Description Logic for Vision-Based Intersection Understanding

Britta Hummel, Werner Thiemann, Irina Lulcheva
• **Motivation:** Road recognition for toy worlds only?

• **DL Road Network Knowledge Base Development**
  – DL Tutorial
  – Hypothesis Space
  – Sensor Input

• **DL Inference for Semantic Road Recognition**
  – Deduction
  – Model Construction
Motivation

Road Recognition

Status Quo

- Since mid 80ies
- Solved for highly restricted domains (highways)
- Few work for more complex domains, then only consideration of special cases
- Geometry only, no semantics

➔ Toy worlds?
Motivation

Common Approach to Road Recognition

1. Project

2. Compare with image cues

3. Update

- Low-dimensional geometry model (clothoid, …)

→ Cannot be generalized to more complex domains
Motivation

1. High-dimensional hypothesis space
2. Few features
   - Narrow field of view
   - Massive occlusions
   - Omitted features
3. Presence of noise
   - Unmodelled objects
   - Decreased feature quality

➡️ Problem is ill-posed!
What is needed?

1. Geometrical Model of arbitrary roads and intersections
2. Massive reduction of hypothesis space size
   - using prior knowledge
   - using large set of complementary sensor data: video object detectors, digital map, positioning sensors, …
3. Conceptual model of arbitrary roads and intersections
   - explicit representation (due to intensive HMI within a DAS)
4. Sound inference & retrieval services on the KB

**Paradigm shift:** Intersection recognition as

... scene understanding task

... mid/high level vision task
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Description Logic

- Decidable subset of 1st order logic
- Syntax:

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individuals</td>
<td>objects of the domain</td>
<td>John</td>
</tr>
<tr>
<td>Concepts</td>
<td>(≈classes) sets of individuals</td>
<td>Human</td>
</tr>
<tr>
<td>Roles</td>
<td>binary relations on individuals</td>
<td>hasChild</td>
</tr>
<tr>
<td>Constructors</td>
<td>to build complex expressions</td>
<td>Man ( \cap ) ( \exists \text{hasChild}.T )</td>
</tr>
</tbody>
</table>

- Semantics: Set-theoretic
Description Logic

- **Axioms** form sentences

<table>
<thead>
<tr>
<th>Terminological Axioms</th>
<th>C ⊑ D</th>
<th>Father ≡ Man ∩ ∃ hasChild.T</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C ⊑ D</td>
<td>Father ⊑ Person</td>
</tr>
<tr>
<td></td>
<td>R ⊑ S</td>
<td>hasChild ⊑ hasDescendent</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Assertional Axioms</th>
<th>i : C</th>
<th>John : Human</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(i,j) : R</td>
<td>(John, Emily) : hasChild</td>
</tr>
</tbody>
</table>

- **A DL Knowledge Base** consists of
  - **Tbox**: Set of terminological axioms
    - state general domain knowledge here
  - **Abox**: Set of assertional axioms
    - state knowledge about particular situation here
  - (Rulebox)
Description Logic

- Classical DL **inference services**:

| Satisfiability Check for TBox and Abox | (Mother $\cap$ Male) is inconsistent |
| Classification of Tbox and Abox | $\mathcal{KB} \models John: Father$ |
| Entailment | $John: \exists$hasChild.Female |
| Retrieval | Retrieve all individuals which are instance of: $\exists_{\geq 3}$hasChild $\cap \neg$Female |

- Non-classical inference

...
Road Network Hypothesis Space

A Geometrical Modelling

B Conceptual Modelling

1. Qualitative spatial relations
2. Road Network taxonomy
3. Geometric Constraints
4. Road building / Semantic Constraints
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a) Degree of overlap (RCC-Calculus)

b) Rel. orientation
c) Rel. position
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Arbitrary Sample
Road Network Hypothesis Space

A Geometrical Modelling

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// Lanes are externally connected
// only to lanes or dividers.
Lane \( \sqsubseteq \forall \text{EC} \cdot (\text{Lane} \sqsubseteq \text{Divider}) \)

// Lanes only have arrows
// as proper parts.
Lane \( \sqsubseteq \forall \text{PP} \cdot \text{Arrow} \)

...
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Arbitrary Road Sample
Road Network Hypothesis Space

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// Only right turn lanes can be right of right turn lane
RightTurnLane ⊆ ∀ hasEastNeighbor.RightTurnLane

// A one way road does not have a u-turn lane.
OneWayRoad ⊆ ∀ NTTP.¬UTurnLane

// All autobahns and highways are one way roads.
Autobahn ∪ Highway ⊆ OneWayRoad
Road Network Hypothesis Space

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Arbitrary Sample
Sensor Data Input

1. Digital Map
2. GPS & Map Matching
3. Video/Laser-based object detectors
Sensor Data Input

1. Digital Map

2. GPS & Map Matching

3. Video/Laser-based object detectors

Symbol Grounding

[...] // r4: not(OneWayRoad)
[...] // r4: has 4 Lanes
[...] // r4: leads to junction with 4 branches
[...] // Closed World Assumption
Sensor Data Input

1. Digital Map

2. GPS & Map Matching

3. Video/Laser-based object detectors

Symbol Grounding

egovehicle : Vehicle // create new vehicle
(egovehicle, r_4) : NTPP^- // is inverse proper part of road r_4
(egovehicle, r_4) : ll // is parallel to road r_4
Sensor Data Input

1. Digital Map
2. GPS & Map Matching
3. Video/Laser-based object detectors

Symbol Grounding

[...] // i1: RoadCurb
[...] // i2: StraightAheadArrow
[...] // i3: DividerMarking50-20
[...] // state spatial relations
[...] // Open World Assumption
Motivation: Road recognition for toy worlds only?

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DL Inference for Semantic Road Recognition
  - Deduction
  - Model Construction
1. Draw all conclusions, given the KB (i.e. prior knowledge & sensor data)
   ➔ Deduction

2. Generate all intersection hypotheses
   ➔ Model construction

   ➔ Video-based hypothesis test / Deformable Model matching

\[ \mathcal{KB} \models l_{4.1} : \text{OneWayN} \sqcap \text{BicycleLane} \sqcap \text{StraightAheadLane} \]
\[ l_{4.2} : \text{OneWayN} \sqcap \text{CarLane} \sqcap \text{StraightAheadLane} \]
\[ l_{4.3} : \text{OneWayS} \]
\[ l_{4.4} : \text{OneWayS} \]
\[ \mathcal{KB} \models (\text{egovehicle}, l_{4.2}) : \text{NTPP}^- \]
Inference

1. Draw all conclusions, given the KB (i.e. prior knowledge & sensor data)
   ➔ Deduction

2. Generate all intersection hypotheses
   ➔ Model construction

   ➔ Video-based hypothesis test / Deformable Model matching

\[ H = \left( \begin{array}{c} \text{Abox } A_1 \\ \vdots \\ \text{Abox } A_n \end{array} \right) \]
Inference

1. Draw all conclusions, given the KB (i.e. prior knowledge & sensor data)
   ➔ Deduction

2. Generate all intersection hypotheses
   ➔ Model construction

➔ Video-based hypothesis test / Deformable Model matching
Demo: Video

geometry model generated from 1st order knowledge base containing ground truth data
Summary

Motivation:
• Road recognition works in toy worlds only
• A massive augmentation of prior knowledge is needed

Knowledge Representation:
• Introduction of DL as a formal, explicit, and readable knowledge representation formalism for real-world high-level scene interpretation
• Development of a DL RoadNetwork KB
  – High-level conceptual constraints
  – Map, Positioning, Video/Laser sensors

Inference:
• Deductive reasoning for querying the KB
• Model Construction for returning the set of intersection hypotheses
• Natural handling of partial observability, differing abstraction layers and incremental additions
Outlook

- Hypothesize & Test
- Migration to probabilistic logic (MLN, SLP)
- Rule Learning from Training Data
Thanks for your attention.
Results 1-4: \[ \mathcal{KB} \models l_{4.1} : \text{OneWayN} \land \text{BicycleLane} \land \text{StraightAheadLane} \]
\[ l_{4.2} : \text{OneWayN} \land \text{CarLane} \land \text{StraightAheadLane} \]
\[ l_{4.3} : \text{OneWayS} \]
\[ l_{4.4} : \text{OneWayS} \]

Result 5: \[ // The vehicle is on lane \ l_{4.2}. \]
\[ \mathcal{KB} \models (\text{egovehicle}, l_{4.2}) : \text{NTPP}^- , \text{iff } i = 2 . \]
Proof sketch: The TBox of the KB contains the following statements:

// Marking50-20 is a divider for bicycle lanes.
Marking50-20 ⊑ ∃isLaterallyConnectedTo.BicycleLane

// This type of arrow only occurs on car lanes.
Arrow ⊑ ∀NTPP¬.CarLane

// Bicycle lanes are not next to each other.
BicycleLane ⊑ ∀hasNeighbor.CarLane
Example: Proof of Result 5

These deductively lead to:

**Result 5a:**

// The driver’s lane is a car lane (fortunately : ) ),
// and right of it, there is a bicycle lane.

$$KB \models egovehicle : \exists NTPP^-. (\text{CarLane} \cap \exists \text{hasEastNeighbor.BicycleLane})$$
Example: Proof of Result 5

Result 5b:

// Right of the bicycle lane there can only be a car lane.

$$\mathcal{KB} \models egovehicle : \exists \text{NTPP}^-. (\text{CarLane} \sqcap$$

$$\exists \text{hasEastNeighbor} . (\text{BicycleLane} \sqcap$$

$$\forall \text{hasEastNeighbor} . \text{CarLane}))$$
// A lane with a straight ahead arrow is a straight ahead lane

[...]

// Right neighbors of straight ahead lanes are straight ahead or right turn lanes only.

[...]

// Bicycle lanes do not occur between lanes of the same turning lane type

[...]
Example: Proof of Result 5

Result 5c:

// Right of the bicycle lane can only be a right turn lane.

\[ KB \models \text{egovehicle} : \exists! \text{NTPP}^- (\text{CarLane} \sqcap \exists \text{hasEastNeighbor}. (\text{BicycleLane} \sqcap \forall \text{hasEastNeighbor}. \text{RightTurnLane})) \]
Intermediate result:

As r1 is a OneWayRoad towards the junction, r4 cannot have a right turn lane.

Result 5d:

// There is no more lane right of the bicycle lane.

\[ \mathcal{KB} \models egovehicle : \exists \text{NTPP}^{-}.(\text{CarLane} \sqcap \exists \text{hasEastNeighbor}.(\text{BicycleLane} \sqcap \neg \exists \text{hasEastNeighbor})) \]
Example: Proof of Result 5

- **Closed World Assumption** for map data

\[\implies \quad // \text{The vehicle is on lane } l_{4,2}.\]

\[\mathcal{KB} \models (\text{egovehicle}, l_{4,i}) : \text{NTPP}^{-}, \text{iff } i = 2. \qed\]
Evidence (ABOX):
RightTurnArrow(arrow1);
SingleLongDashedDivider(divider1);

Hypothesization:
Lane(lane1);
hasMarking(lane1,arrow1);

Hypothesization:
isConnectedWithRightDivider(divider1);
isConnectedWithLeftDivider(divider2);

Hypothesization:
Road(road1);
isPartOf(lane1,road1);

Hypothesization:
Lane(lane2);
hasRightNeighbor(lane1,lane2);

Deduction:
isPartOf(lane2,road1);
RightTurnLane(lane2);

Deduction:
MarkedRoad(road1);

non-trivial

Hypothesization:

PhysicalDivider(divider2);

DividerMarking(divider2);
Hypothesize&Test

model complete