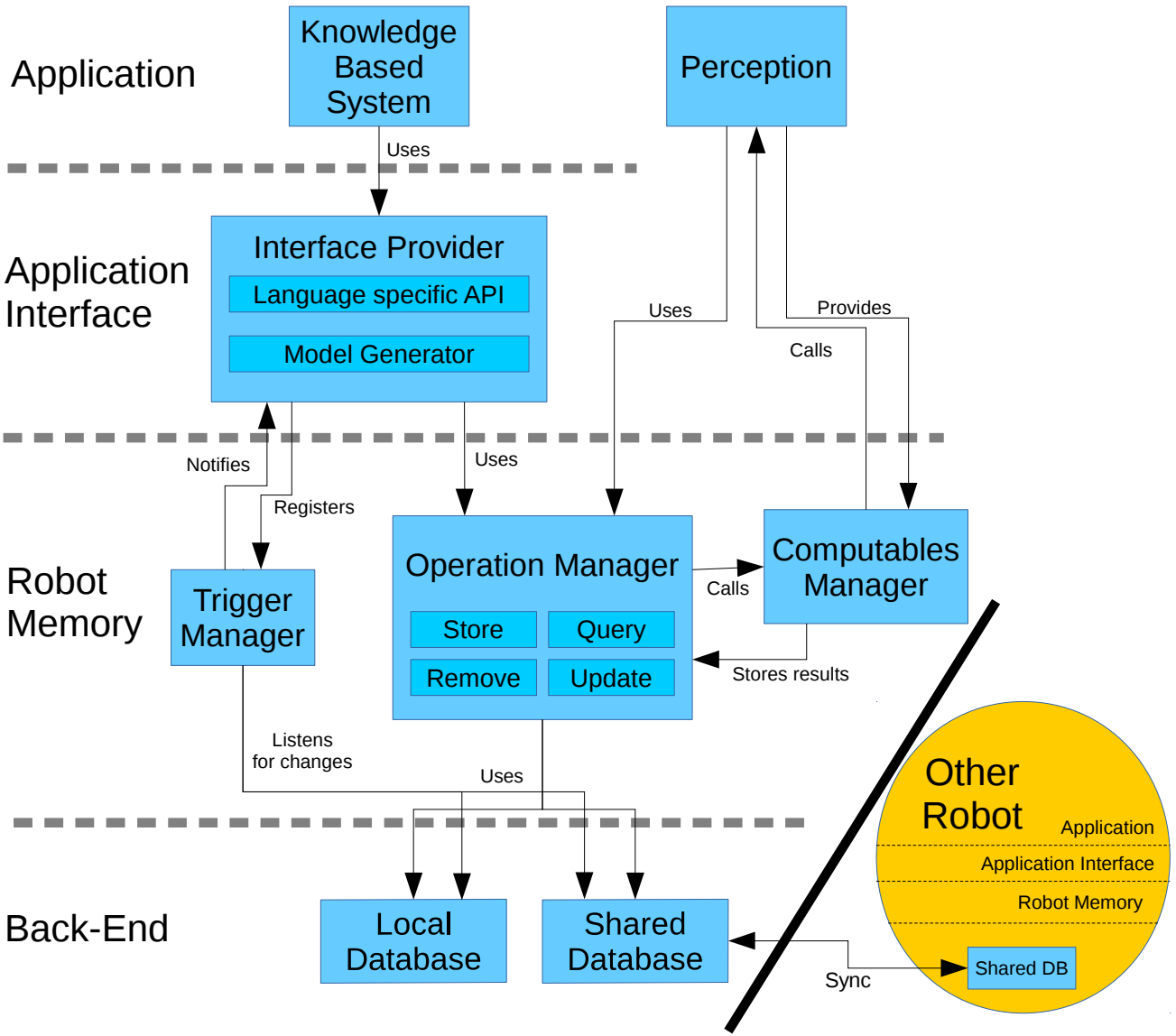
Trigger

Callback

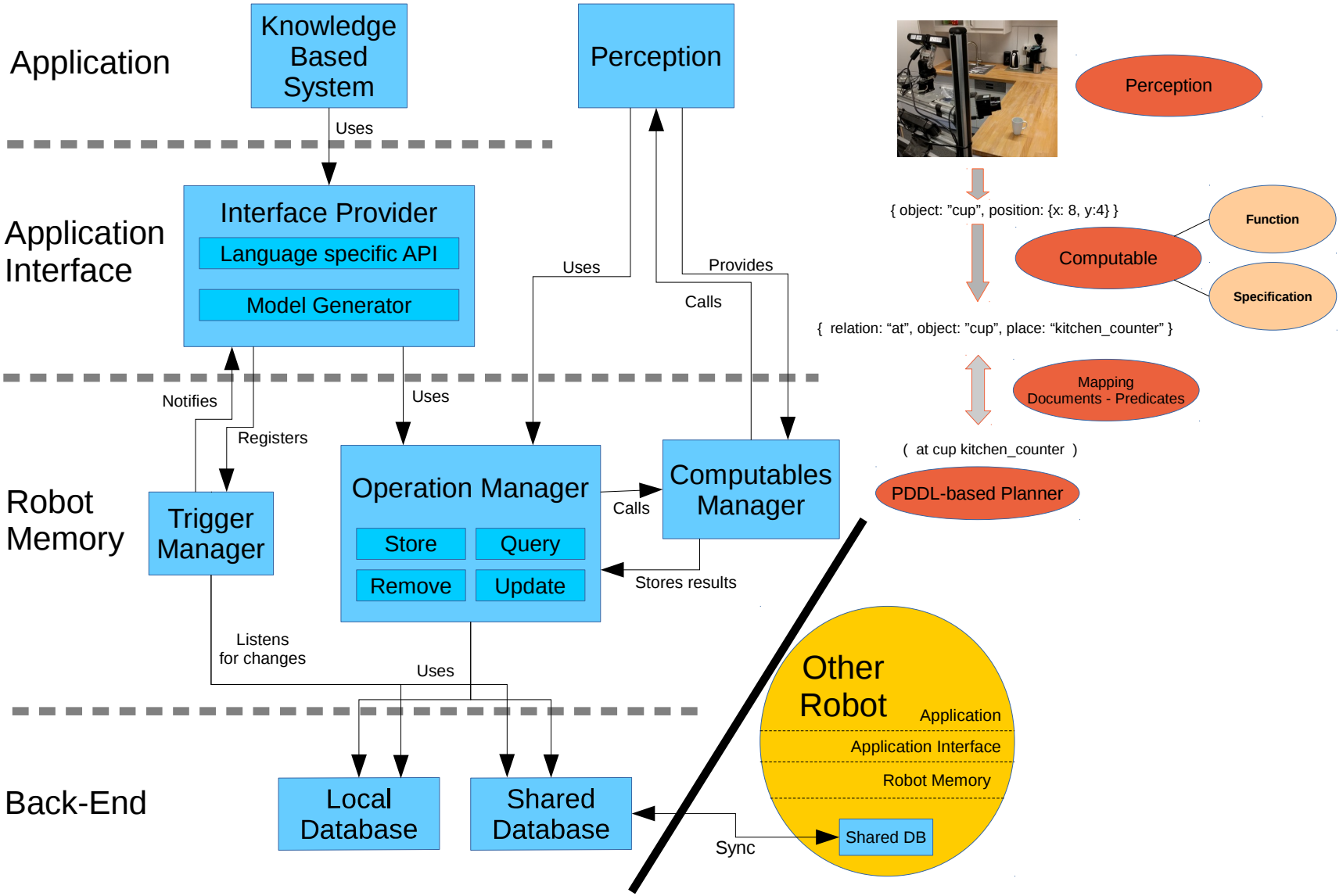
Query:
{ object: {$exists: true},
position.x: {$gt: 0} }

Motion Planner

Architecture



Architecture



Back-End and Robot Memory

Distribution in multi-robot system

- Write operations only on primary instance
- Eventual consistency on secondaries

Robot Memory

- Modifying queries and inserts
- Trigger and computable managers
- Caching of computed documents
- Automated start-up of MongoDB

CLIPS Interface

CLIPS Characteristics

- Fact base as working memory

```
(cap-station (name M-CS1) (loaded NONE) (caps-on-shelf 3))
```

- Condition-action rules
- Procedural functions

Robot Memory Interface

- Provide operation and traversal functions in CLIPS
- Mapping between facts and documents

```
{ relation: "cap-station", name: "M-CS1",
  loaded: "NONE", caps-on-shelf: NumberLong(3)}
```

- Assert trigger events as facts

PDDL Interface

PDDL Characteristics

- Domain definition and problem description as input
- Predicates represent information

```
(:goal (on A B))
(:init (on-table A) (on-table B))
```

Robot Memory Interface

- Mapping of documents to predicates
- Generation of problem description from template

```
(:goal <<GOAL>>)
(:init  <<#ONTABLE|{relation:'on-table'}>>
          (on-table <<object>>) <</ONTABLE>>))
```

```
{ relation: "on-table", object: "A"},
{ relation: "on-table", object: "B"}
```

- Parses resulting plans and inserts them as documents

OpenRAVE Interface

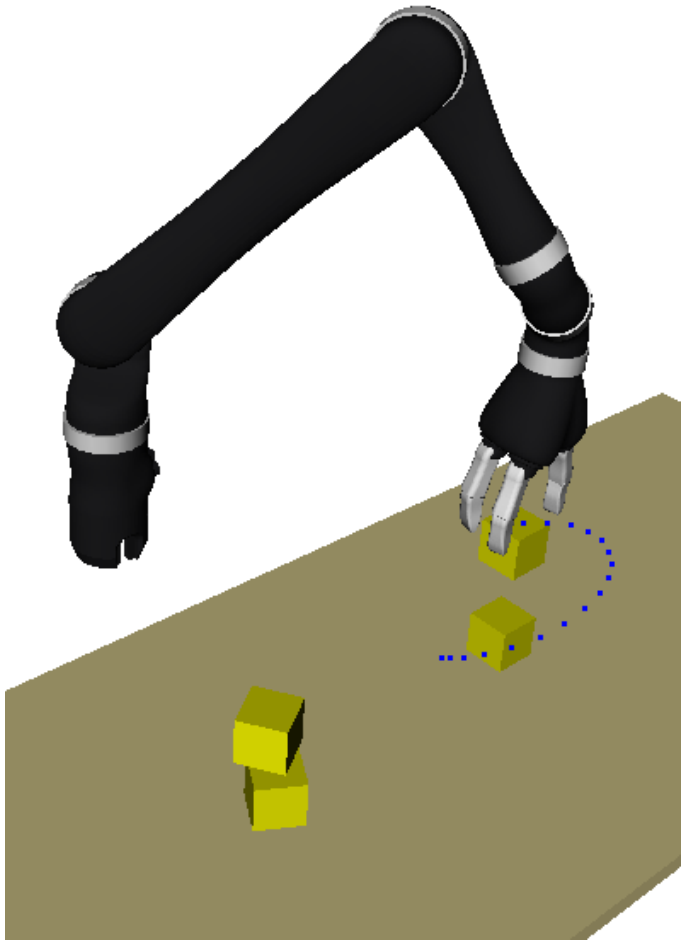
OpenRAVE Characteristics

- Geometric motion planner
- Operates in continuous space

Robot Memory Interface

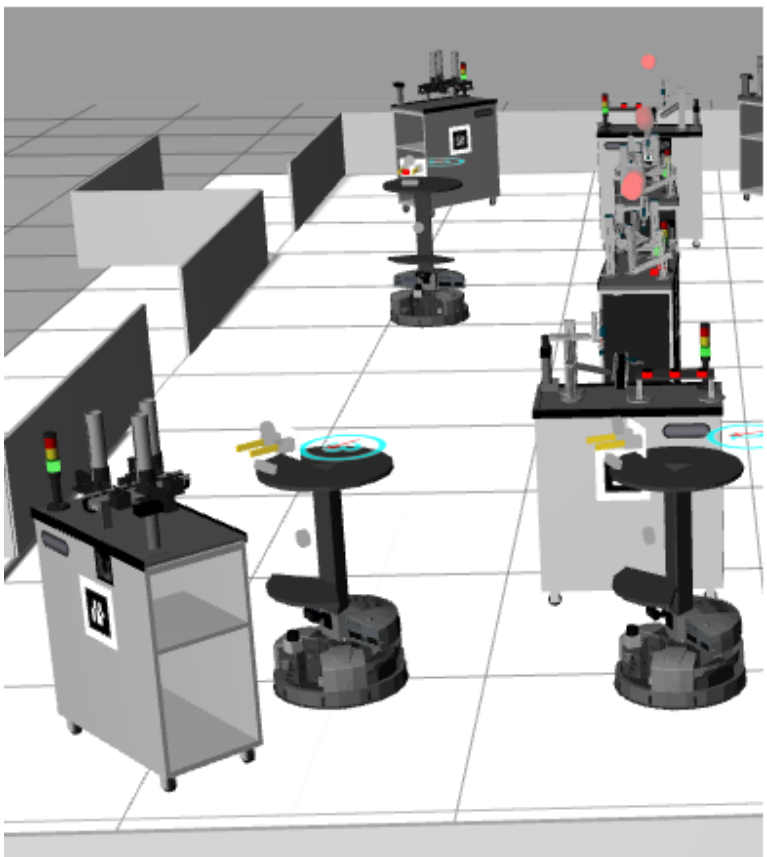
- Updates planner scene based on positions represented in documents

```
{
  block: "B",
  frame: "map",
  translation:
    [0.43, -0.04, 0.01]
}
```

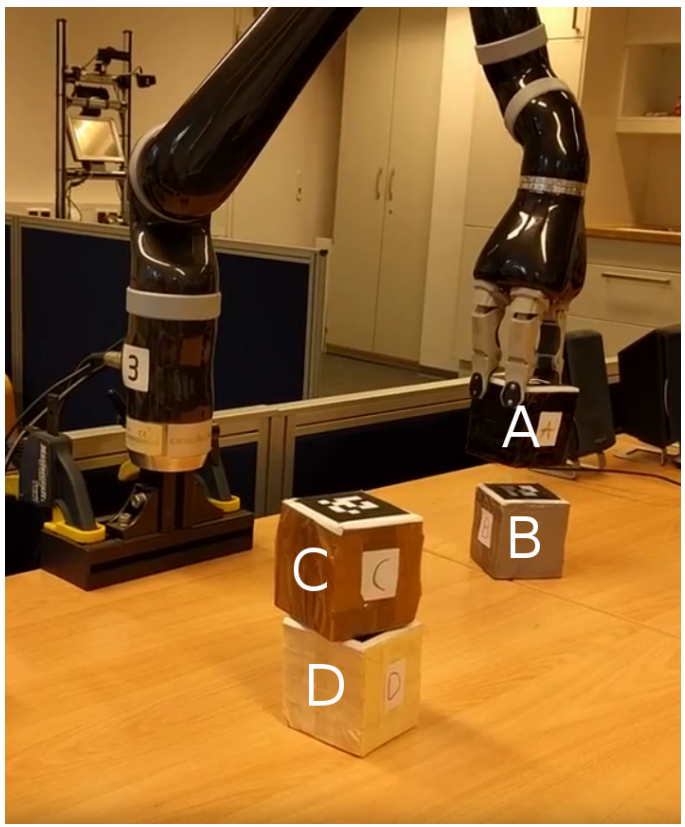


Application and evaluation scenarios

World model synchronization between robots in the RCLL



Blocks world with a robot arm



Qualitative Evaluation

Experience from evaluation scenarios

- Flexible storage and expressive querying
- Convenient memory sharing between KBS and in distributed system
- Allows hybrid reasoning with computables (e.g. `on-table` derived from geometric position)
- Triggers useful for worldmodel updates and messages

- Beneficial for AI/robot software development
- Especially for combining different planners/reasoners

Qualitative Evaluation: Limitations

Trade-offs / Limitations

- Trigger only for changes of single documents
- No direct trigger evaluation for computables
- Query complexity determined by application

Quantitative Evaluation

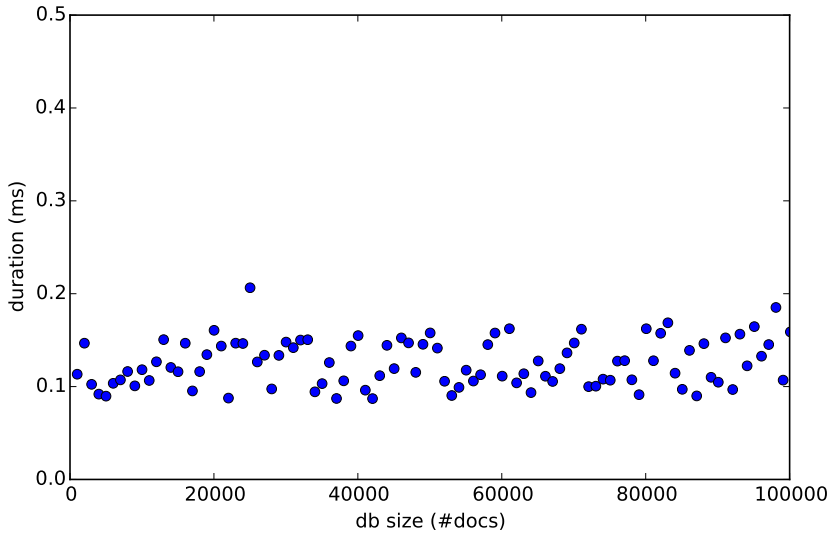
Tidy up scenario

- Robot Memory with information about objects

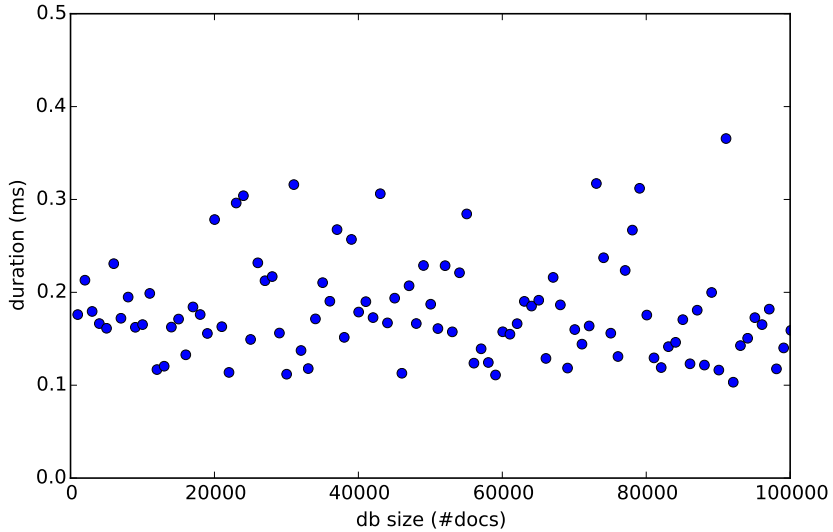
```
{ name: "coffee machine",
  position: "counter",
  tidied: "counter" },
{ name: "milk",
  position: "counter",
  tidied: "fridge" }
```

- Measure operation durations with increasing domain size
- With / without indexing

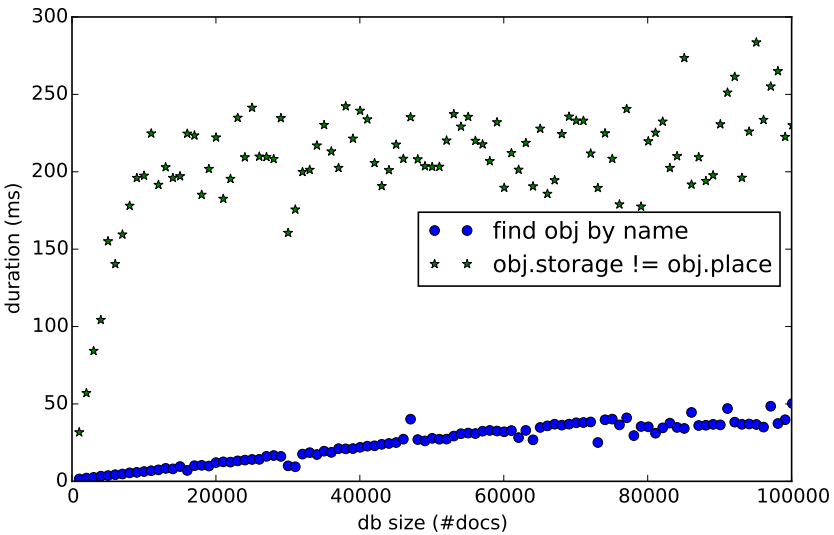
Duration of Robot Memory Operations I



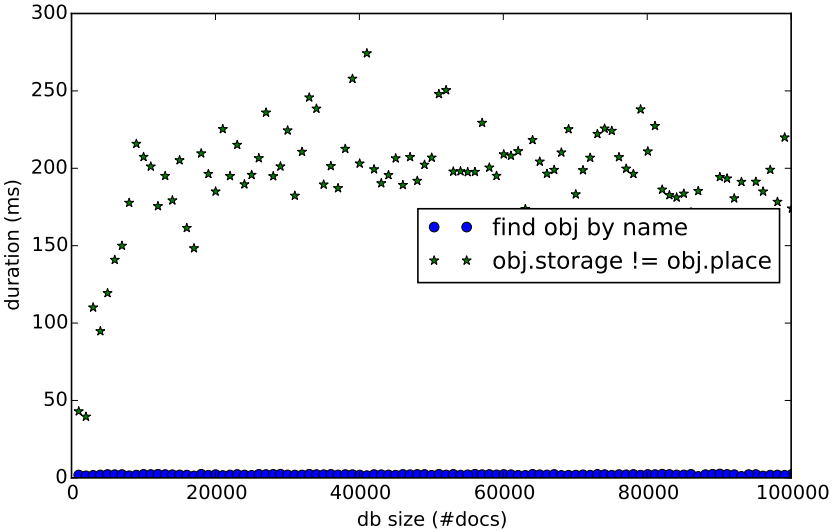
Insertions



Insertions with Indexing

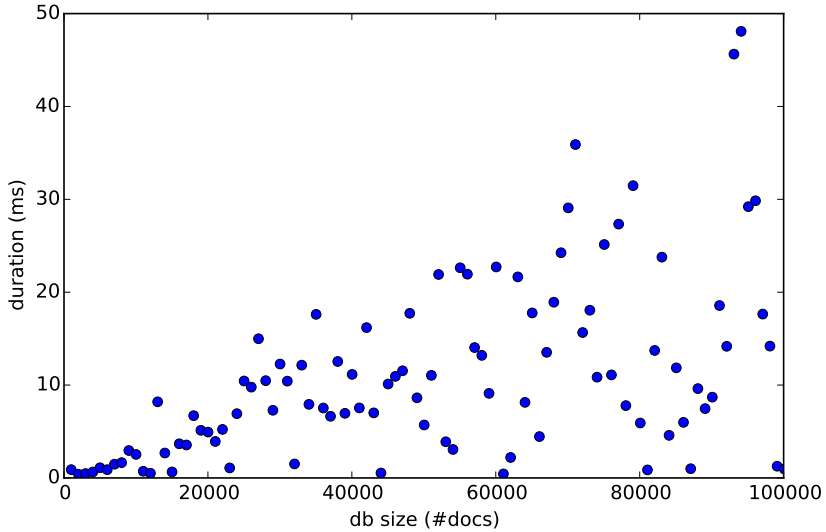


Queries

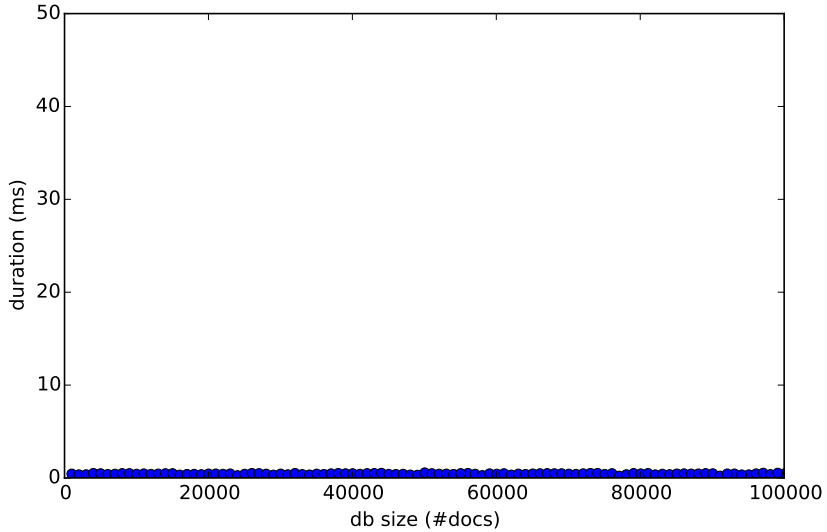


Queries with Indexing

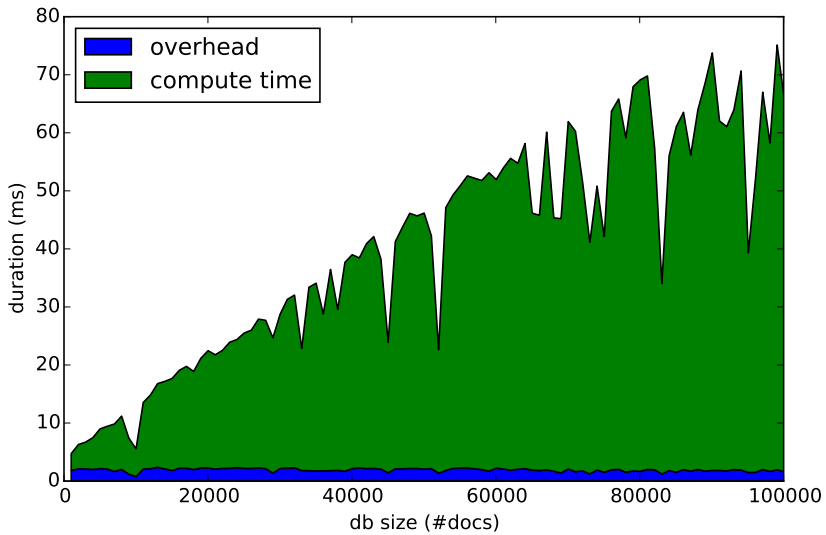
Duration of Robot Memory Operations II



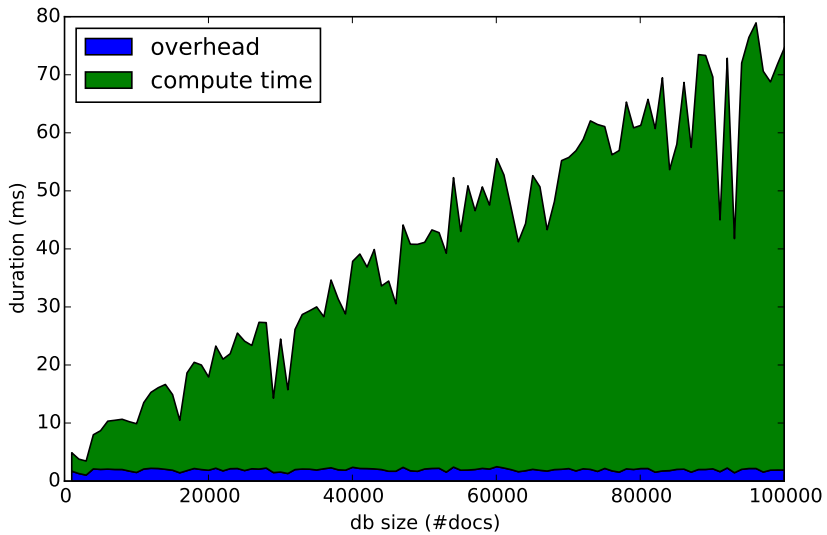
Updates



Updates with Indexes



Computables



Computables with Indexes

Foundation for Future Projects

Two projects currently using the Robot Memory

- Both for centralized global task planning in the RCLL
- Reactive ASP and real-time constraints
- PDDL with temporal aspects

Beneficial features

- Distributed memory shared by planner and executives
- CLIPS agent integration
- Triggers for notifications
- PDDL problem definition generation

Conclusion and Questions

Generic Robot Memory

flexible storage and expressive querying for hybrid reasoning and world model sharing between different KBS

- Document-oriented representation and querying
- Distributable and persistent
- Theoretical foundation
- Triggers for notification
- Computables
- Symbolic/spatio-temporal
- Beneficial and efficient in application scenarios
- Foundation for future projects

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Int. Journal of Robotics Research (IJRR).

Theoretical Foundation

Definition of documents representing knowledge

e.g. $\{(\text{"}object\text{"}, \text{"}cup\text{"}), (\text{"}room\text{"}, \text{"}kitchen\text{"}), (\text{"}position\text{"}, \{(\text{"}x\text{"}, 8), (\text{"}y\text{"}, 4)\})\}$

1. **Keys:** $\mathcal{K} := \Sigma^*$
2. **Atomic values:** $\mathcal{V}_0$ are constants
3. **Unnested key-value pairs:** $\mathcal{P}_0 := \mathcal{K} \times \mathcal{V}_0$
4. **Unnested documents:**

$$\mathcal{D}_0 := \{d \in \mathbb{P}(\mathcal{P}_0) | \forall (k, v), (k', v') \in d, k \neq k' \vee (k, v) = (k', v')\}$$

With nesting

1. **Values:** $\mathcal{V}_n := \mathcal{V}_{n-1} \cup \mathcal{D}_{n-1}$
2. **Key-Value Pairs:** $\mathcal{P}_n := \mathcal{K} \times \mathcal{V}_n$
3. **Documents:**

$$\mathcal{D}_n := \{d \in \mathbb{P}(\mathcal{P}_n) | \forall (k, v), (k', v') \in d, k \neq k' \vee (k, v) = (k', v')\}$$

Finitely nested documents: $\mathcal{D} = \cup_{n \in \mathbb{N}} \mathcal{D}_n$

Values: $\mathcal{V} = \cup_{n \in \mathbb{N}} \mathcal{V}_n$

Theoretical Foundation

Definition Robot Memory

1. **Database:** finite set $\mathcal{DB} \subset \mathcal{D}$
2. **Query:** represented by document $q \in \mathcal{D}$
   yields set of documents $r \subset \mathcal{DB}$ as result
   e.g. $q = \{(\text{"}\textit{object}\text{"}, \text{"}\textit{cup}\text{"}), (\text{"}\textit{room}\text{"}, \text{"}\textit{kitchen}\text{"})\}$
3. **Computable:** $f : \mathcal{D} \to \mathbb{P}(\mathcal{D})$
4. **Set of Computables:** $\mathcal{C}$
5. **Robot Memory:** $\mathcal{RM} = (\mathcal{DB}, \mathcal{C})$
6. **Memorized Documents:** $mem(\mathcal{RM}) = \mathcal{DB} \cup \bigcup_{f \in \mathcal{C}} f(\mathcal{D})$

Theoretical Foundation

Mapping into PDDL

e.g. $map_p(\{(\text{"}predicate\text{"}, \text{"}at\text{"}), (\text{"}object\text{"}, \text{"}cup\text{"}), (\text{"}room\text{"}, \text{"}kitchen\text{"})\})$
$= at(map_f(\text{"}cup\text{"}), map_f(\text{"}kitchen\text{"})) = at(cup, kitchen).$

1. **Predicate symbols $\mathcal{R}$, Function symbols $\mathcal{F}$**
2. **Name mapping:**

$$name_{pred} : \mathcal{R} \to \Sigma^* \text{ and } name_{func} : \mathcal{F} \to \Sigma^*$$
$$name_{pred-atr} : \mathcal{R} \times \mathbb{N} \to \mathcal{K} \text{ and } name_{func-atr} : \mathcal{F} \times \mathbb{N} \to \mathcal{K}$$

3. **Map to predicate:**

$map_p(d) = p(map_f(v_1), ..., map_f(v_n))$, iff p is a n-array predicate in $\mathcal{R}$,
$(\text{"}predicate\text{"}, name_{pred}(p)) \in d, \forall i \in \{1..n\}(name_{pred-atr}(p, i), v_i) \in d$
$map_p(d) = nil_p, otherwise$

Theoretical Foundation

Mapping into PDDL

e.g. $map_p(\{(\text{"}predicate\text{"}, \text{"}at\text{"}), (\text{"}object\text{"}, \text{"}cup\text{"}), (\text{"}room\text{"}, \text{"}kitchen\text{"})\})$
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$$name_{pred} : \mathcal{R} \to \Sigma^* \text{ and } name_{func} : \mathcal{F} \to \Sigma^*$$
$$name_{pred-atr} : \mathcal{R} \times \mathbb{N} \to \mathcal{K} \text{ and } name_{func-atr} : \mathcal{F} \times \mathbb{N} \to \mathcal{K}$$

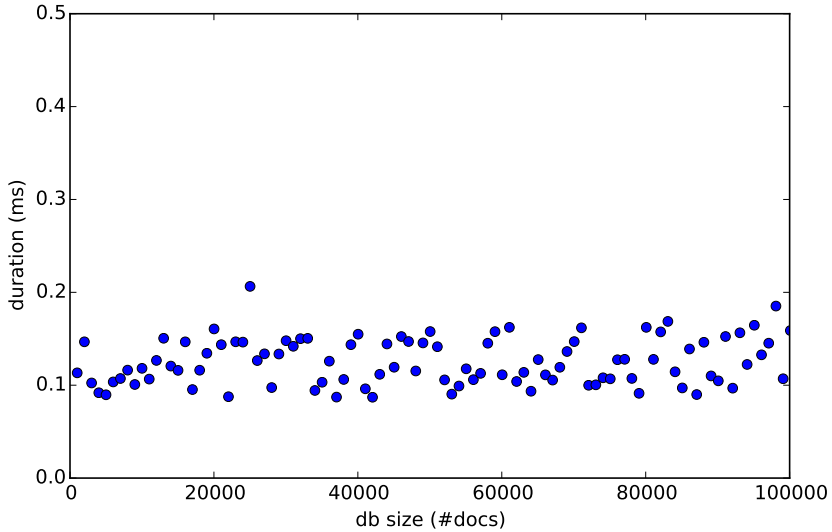
3. **Map to predicate**
4. **Map to function term:**

$map_f(v) = v, v \in \mathcal{V}_0$
$map_f(d) = f(map_f(v_1), ..., map_f(v_n)),$ iff f is a n-array function in $\mathcal{F}$,
$(\text{"}function\text{"}, name_{func}(f)) \in d, \forall i \in \{1..n\}(name_{func-atr}(f, i), v_i) \in d$
$map_f(d) = nil_f, otherwise$

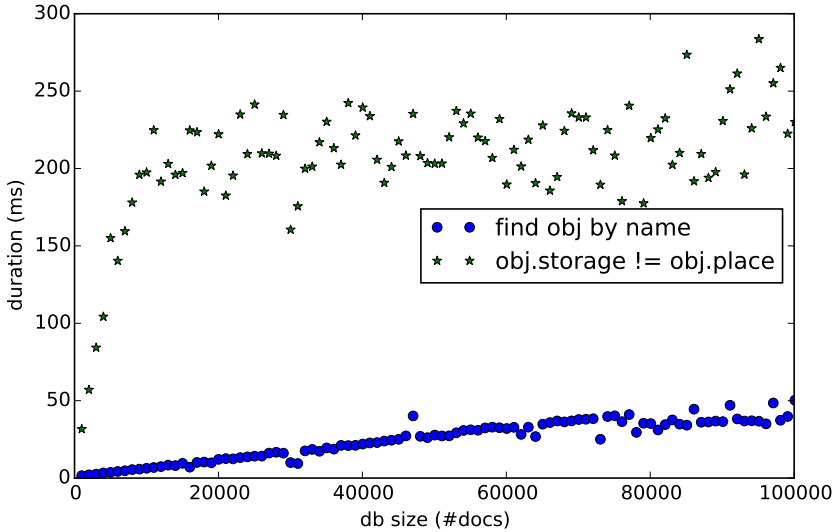
Trigger/Oplog document

```
{
  ns: "syncedrobmem.clipswm",
  ts: Timestamp(1485369072, 5),
  op: "i",
  o: {
    _id : ObjectId("58c14a14"),
    relation: "order",
    id: 2,
    complexity: "C0",
    delivery-gate: 3,
    quantity-requested: 1,
    quantity-delivered: 0,
    begin: 209,
    end: 282 }
}
```

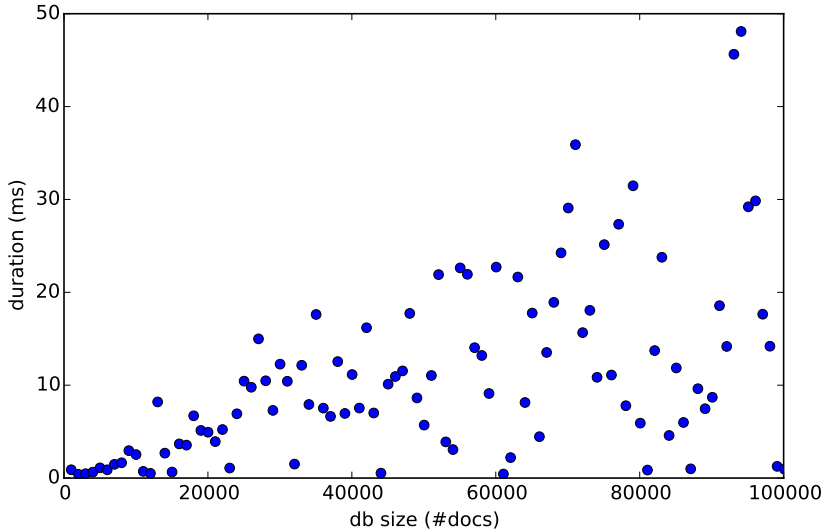
Evaluation: Duration without Indexing



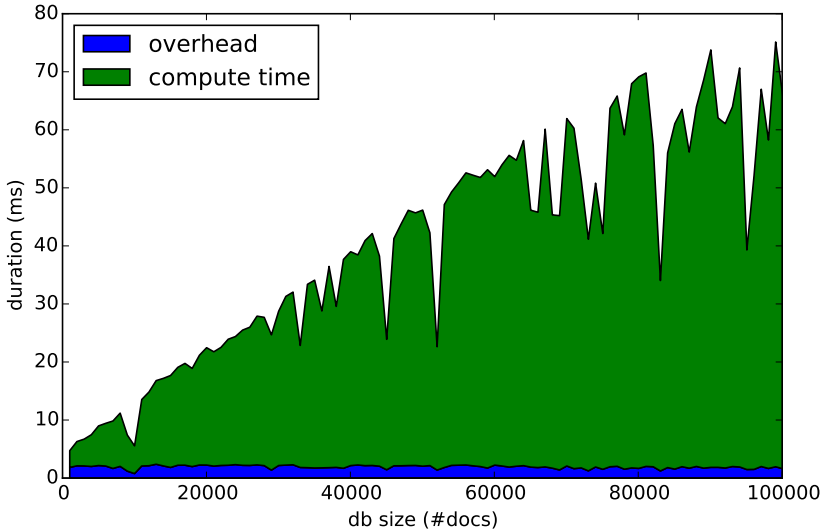
(a) Insertions



(b) Queries

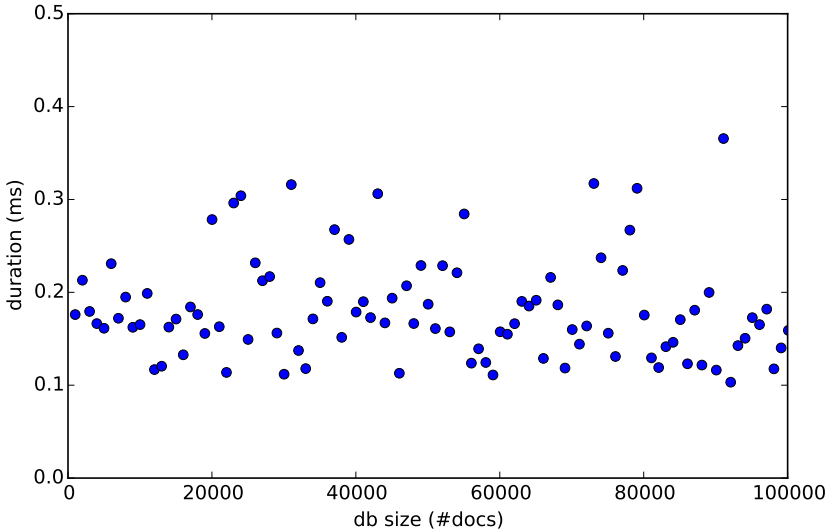


(c) Updates

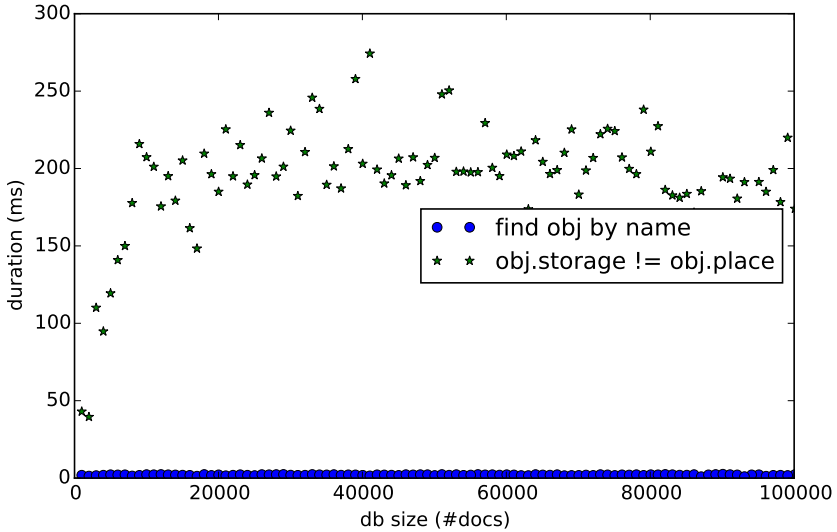


(d) Computables

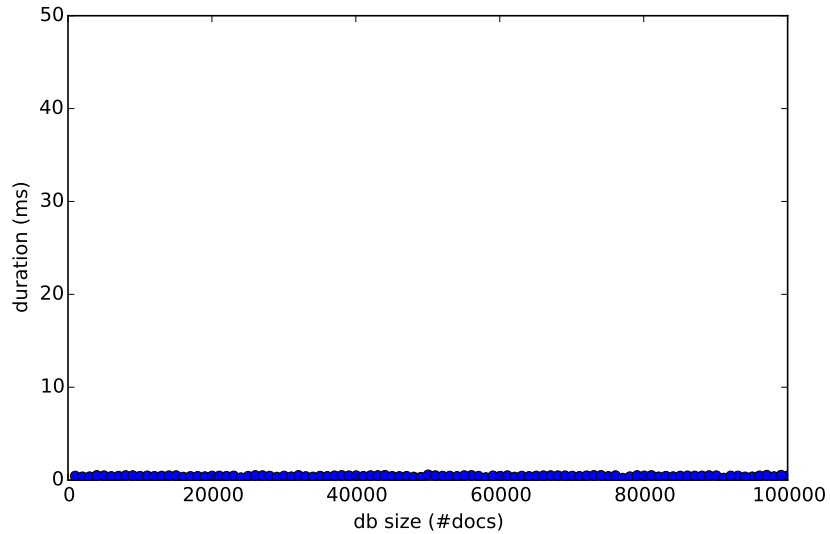
Evaluation: Durations with Indexing



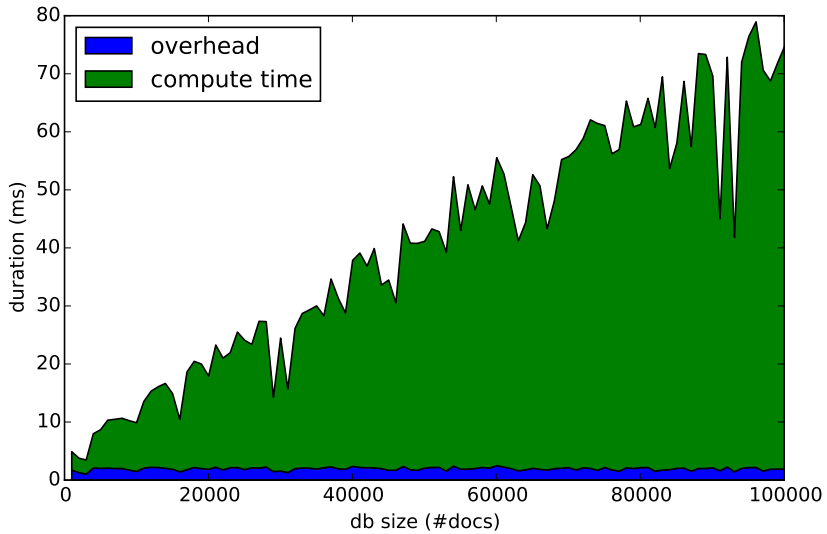
(a) Insertions



(b) Queries

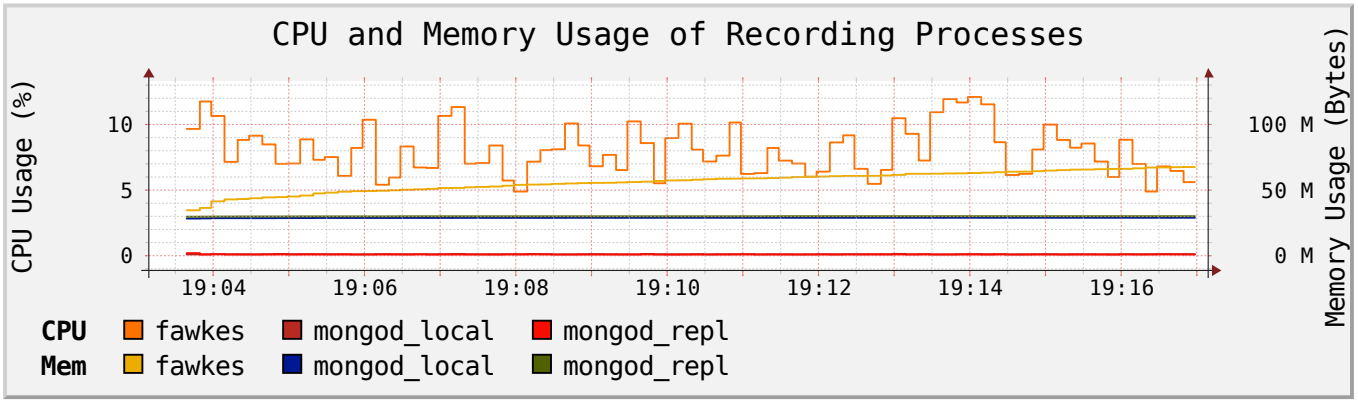


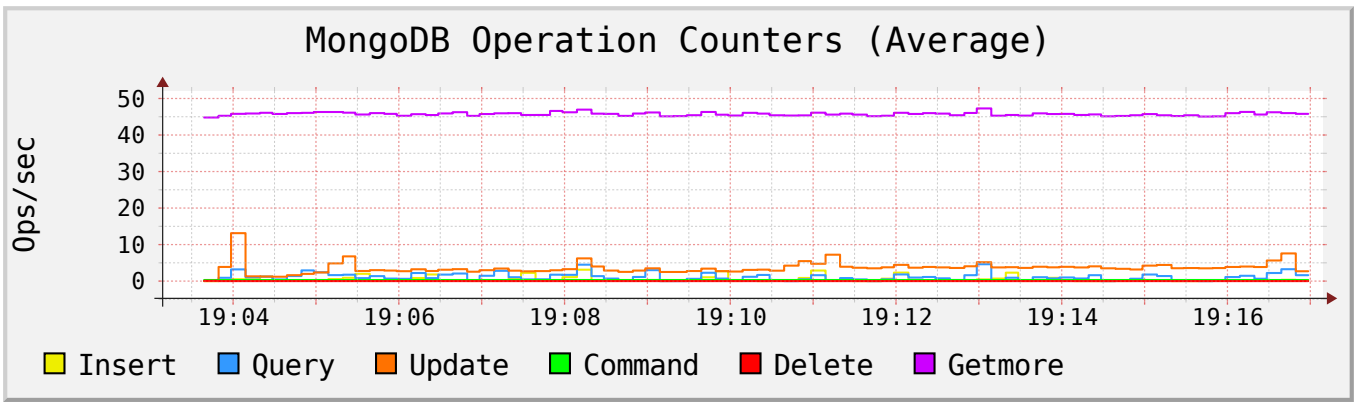
(c) Updates

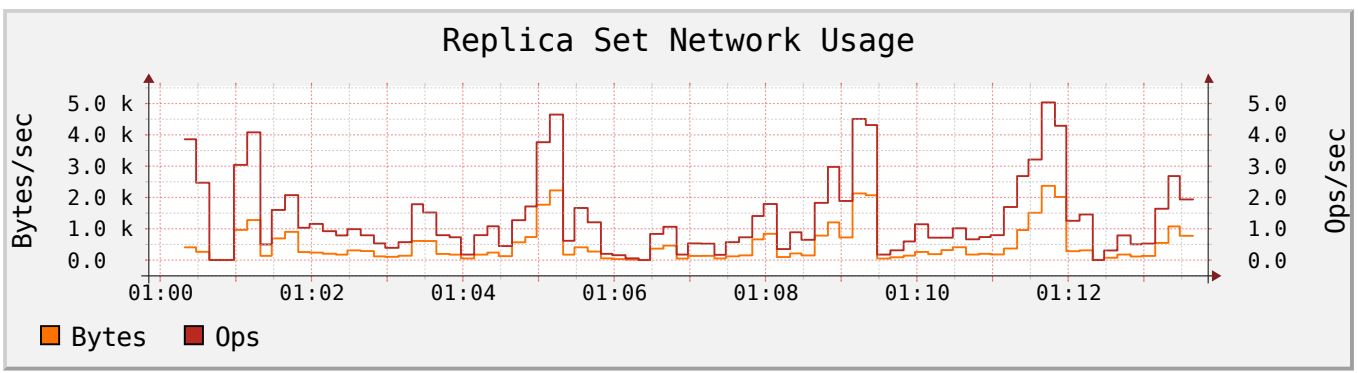


(d) Computables

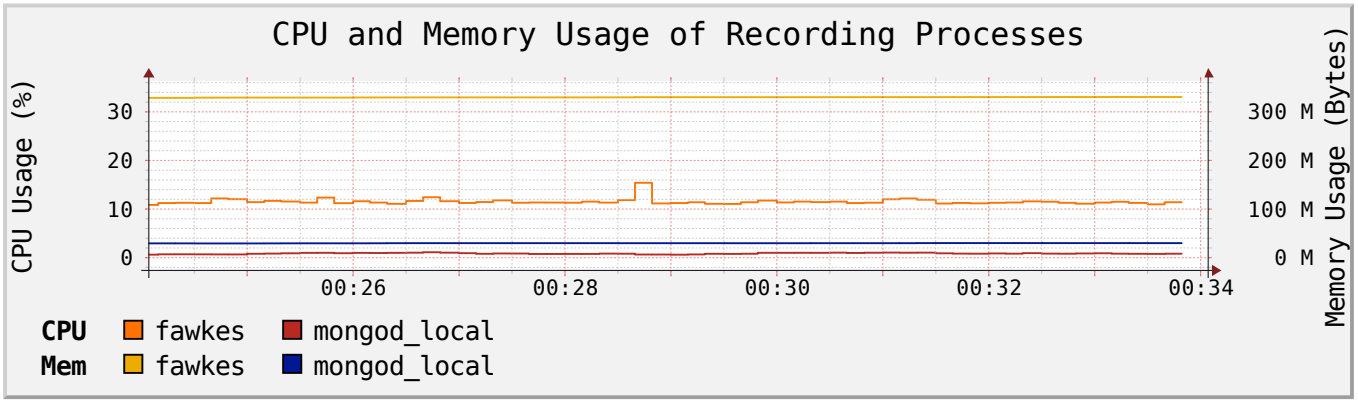
Evaluation: Benchmarks RCLL

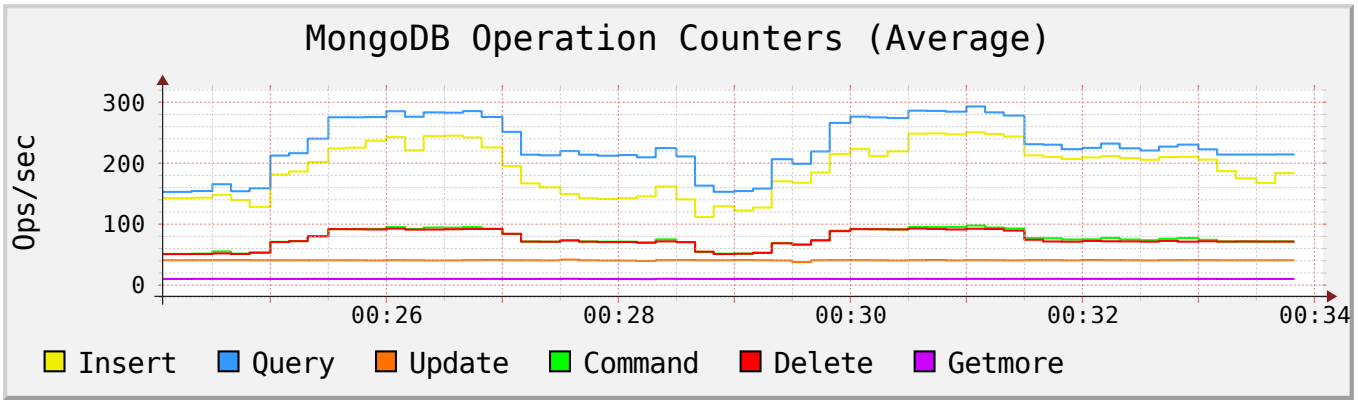






Evaluation: Benchmarks Blocks World





Fawkes

Fawkes

- Robot Software Framework
- Component-based software design
- Hybrid blackboard communication infrastructure with specific interfaces/messages

$\Rightarrow$ Robot Memory available as Fawkes plugin