Manage the Data from Indoor Spaces: Models, Indexes & Query Processing

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Overview

About This Work...

Scalable Continuous Range Monitoring of Moving Objects in Symbolic Indoor Space. [2]
B. Yang, H. Lu, and C. S. Jensen.

- Published in *CIKM' 2009*.
- Application: continuously monitor indoor moving objects for space use analysis or security purposes.
- An incremental, query-aware continuous range query processing technique for objects moving in indoor space.
- Use maximum speed constraint on object movement to refine the uncertain results.

Motivation

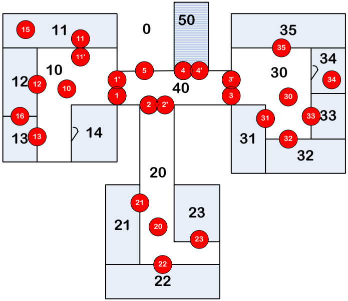
- People spend much time in indoor spaces.
- Indoor spaces are becoming increasingly larger and complex.
  - E.g., London Underground, 268 stations, 408 kilometers of network, +4 million daily passengers.
- Indoor monitoring of people can help support.
  - space use analysis
  - security purposes

Preliminaries: Indoors vs. Outdoors

- Modeling of indoor spaces do not assume
  - Euclidean space. (since obstacles render movement more constrained)
  - Spatial network. (since indoor movement is less constrained than movements in polylines)
- Instead indoor spaces are characterized by entities [1].
  - Doors, rooms, hallways, staircase, etc.
- **Symbolic models** are more suitable [3].
- *GPS* and *cellular tracking* do not work indoors.
- Sensing devices are used to detect objects within their activation range, e.g., RFID readers or Bluetooth hotspots.

Positioning Devices Deployment Graph

- Two types of positioning devices
  - Partitioning Device – *undirected* (**UP**), e.g., d_{21} – *directed* (**DP**), e.g., d_{11} and $d_{11'}$
  - Presence Device – (**PR**)
- Note an indoor space is partitioned into *activation ranges* and *cells*



Deployment Graph

- $G = \{C, E, \Sigma_{devices}, l_E\}$
- C: the set of cells
- E: the set of edges, $\{c_i, c_j\}$ where $c_i, c_j \in C$
- $\Sigma_{devices}$: a mapping from $deviceID$ to activation range and type
- l_E maps an edge to a set of positioning devices, i.e., $E \rightarrow 2^{\Sigma_{devices}}$

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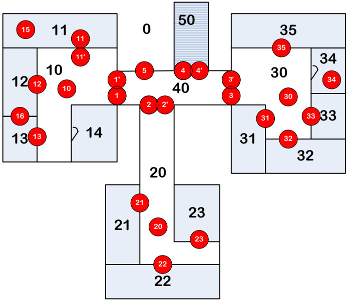
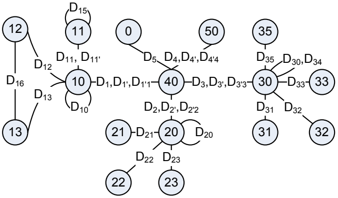
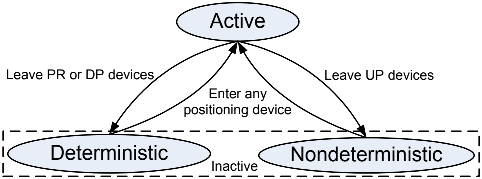




States of Indoor Moving Objects



- An object is in an **active state** when it is inside the activation range of a positioning device.
- Otherwise the object is in an **inactive state**
- When an object is in the inactive state it is
  - **nondeterministic** if it can be in more than one cell
  - **deterministic** if it is in one specific cell

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RFID Deployment Graph Construction

Algorithm 1 updateHashTables(Pre-processing output O, DeploymentGraph G)

IDSet $sSet \leftarrow \emptyset$;
if $O.flag = ENTER$ **then**
  $sSet \leftarrow OHT[O.objectID].IDSet$;
  if $OHT[O.objectID].STATE = Active$ **then**
    for the single element c in $sSet$ **do**
      Delete $O.objectID$ from $DHT[c]$;
  else if $OHT[O.objectID].STATE = Deterministic$ **then**
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    for each element c in $sSet$ **do**
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  Add $O.objectID$ to $DHT[O.deviceID]$;
  $OHT[O.objectID] \leftarrow (Active, O.t, \{O.deviceID\})$;
else
  Delete $O.objectID$ from $DHT[O.deviceID]$;
  $sSet \leftarrow G.\ell_E^{-1}(O.deviceID)$;
  if $Devices(O.deviceID).TYPE$ = UP **then**
    $OHT[O.objectID] \leftarrow (Nondeterministic, O.t, sSet)$;
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5. Lines 18–25: if the device is undirected, set O in OHT and add O to CNHT for the cells in sSet, else apply the same to CDHT

Continuous Range Monitoring: Query Definition

- A *Continuous Range Monitoring Query* (CRMQ)
  - takes an **indoor spatial range** R as parameter
  - keeps reporting the objects when it is registered for a certain time frame $[t_s, t_e]$
- The **query result** $\mathcal{M}$ – the set of moving objects in R - is maintained as follows:

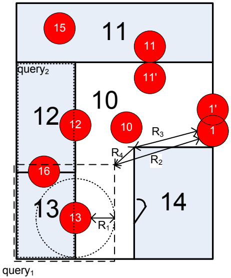
  $$\forall t \in [t_s, t_e] : o \in CRMQ[R](\mathcal{M}) \Leftrightarrow o \in \mathcal{M} \wedge pos_{\mathcal{M}}(o, t) \in R$$

  where $pos_{\mathcal{M}}$ is a function that can determine the position of object o at time t
- Multiple monitoring queries may coexist

Critical Devices

For a CRMQ query, a *critical device* is one from which a new observation can potentially change the query result (either certain or uncertain). Use a *Device Query Hash Table* (DQHT) to record the relationships:

$$DQHT[deviceID] = \{(queryID, CLASS)\}$$



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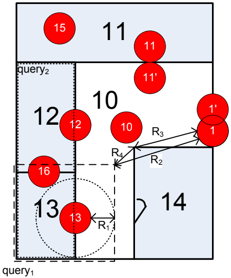

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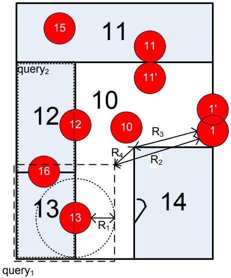

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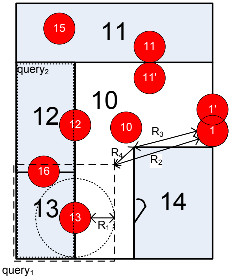

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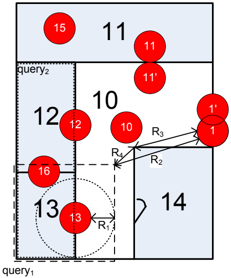

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- CLASS4 – Device is disjoint from R and at least one of its corresponding cells in $C_{ic} = \{c | c \sqcap R \neq \varnothing\}$, e.g., $(device_1, query_1)$

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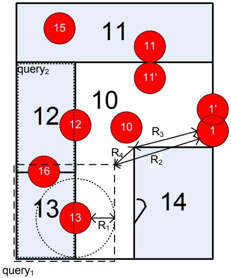

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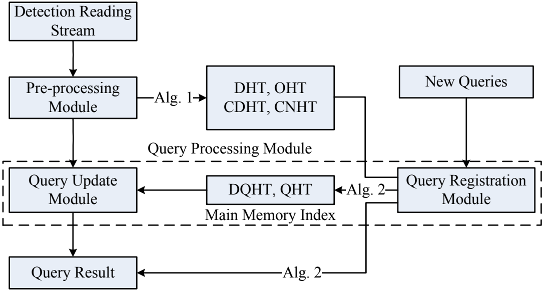
- CLASS5 – Device is disjoint from R and at least one of its corresponding cells in $C_{ex} = \{c | \{c, c'\} \in G.E, c' \in C_{ic}\}$, but none of them are in C_{ic}, e.g., $(device_{10}, query_2)$

Query Registration

- To handle concurrent CRMQs, a *Query Hash Table* is created hold the results
    - $QHT[queryID] = (CR, UR);\ CR \subseteq O_{indoor}, UR \subseteq O_{indoor}$
    - where CR is the certain result and UR is the uncertain result
- Overview



Query Registration Algorithm (I)

Algorithm 2 register (Range R, DeploymentGraph G)

deviceSet $D_c \leftarrow \emptyset$, $D_{uc} \leftarrow \emptyset$;
cellSet $C_c \leftarrow \emptyset$, $C_{uc} \leftarrow \emptyset$, $C_{ex} \leftarrow \emptyset$;
objectSet $R_c \leftarrow \emptyset$, $R_{uc} \leftarrow \emptyset$;
CriticalDeviceList(deviceID, CLASS) $cd \leftarrow \emptyset$;
Generate a new identifier $queryID$ for the query;
$D_c \leftarrow$ Devices that are covered by R;
$D_{uc} \leftarrow$ Devices that intersect with R;
$C_c \leftarrow$ Cells which are covered by R;
$C_{uc} \leftarrow$ Cells that intersect with R;
for each device d in D_c **do**
    if all the cells in $G.\ell_E^{-1}(d)$ are in C_c **then**
        Add (d, $CLASS1$) to cd;
    else if one of the cells in $G.\ell_E^{-1}(d)$ is in C_{uc} **then**
        Add (d, $CLASS2$) to cd;
for each device d in D_{uc} **do**
    Add (d, $CLASS3$) to cd;
for each edge e in G **do**
    if $(C_c \cup C_{uc}) \cap e \neq \emptyset$ AND $(C_c \cup C_{uc}) \cap e \neq (C_c \cup C_{uc})$ **then**
        if $G.\ell_E(e) \notin cd.deviceID$ **then**
            Add $(G.\ell_E(e)$, $CLASS4)$ to cd;
        $C_{ex} \leftarrow C_{ex} \cup e \setminus (C_c \cup C_{uc})$;
for each edge e in G **do**
    if $C_{ex} \cap e \neq \emptyset$ **then**
        if $G.\ell_E(e) \notin cd.deviceID$ **then**
            Add $(G.\ell_E(e)$, $CLASS5)$ to cd;

Query Registration Algorithm (I)

Algorithm 2 register (Range R, DeploymentGraph G)

1: deviceSet $D_c \leftarrow \emptyset$, $D_{uc} \leftarrow \emptyset$;
2: cellSet $C_c \leftarrow \emptyset$, $C_{uc} \leftarrow \emptyset$, $C_{ex} \leftarrow \emptyset$;
3: objectSet $R_c \leftarrow \emptyset$, $R_{uc} \leftarrow \emptyset$;
4: CriticalDeviceList(deviceID, CLASS) $cd \leftarrow \emptyset$;
5: Generate a new identifier $queryID$ for the query;
6: $D_c \leftarrow$ Devices that are covered by R;
7: $D_{uc} \leftarrow$ Devices that intersect with R;
8: $C_c \leftarrow$ Cells which are covered by R;
9: $C_{uc} \leftarrow$ Cells that intersect with R;
10: **for** each device d in D_c **do**
11:     **if** all the cells in $G.\ell_E^{-1}(d)$ are in C_c **then**
12:         Add (d, $CLASS1$) to cd;
13:     **else if** one of the cells in $G.\ell_E^{-1}(d)$ is in C_{uc} **then**
14:         Add (d, $CLASS2$) to cd;
15: **for** each device d in D_{uc} **do**
16:     Add (d, $CLASS3$) to cd;
17: **for** each edge e in G **do**
18:     **if** $(C_c \cup C_{uc}) \cap e \neq \emptyset$ AND $(C_c \cup C_{uc}) \cap e \neq (C_c \cup C_{uc})$ **then**
19:         **if** $G.\ell_E(e) \notin cd.deviceID$ **then**
20:             Add ($G.\ell_E(e)$, $CLASS4$) to cd;
21:         $C_{ex} \leftarrow C_{ex} \cup e \setminus (C_c \cup C_{uc})$;
22: **for** each edge e in G **do**
23:     **if** $C_{ex} \cap e \neq \emptyset$ **then**
24:         **if** $G.\ell_E(e) \notin cd.deviceID$ **then**
25:             Add ($G.\ell_E(e)$, $CLASS5$) to cd;

1. Lines 1–9: Initialization

Query Registration Algorithm (I)

Algorithm 2 register (Range R, DeploymentGraph G)

1: deviceSet $D_c \leftarrow \emptyset$, $D_{uc} \leftarrow \emptyset$;
2: cellSet $C_c \leftarrow \emptyset$, $C_{uc} \leftarrow \emptyset$, $C_{ex} \leftarrow \emptyset$;
3: objectSet $R_c \leftarrow \emptyset$, $R_{uc} \leftarrow \emptyset$;
4: CriticalDeviceList(deviceID, CLASS) $cd \leftarrow \emptyset$;
5: Generate a new identifier $queryID$ for the query;
6: $D_c \leftarrow$ Devices that are covered by R;
7: $D_{uc} \leftarrow$ Devices that intersect with R;
8: $C_c \leftarrow$ Cells which are covered by R;
9: $C_{uc} \leftarrow$ Cells that intersect with R;
10: **for** each device d in D_c **do**
11:     **if** all the cells in $G.\ell_E^{-1}(d)$ are in C_c **then**
12:         Add (d, $CLASS1$) to cd;
13:     **else if** one of the cells in $G.\ell_E^{-1}(d)$ is in C_{uc} **then**
14:         Add (d, $CLASS2$) to cd;
15: **for** each device d in D_{uc} **do**
16:     Add (d, $CLASS3$) to cd;
17: **for** each edge e in G **do**
18:     **if** $(C_c \cup C_{uc}) \cap e \neq \emptyset$ AND $(C_c \cup C_{uc}) \cap e \neq (C_c \cup C_{uc})$ **then**
19:         **if** $G.\ell_E(e) \notin cd.deviceID$ **then**
20:             Add ($G.\ell_E(e)$, $CLASS4$) to cd;
21:         $C_{ex} \leftarrow C_{ex} \cup e \setminus (C_c \cup C_{uc})$;
22: **for** each edge e in G **do**
23:     **if** $C_{ex} \cap e \neq \emptyset$ **then**
24:         **if** $G.\ell_E(e) \notin cd.deviceID$ **then**
25:             Add ($G.\ell_E(e)$, $CLASS5$) to cd;

1. Lines 1–9: Initialization
2. Lines 10–14: Add possible devices to CriticalDeviceList cd (CLASS1 and CLASS2)

Query Registration Algorithm (I)

Algorithm 2 register (Range R, DeploymentGraph G)

1: deviceSet $D_c \leftarrow \emptyset$, $D_{uc} \leftarrow \emptyset$;
2: cellSet $C_c \leftarrow \emptyset$, $C_{uc} \leftarrow \emptyset$, $C_{ex} \leftarrow \emptyset$;
3: objectSet $R_c \leftarrow \emptyset$, $R_{uc} \leftarrow \emptyset$;
4: CriticalDeviceList(deviceID, CLASS) $cd \leftarrow \emptyset$;
5: Generate a new identifier $queryID$ for the query;
6: $D_c \leftarrow$ Devices that are covered by R;
7: $D_{uc} \leftarrow$ Devices that intersect with R;
8: $C_c \leftarrow$ Cells which are covered by R;
9: $C_{uc} \leftarrow$ Cells that intersect with R;
10: **for each** device d in D_c **do**
11:     **if** all the cells in $G.\ell_E^{-1}(d)$ are in C_c **then**
12:         Add (d, $CLASS1$) to cd;
13:     **else if** one of the cells in $G.\ell_E^{-1}(d)$ is in C_{uc} **then**
14:         Add (d, $CLASS2$) to cd;
15: **for each** device d in D_{uc} **do**
16:     Add (d, $CLASS3$) to cd;
17: **for each** edge e in G **do**
18:     **if** $(C_c \cup C_{uc}) \cap e \neq \emptyset$ AND $(C_c \cup C_{uc}) \cap e \neq (C_c \cup C_{uc})$ **then**
19:         **if** $G.\ell_E(e) \notin cd.deviceID$ **then**
20:             Add ($G.\ell_E(e)$, $CLASS4$) to cd;
21:         $C_{ex} \leftarrow C_{ex} \cup e \setminus (C_c \cup C_{uc})$;
22: **for each** edge e in G **do**
23:     **if** $C_{ex} \cap e \neq \emptyset$ **then**
24:         **if** $G.\ell_E(e) \notin cd.deviceID$ **then**
25:             Add ($G.\ell_E(e)$, $CLASS5$) to cd;

1. Lines 1–9: Initialization
2. Lines 10–14: Add possible devices to CriticalDeviceList cd (CLASS1 and CLASS2)
3. Lines 15–16: Add possible CLASS3 devices

Query Registration Algorithm (I)

Algorithm 2 register (Range R, DeploymentGraph G)

1: deviceSet $D_c \leftarrow \emptyset$, $D_{uc} \leftarrow \emptyset$;
2: cellSet $C_c \leftarrow \emptyset$, $C_{uc} \leftarrow \emptyset$, $C_{ex} \leftarrow \emptyset$;
3: objectSet $R_c \leftarrow \emptyset$, $R_{uc} \leftarrow \emptyset$;
4: CriticalDeviceList(deviceID, CLASS) $cd \leftarrow \emptyset$;
5: Generate a new identifier $queryID$ for the query;
6: $D_c \leftarrow$ Devices that are covered by R;
7: $D_{uc} \leftarrow$ Devices that intersect with R;
8: $C_c \leftarrow$ Cells which are covered by R;
9: $C_{uc} \leftarrow$ Cells that intersect with R;
10: **for each** device d in D_c **do**
11:     **if** all the cells in $G.\ell_E^{-1}(d)$ are in C_c **then**
12:         Add (d, $CLASS1$) to cd;
13:     **else if** one of the cells in $G.\ell_E^{-1}(d)$ is in C_{uc} **then**
14:         Add (d, $CLASS2$) to cd;
15: **for each** device d in D_{uc} **do**
16:     Add (d, $CLASS3$) to cd;
17: **for each** edge e in G **do**
18:     **if** $(C_c \cup C_{uc}) \cap e \neq \emptyset$ AND $(C_c \cup C_{uc}) \cap e \neq (C_c \cup C_{uc})$ **then**
19:         **if** $G.\ell_E(e) \notin cd.deviceID$ **then**
20:             Add ($G.\ell_E(e)$, $CLASS4$) to cd;
21:         $C_{ex} \leftarrow C_{ex} \cup e \setminus (C_c \cup C_{uc})$;
22: **for each** edge e in G **do**
23:     **if** $C_{ex} \cap e \neq \emptyset$ **then**
24:         **if** $G.\ell_E(e) \notin cd.deviceID$ **then**
25:             Add ($G.\ell_E(e)$, $CLASS5$) to cd;

1. Lines 1–9: Initialization
2. Lines 10–14: Add possible devices to CriticalDeviceList cd (CLASS1 and CLASS2)
3. Lines 15–16: Add possible CLASS3 devices
4. Lines 17–20: Add possible CLASS4 devices

Query Registration Algorithm (I)

Algorithm 2 register (Range R, DeploymentGraph G)

1: deviceSet $D_c \leftarrow \emptyset$, $D_{uc} \leftarrow \emptyset$;
2: cellSet $C_c \leftarrow \emptyset$, $C_{uc} \leftarrow \emptyset$, $C_{ex} \leftarrow \emptyset$;
3: objectSet $R_c \leftarrow \emptyset$, $R_{uc} \leftarrow \emptyset$;
4: CriticalDeviceList(deviceID, CLASS) $cd \leftarrow \emptyset$;
5: Generate a new identifier $queryID$ for the query;
6: $D_c \leftarrow$ Devices that are covered by R;
7: $D_{uc} \leftarrow$ Devices that intersect with R;
8: $C_c \leftarrow$ Cells which are covered by R;
9: $C_{uc} \leftarrow$ Cells that intersect with R;
10: **for each** device d in D_c **do**
11:     **if** all the cells in $G.\ell_E^{-1}(d)$ are in C_c **then**
12:         Add $(d, \mathit{CLASS1})$ to cd;
13:     **else if** one of the cells in $G.\ell_E^{-1}(d)$ is in C_{uc} **then**
14:         Add $(d, \mathit{CLASS2})$ to cd;
15: **for each** device d in D_{uc} **do**
16:     Add $(d, \mathit{CLASS3})$ to cd;
17: **for each** edge e in G **do**
18:     **if** $(C_c \cup C_{uc}) \cap e \neq \emptyset$ AND $(C_c \cup C_{uc}) \cap e \neq (C_c \cup C_{uc})$ **then**
19:         **if** $G.\ell_E(e) \notin cd.deviceID$ **then**
20:             Add $(G.\ell_E(e), \mathit{CLASS4})$ to cd;
21:         $C_{ex} \leftarrow C_{ex} \cup e \setminus (C_c \cup C_{uc})$;
22: **for each** edge e in G **do**
23:     **if** $C_{ex} \cap e \neq \emptyset$ **then**
24:         **if** $G.\ell_E(e) \notin cd.deviceID$ **then**
25:             Add $(G.\ell_E(e), \mathit{CLASS5})$ to cd;

1. Lines 1–9: Initialization
2. Lines 10–14: Add possible devices to CriticalDeviceList cd (CLASS1 and CLASS2)
3. Lines 15–16: Add possible CLASS3 devices
4. Lines 17–20: Add possible CLASS4 devices
5. Line 21: Determine extended cell set C_{ex}

Query Registration Algorithm (I)

Algorithm 2 register (Range R, DeploymentGraph G)

1: deviceSet $D_c \leftarrow \emptyset$, $D_{uc} \leftarrow \emptyset$;
2: cellSet $C_c \leftarrow \emptyset$, $C_{uc} \leftarrow \emptyset$, $C_{ex} \leftarrow \emptyset$;
3: objectSet $R_c \leftarrow \emptyset$, $R_{uc} \leftarrow \emptyset$;
4: CriticalDeviceList(deviceID, CLASS) $cd \leftarrow \emptyset$;
5: Generate a new identifier $queryID$ for the query;
6: $D_c \leftarrow$ Devices that are covered by R;
7: $D_{uc} \leftarrow$ Devices that intersect with R;
8: $C_c \leftarrow$ Cells which are covered by R;
9: $C_{uc} \leftarrow$ Cells that intersect with R;
10: **for** each device d in D_c **do**
11:     **if** all the cells in $G.\ell_E^{-1}(d)$ are in C_c **then**
12:         Add (d, $CLASS1$) to cd;
13:     **else if** one of the cells in $G.\ell_E^{-1}(d)$ is in C_{uc} **then**
14:         Add (d, $CLASS2$) to cd;
15: **for** each device d in D_{uc} **do**
16:     Add (d, $CLASS3$) to cd;
17: **for** each edge e in G **do**
18:     **if** $(C_c \cup C_{uc}) \cap e \neq \emptyset$ AND $(C_c \cup C_{uc}) \cap e \neq (C_c \cup C_{uc})$ **then**
19:         **if** $G.\ell_E(e) \notin cd.deviceID$ **then**
20:             Add ($G.\ell_E(e)$, $CLASS4$) to cd;
21:         $C_{ex} \leftarrow C_{ex} \cup e \setminus (C_c \cup C_{uc})$;
22: **for** each edge e in G **do**
23:     **if** $C_{ex} \cap e \neq \emptyset$ **then**
24:         **if** $G.\ell_E(e) \notin cd.deviceID$ **then**
25:             Add ($G.\ell_E(e)$, $CLASS5$) to cd;

1. Lines 1–9: Initialization
2. Lines 10–14: Add possible devices to CriticalDeviceList cd (CLASS1 and CLASS2)
3. Lines 15–16: Add possible CLASS3 devices
4. Lines 17–20: Add possible CLASS4 devices
5. Line 21: Determine extended cell set C_{ex}
6. Lines 22–25: Add possible CLASS5 devices

Query Registration Algorithm (II)

```
for each device d in D_c do
    R_c ← R_c ∪ DHT[d];
for each device d in D_uc do
    R_uc ← R_uc ∪ DHT[d];
for each cell c in C_c do
    R_c ← R_c ∪ CDHT[c];
if |C_c| > 1 then
    for each nondeterministic object o in C_c do
        if OHT[o].IDSet ⊂ C_c then
            Add o into R_c;
        else
            Add o into R_uc
else
    R_uc ← R_uc ∪ CNHT[c];
for each cell c in C_uc do
    R_c ← R_c ∪ CDHT[c];  R_uc ← R_uc ∪ CNHT[c];
QHT[queryID] ← (R_c, R_uc);
for each item a in cd do
    Add (queryID, a.CLASS) into DQHT[a.deviceID];
```

Query Registration Algorithm (II)

26: **for** each device d in D_c **do**
27:     $R_c \leftarrow R_c \cup DHT[d]$;
28: **for** each device d in D_{uc} **do**
29:     $R_{uc} \leftarrow R_{uc} \cup DHT[d]$;
30: **for** each cell c in C_c **do**
31:     $R_c \leftarrow R_c \cup CDHT[c]$;
32: **if** $|C_c| > 1$ **then**
33:     **for** each nondeterministic object o in C_c **do**
34:         **if** $OHT[o].IDSet \subset C_c$ **then**
35:             Add o into R_c;
36:         **else**
37:             Add o into R_{uc}
38: **else**
39:     $R_{uc} \leftarrow R_{uc} \cup CNHT[c]$;
40: **for** each cell c in C_{uc} **do**
41:     $R_c \leftarrow R_c \cup CDHT[c]$; $R_{uc} \leftarrow R_{uc} \cup CNHT[c]$;
42: $QHT[queryID] \leftarrow (R_c, R_{uc})$;
43: **for** each item a in cd **do**
44:     Add $(queryID, a.CLASS)$ into $DQHT[a.deviceID]$;

1. **Lines 26–27:** Add active objects from DHT to the certain result

Query Registration Algorithm (II)

```
26: for each device d in D_c do
27:     R_c ← R_c ∪ DHT[d];
28: for each device d in D_uc do
29:     R_uc ← R_uc ∪ DHT[d];
30: for each cell c in C_c do
31:     R_c ← R_c ∪ CDHT[c];
32: if |C_c| > 1 then
33:     for each nondeterministic object o in C_c do
34:         if OHT[o].IDSet ⊂ C_c then
35:             Add o into R_c;
36:         else
37:             Add o into R_uc
38: else
39:     R_uc ← R_uc ∪ CNHT[c];
40: for each cell c in C_uc do
41:     R_c ← R_c ∪ CDHT[c];  R_uc ← R_uc ∪ CNHT[c];
42: QHT[queryID] ← (R_c, R_uc);
43: for each item a in cd do
44:     Add (queryID, a.CLASS) into DQHT[a.deviceID];
```

1. **Lines 26–27:** Add active objects from DHT to the certain result
2. **Lines 28–29:** Intersected device set, add active objects from DHT to the uncertain result

Query Registration Algorithm (II)

26: **for** each device d in D_c **do**
27: $\quad R_c \leftarrow R_c \cup DHT[d]$;
28: **for** each device d in D_{uc} **do**
29: $\quad R_{uc} \leftarrow R_{uc} \cup DHT[d]$;
30: **for** each cell c in C_c **do**
31: $\quad R_c \leftarrow R_c \cup CDHT[c]$;
32: **if** $|C_c| > 1$ **then**
33: $\quad$ **for** each nondeterministic object o in C_c **do**
34: $\quad\quad$ **if** $OHT[o].IDSet \subset C_c$ **then**
35: $\quad\quad\quad$ Add o into R_c;
36: $\quad\quad$ **else**
37: $\quad\quad\quad$ Add o into R_{uc}
38: **else**
39: $\quad R_{uc} \leftarrow R_{uc} \cup CNHT[c]$;
40: **for** each cell c in C_{uc} **do**
41: $\quad R_c \leftarrow R_c \cup CDHT[c]$; $R_{uc} \leftarrow R_{uc} \cup CNHT[c]$;
42: $QHT[queryID] \leftarrow (R_c, R_{uc})$;
43: **for** each item a in cd **do**
44: $\quad$ Add $(queryID, a.CLASS)$ into $DQHT[a.deviceID]$;

1. Lines 26–27: Add active objects from DHT to the certain result
2. Lines 28–29: Intersected device set, add active objects from DHT to the uncertain result
3. Lines 30–31: From covered cells, add deterministic objects to the certain result

Query Registration Algorithm (II)

26: **for** each device d in D_c **do**
27: $\quad R_c \leftarrow R_c \cup DHT[d]$;
28: **for** each device d in D_{uc} **do**
29: $\quad R_{uc} \leftarrow R_{uc} \cup DHT[d]$;
30: **for** each cell c in C_c **do**
31: $\quad R_c \leftarrow R_c \cup CDHT[c]$;
32: **if** $|C_c| > 1$ **then**
33: $\quad$ **for** each nondeterministic object o in C_c **do**
34: $\quad\quad$ **if** $OHT[o].IDSet \subset C_c$ **then**
35: $\quad\quad\quad$ Add o into R_c;
36: $\quad\quad$ **else**
37: $\quad\quad\quad$ Add o into R_{uc}
38: **else**
39: $\quad R_{uc} \leftarrow R_{uc} \cup CNHT[c]$;
40: **for** each cell c in C_{uc} **do**
41: $\quad R_c \leftarrow R_c \cup CDHT[c]$; $R_{uc} \leftarrow R_{uc} \cup CNHT[c]$;
42: $QHT[queryID] \leftarrow (R_c, R_{uc})$;
43: **for** each item a in cd **do**
44: $\quad$ Add $(queryID, a.CLASS)$ into $DQHT[a.deviceID]$;

1. Lines 26–27: Add active objects from DHT to the certain result
2. Lines 28–29: Intersected device set, add active objects from DHT to the uncertain result
3. Lines 30–31: From covered cells, add deterministic objects to the certain result
4. Lines 32-37: If more than one cell, check nondeterministic objects. If all its possible cells are in C_c add the object to the certain result, else uncertain result

Query Registration Algorithm (II)

26: **for** each device d in D_c **do**
27: $\quad R_c \leftarrow R_c \cup DHT[d]$;
28: **for** each device d in D_{uc} **do**
29: $\quad R_{uc} \leftarrow R_{uc} \cup DHT[d]$;
30: **for** each cell c in C_c **do**
31: $\quad R_c \leftarrow R_c \cup CDHT[c]$;
32: **if** $|C_c| > 1$ **then**
33: $\quad$ **for** each nondeterministic object o in C_c **do**
34: $\quad\quad$ **if** $OHT[o].IDSet \subset C_c$ **then**
35: $\quad\quad\quad$ Add o into R_c;
36: $\quad\quad$ **else**
37: $\quad\quad\quad$ Add o into R_{uc}
38: **else**
39: $\quad R_{uc} \leftarrow R_{uc} \cup CNHT[c]$;
40: **for** each cell c in C_{uc} **do**
41: $\quad R_c \leftarrow R_c \cup CDHT[c]$; $R_{uc} \leftarrow R_{uc} \cup CNHT[c]$;
42: $QHT[queryID] \leftarrow (R_c, R_{uc})$;
43: **for** each item a in cd **do**
44: $\quad$ Add $(queryID, a.CLASS)$ into $DQHT[a.deviceID]$;

1. Lines 26–27: Add active objects from DHT to the certain result
2. Lines 28–29: Intersected device set, add active objects from DHT to the uncertain result
3. Lines 30–31: From covered cells, add deterministic objects to the certain result
4. Lines 32-37: If more than one cell, check nondeterministic objects. If all its possible cells are in C_c add the object to the certain result, else uncertain result
5. Lines 38–39: Only one cell. Nondeterministic objects are added to the uncertain result

Query Registration Algorithm (II)

26: **for** each device d in D_c **do**
27: $\quad R_c \leftarrow R_c \cup DHT[d]$;
28: **for** each device d in D_{uc} **do**
29: $\quad R_{uc} \leftarrow R_{uc} \cup DHT[d]$;
30: **for** each cell c in C_c **do**
31: $\quad R_c \leftarrow R_c \cup CDHT[c]$;
32: **if** $|C_c| > 1$ **then**
33: $\quad$ **for** each nondeterministic object o in C_c **do**
34: $\quad\quad$ **if** $OHT[o].IDSet \subset C_c$ **then**
35: $\quad\quad\quad$ Add o into R_c;
36: $\quad\quad$ **else**
37: $\quad\quad\quad$ Add o into R_{uc}
38: **else**
39: $\quad R_{uc} \leftarrow R_{uc} \cup CNHT[c]$;
40: **for** each cell c in C_{uc} **do**
41: $\quad R_c \leftarrow R_c \cup CDHT[c]$; $\quad R_{uc} \leftarrow R_{uc} \cup CNHT[c]$;
42: $QHT[queryID] \leftarrow (R_c, R_{uc})$;
43: **for** each item a in cd **do**
44: $\quad$ Add $(queryID, a.CLASS)$ into $DQHT[a.deviceID]$;

1. Lines 26–27: Add active objects from DHT to the certain result
2. Lines 28–29: Intersected device set, add active objects from DHT to the uncertain result
3. Lines 30–31: From covered cells, add deterministic objects to the certain result
4. Lines 32-37: If more than one cell, check nondeterministic objects. If all its possible cells are in C_c add the object to the certain result, else uncertain result
5. Lines 38–39: Only one cell. Nondeterministic objects are added to the uncertain result
6. Lines 40–41: Intersected set. Add all objects to the uncertain result

Query Registration Algorithm (II)

26: **for** each device d in D_c **do**
27: $\quad R_c \leftarrow R_c \cup DHT[d]$;
28: **for** each device d in D_{uc} **do**
29: $\quad R_{uc} \leftarrow R_{uc} \cup DHT[d]$;
30: **for** each cell c in C_c **do**
31: $\quad R_c \leftarrow R_c \cup CDHT[c]$;
32: **if** $|C_c| > 1$ **then**
33: $\quad$ **for** each nondeterministic object o in C_c **do**
34: $\quad\quad$ **if** $OHT[o].IDSet \subset C_c$ **then**
35: $\quad\quad\quad$ Add o into R_c;
36: $\quad\quad$ **else**
37: $\quad\quad\quad$ Add o into R_{uc}
38: **else**
39: $\quad R_{uc} \leftarrow R_{uc} \cup CNHT[c]$;
40: **for** each cell c in C_{uc} **do**
41: $\quad R_c \leftarrow R_c \cup CDHT[c]$; $\quad R_{uc} \leftarrow R_{uc} \cup CNHT[c]$;
42: $QHT[queryID] \leftarrow (R_c, R_{uc})$;
43: **for** each item a in cd **do**
44: $\quad$ Add $(queryID, a.CLASS)$ into $DQHT[a.deviceID]$;

1. Lines 26–27: Add active objects from DHT to the certain result
2. Lines 28–29: Intersected device set, add active objects from DHT to the uncertain result
3. Lines 30–31: From covered cells, add deterministic objects to the certain result
4. Lines 32-37: If more than one cell, check nondeterministic objects. If all its possible cells are in C_c add the object to the certain result, else uncertain result
5. Lines 38–39: Only one cell. Nondeterministic objects are added to the uncertain result
6. Lines 40–41: Intersected set. Add all objects to the uncertain result
7. Line 42: Results added to QHT

Query Registration Algorithm (II)

26: **for** each device d in D_c **do**
27: $\quad R_c \leftarrow R_c \cup DHT[d]$;
28: **for** each device d in D_{uc} **do**
29: $\quad R_{uc} \leftarrow R_{uc} \cup DHT[d]$;
30: **for** each cell c in C_c **do**
31: $\quad R_c \leftarrow R_c \cup CDHT[c]$;
32: **if** $|C_c| > 1$ **then**
33: $\quad$ **for** each nondeterministic object o in C_c **do**
34: $\quad\quad$ **if** $OHT[o].IDSet \subset C_c$ **then**
35: $\quad\quad\quad$ Add o into R_c;
36: $\quad\quad$ **else**
37: $\quad\quad\quad$ Add o into R_{uc}
38: **else**
39: $\quad R_{uc} \leftarrow R_{uc} \cup CNHT[c]$;
40: **for** each cell c in C_{uc} **do**
41: $\quad R_c \leftarrow R_c \cup CDHT[c]$; $R_{uc} \leftarrow R_{uc} \cup CNHT[c]$;
42: $QHT[queryID] \leftarrow (R_c, R_{uc})$;
43: **for** each item a in cd **do**
44: $\quad$ Add $(queryID, a.CLASS)$ into $DQHT[a.deviceID]$;

1. Lines 26–27: Add active objects from DHT to the certain result
2. Lines 28–29: Intersected device set, add active objects from DHT to the uncertain result
3. Lines 30–31: From covered cells, add deterministic objects to the certain result
4. Lines 32-37: If more than one cell, check nondeterministic objects. If all its possible cells are in C_c add the object to the certain result, else uncertain result
5. Lines 38–39: Only one cell. Nondeterministic objects are added to the uncertain result
6. Lines 40–41: Intersected set. Add all objects to the uncertain result
7. Line 42: Results added to QHT
8. Lines 43–44: DQHT entry is created for each critical device

Query Result Updates

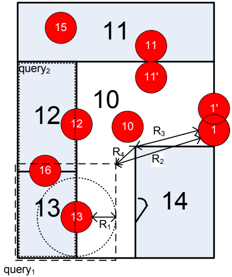
- When an object enters the activation range of a critical device:
  - For $\mathrm{CLASS1}$ or $\mathrm{CLASS2}$ devices the object is the certain result
  - For $\mathrm{CLASS3}$ devices the object is possibly in the query range
  - For $\mathrm{CLASS4}$ or $\mathrm{CLASS5}$ devices the object is not in the query range
- When an object leaves:
  - For $\mathrm{CLASS1}, 3, 5$ devices there are no changes
  - For $\mathrm{CLASS2}$ devices the object may still be in the query range, thus it is moved to the uncertain result
  - For $\mathrm{CLASS4}$ devices the object may be in a cell that intersects with the query range and it added to the uncertain result

Table 1: Query Updates w.r.t. Critical Devices

	ENTER	LEAVE
CLASS1	$CR \cup \{o\}$, $UR \setminus \{o\}$	CR, UR
CLASS2	$CR \cup \{o\}$, $UR \setminus \{o\}$	$CR \setminus \{o\}$, $UR \cup \{o\}$
CLASS3	$CR \setminus \{o\}$, $UR \cup \{o\}$	CR, UR
CLASS4	$CR \setminus \{o\}$, $UR \setminus \{o\}$	CR, $UR \cup \{o\}$
CLASS5	$CR \setminus \{o\}$, $UR \setminus \{o\}$	CR, UR

Deferred Query Updates

- Deferred query updates is the concept of postponing updates where we already know the result
- The time a query result is still valid is calculated from *minimum indoor walking distance* divided by the *maximum speed* an object can travel



Consider $query_1$, after the object o leaves a CLASS2 critical device $devoce_{13}$, it should be moved from certain to uncertain result.

Let V_{max} be the maximum speed, if $R_1 = V_{max} * \Delta t$, the certain result can be maintained without updating for an extra period of time Δt.

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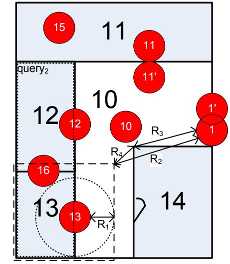


Consider $query_1$, after the object o leaves a $\mathrm{CLASS2}$ critical device $devoce_{13}$, it should be moved from certain to uncertain result.

Let V_{max} be the maximum speed, if $R_1 = V_{max} * \Delta t$, the certain result can be maintained without updating for an extra period of time Δt.

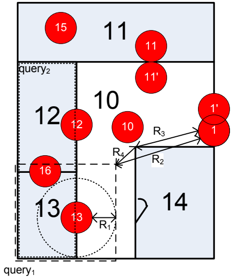
Probabilistic Analysis of Uncertain Results

To analyze probability that o is in the query range R. Assume that the possible locations in a given indoor space conform a uniform distribution within all reachable regions constrained by its maximum speed.

1. Probabilities for Active Objects

Formally, the probability that an active object o is in the range R is defined as:

$$prob(o\Theta R) = \frac{Area(Devices(d).ActRange \sqcap R)}{Area(Devices(d).ActRange)} \tag{1}$$



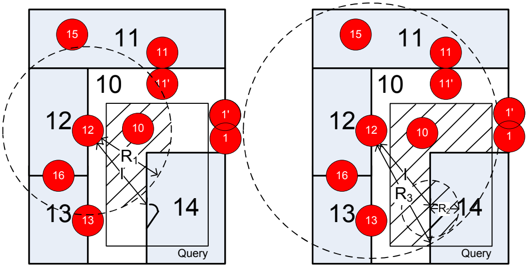
Consider $device_{16}$, a CLASS3 device for $query_1$, the probability for an active object in $device_{16}$ to be in the query range is calculated as ...

Probabilistic Analysis of Uncertain Results

2. Probabilities for Inactive Objects

For the case that after leaving $\mathrm{CLASS}2, 3, 4$ devices, the probabilities for inactive objects can be defined based on the maximum speed constraint.

An example for an inactive object that just leaves $device_{12}$...



Conclusion

- A solution with a symbolic model of the floor plan, device locations, and activation ranges
- Data is stored in several hash tables which make it possible to efficiently locate a specific object (result is a signle room/cell, or a set of rooms/cells)
- Future work
  - sharing of query processing among concurrent queries
  - common critical devices exploitation
  - other types of queries: range and kNN
  - further investigate the probability analysis

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The End. Thanks :)