A workflow for modeling, visualizing, and querying uncertain (GPS-)localization using interval arithmetic

Wolfram Luther

Computer Graphics, Digital Image Processing, Scientific Computing

University of Duisburg-Essen

Overview

- Motivation and Project Context
- Geographic Information Systems (GIS)
- Workflow in GIS Applications
- GPS-Localization
- Uncertainty Modeling with Dempster-Shafer Theory
- Query Language
- 3D Visualization
- Truck Application

Motivation and Project Context

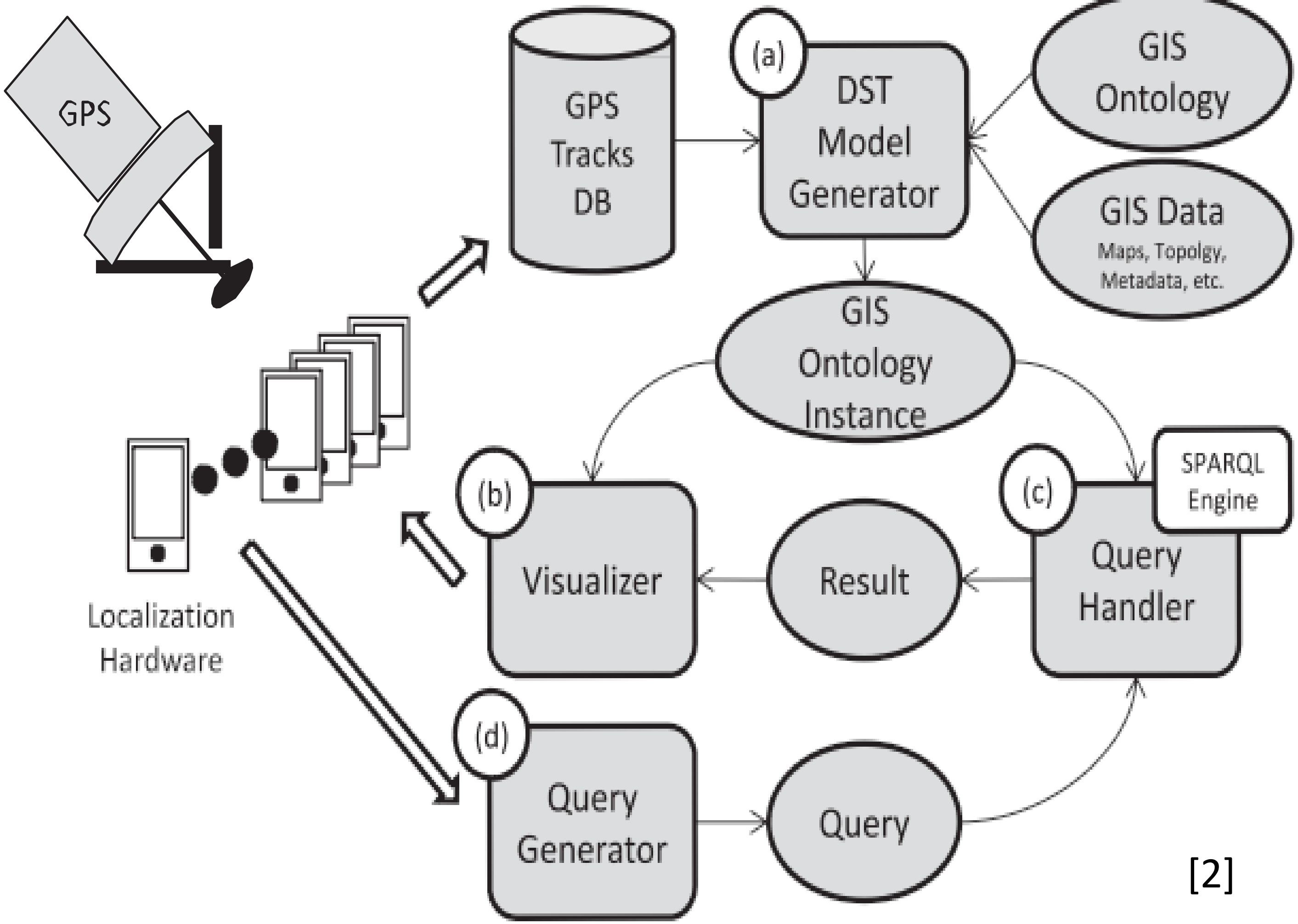
- Practice-driven advance of studies PRASEDEC (DAAD)
- Integration of Applied Course Modules into Degree Programmes at the University of Chile (2013-2016)
- ASW1: Smart Geographic Information Systems
  - Introduction to GIS
  - GPS sensing and localization
  - Uncertainty modeling
  - Spatial concept ontology
  - Query languages with uncertainty
  - Dempster-Shafer Toolbox with intervals
  - Visualization
  - Applications, scenarios, implementation
  - Exercises and software (together with MS Chile)

Geographic Information Systems

- GIS as collection of tools to gather, classify, manage, retrieve, analyze, transform, enrich, visualize, and share geo-referenced spatial data
- GIS objects can have spatial and non-spatial attributes and relations
- Spatial attributes deal with coordinate systems, relations rely on topological, directional, proximal or distance features and connectivity containment using contiguity predicates
- Operations on GIS objects provide insight into real world phenomena
- Aleatoric and epistemic uncertainty in attributes

Workflow in GIS Applications

Workflow introducing two-dimensional DST models describing uncertainty in an interactive query process in GIS application scenarios



[2]

Localization Approaches

- Initial object position and direction (x; y; θ)
- Autonomous robot: vision systems, beacons, landmarks, or GPS
- Markovian Localization Framework
  - (Extended) Kalman or Bayesian filter techniques
- Wide Area Augmentation System (WAAS), Differential GPS (DGPS), and Assisted GPS (AGPS)
- Inertial Navigation Systems (INS)
- Combining guaranteed interval methods with random approaches

Global Navigation Satellite System (GNSS)

Goal: Determine position (longitude, latitude and altitude coordinates) and time up to a certain precision

- Derive also velocity (direction and absolute value)
- Three independent systems will be available soon (USA GPS, EU Galileo, RUS Glonass)

Measuring the travel time of the satellite signal:

- Receivers have to know the time span of the signal coming from the satellite and reaching the receiver
- GPS receivers are synchronized with the satellites

Global Positioning System (GPS)

Relative satellites-receiver constellation is most important in determining the precision of estimated positions and times.

GPS receivers usually report an error magnification factor as Geometric/Positional/Horizontal/Vertical/Time Dilution of Precision (XDOP).

This entity refers to the influence of satellites’ geometry on time and position/position in a plane/height/time of the receiver.

Reported over three months in 2012: Factor 2.7 for global 99.9% PDOP, worst case 8

Total position error = *(Position error through other influences)* • *(DOP value)*

Typical error causes and ranges:

Error cause	**GPS**
Ephemeris data	1.5m
Satellite clocks	1.5m
Effect of the ionosphere	3.0m
Effect of the troposphere	0.7m
Multipath reception	1.0m
Effect of the receiver	0.5m
Total Root Mean squared error value	**3.0 -10.0m**

Cp. Jean-Marie Zogg : GPS Essentials of Satellite Navigation Compendium 2008

DOP Matrix

- $D := (D_{ij})$, $i,j=1,\dots,4$, $D := (P^T P)^{-1}$
- $P_{i1} := (x_{user} - x_{sat\_i})/R_i$, $P_{i2} := (y_{user} - y_{sat\_i})/R_i$
- $P_{i3} := (z_{user} - z_{sat\_i})/R_i$, $P_{i4} := 1$, $i := 1,\dots,4$,
- $GDOP^2 := D_{11} + D_{22} + D_{33} + D_{44}$
- $PDOP^2 := D_{11} + D_{22} + D_{33}$
- $HDOP^2 := D_{11} + D_{22}$
- $VDOP^2 := D_{33}$
- $TDOP^2 := D_{44}$

Horizontal Distance Error

Rayleigh distribution
used for modeling
GPS error

http://www.gps.gov/systems/gps/performance/accuracy/

Practical Work in PRASEDEC

We work with the data collected on Tuesday, September 3, 2013 between 17 and 18h using several smart phones. There was data from a walk in Parque O'Higgins, Tupper, Beauchef, Blanco Encalada, Jose Miguel Carrera, Domeyko, Almirante Latorre.

Dempster-Shafer for Intervals Theory

Random set

$$(\boldsymbol{A}, M) := \{(\boldsymbol{A}_1, m(\boldsymbol{A}_1)), (\boldsymbol{A}_2, m(\boldsymbol{A}_2)), \ldots, (\boldsymbol{A}_n, m(\boldsymbol{A}_n))\},$$

Interval basic probability assigment

$$\boldsymbol{m} : 2^X \to \boldsymbol{x} \in [0,1] \text{ mit } \boldsymbol{x} \in \mathbb{IF},\ 1 \in \sum_{i=1}^{n} \boldsymbol{m}(\boldsymbol{A}_i),\ \boldsymbol{m}(\emptyset) = [+0, +0].$$

Plausibility and belief

$$\mathrm{PL}(Y) := \sum_{\boldsymbol{A}_i \cap Y \neq \emptyset} (\overline{m}(\boldsymbol{A}_i)),\quad \mathrm{BEL}(Y) := \sum_{\boldsymbol{A}_i \subseteq Y} (\underline{m}(\boldsymbol{A}_i)), \qquad Y \subseteq X.$$

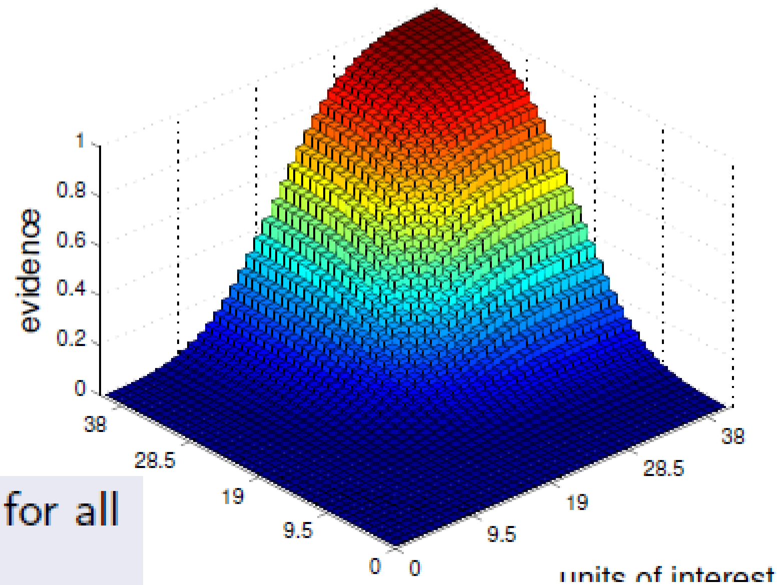
Normalized mass $\boldsymbol{m}(\boldsymbol{A}_i)$ as hull of

$$\underline{m}(\boldsymbol{A}_i) \boxed{\div} \mathrm{fl}_{\triangle}\left(\sum_{\mathrm{j}=1}^{\mathrm{n}} \underline{m}(\boldsymbol{A}_\mathrm{j})\right),\quad \overline{m}(\boldsymbol{A}_i) \boxed{\div} \mathrm{fl}_{\triangledown}\left(\sum_{\mathrm{j}=1}^{\mathrm{n}} \overline{m}(\boldsymbol{A}_\mathrm{j})\right).$$

[1] , [2]

Higher Dimensional Focal Elements

- Positional/Horizontal/Vertical/ Time coordinates *x,y,h,t*
- Example for dealing with HDOP



Cumulative distribution function [2]

Two-dimensional focal elements $A_i = \{A_{ix}, A_{iy}\}$ for all $i = 1, \ldots, n$

$$m : 2^X \to x \in [0,1] \text{ with } x \in \mathbb{IM},$$

$$1 \in \boxed{\sum_{i=1}^{n} m(A_i)}, \; m(\emptyset) = [+0, +0],$$

$$m(C) := \boxed{\sum_{C=(A_{ix}\cap B_{jx}, A_{iy}\cap B_{jy})} m(A_i) \cdot m(B_j)}$$

Dempster‘s rule

Typical Queries

- Compute *Belief* and/or *Plausibility* that a horizontal/vertical/temporal/positional/geometric room contains an object
- Inverse query: find a room where Belief and/or Plausibility is a greater/smaller part of a certain interval
- Compute a Belief and/or Plausibility for more than one object.

Semantic Web

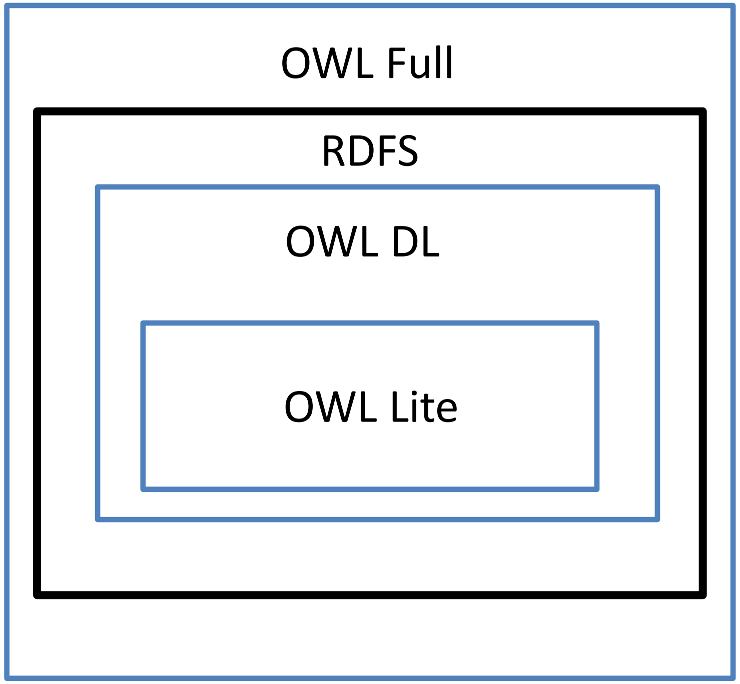
- **XML**: Makes well structured data persistent in a machine and human readable form
- **RDF(S) and OWL**: Description languages for ontologies
- **Ontology**: A ontology is a knowledge base which models knowledge in an application domain
- **Formal logic**: Application of inference, creating new knowledge

RDF (Resource Description Framework)

- RDF is a **formal language** for the description of structured information
- Makes web-based **exchange of data** possible without loosing original semantic
- RDF document is a **directed graph**, where nodes and edges are labeled with unique identifiers, known as URI (Uniform Resource Identifier) -> **composition of peripheral information**

Types of OWL (Web Ontology Language)

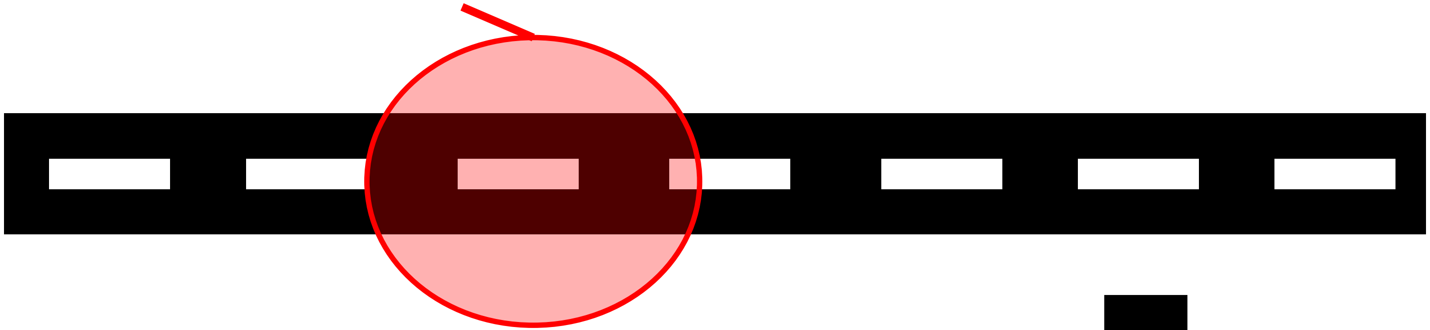
- OWL Lite:
  - Part of OWL DL and OWL Full
  - Decidable
  - Complexity: ExpTime (worst-case)
- OWL DL:
  - Part of OWL Full
  - Decidable
  - Complexity: NExpTime (worst-case)
- OWL Full:
  - Contains OWL DL and OWL Lite
  - Contains complete RDFS
  - Very expressive
  - Undecidable



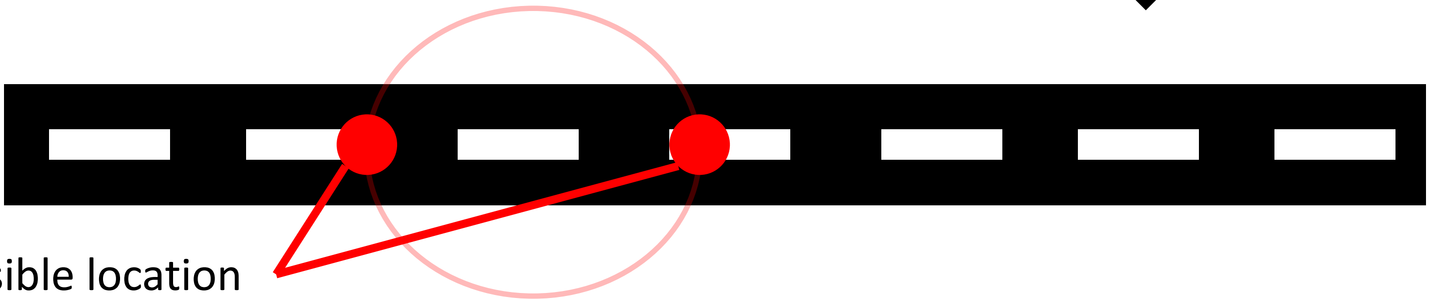
Location Model with Uncertainty

- Main idea:
  - GPS data is uncertain due to errors in measurements
  - Statistic models using belief functions can help to make GPS data accessible for the scenario
  - Domain knowledge can be used to reduce errors
  - Domain knowledge can be described by ontologies

Example



- Domain knowledge:
  - Location is measured in a car
  - Cars are driving on streets

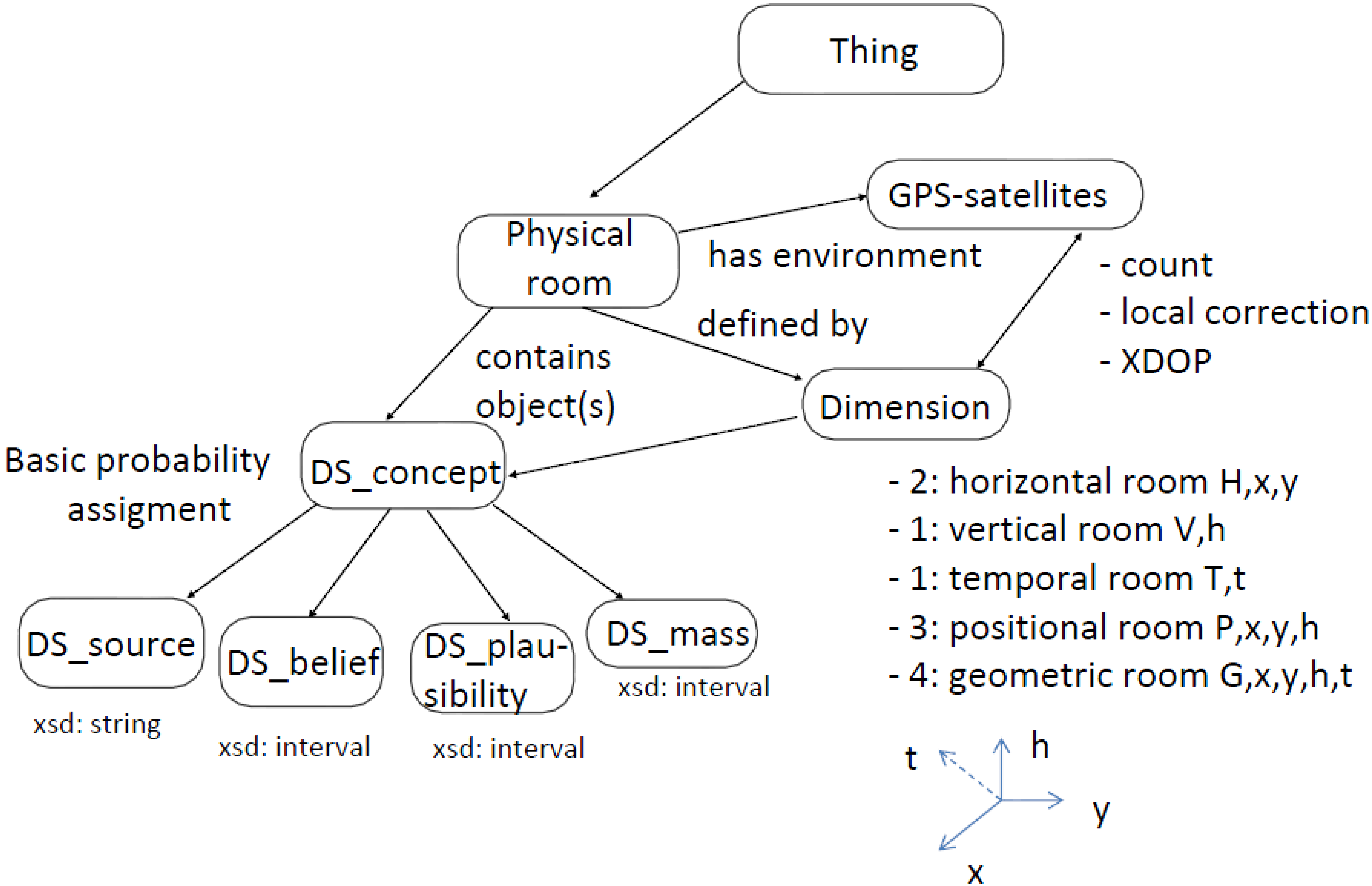


Possible Basic Ontology for GIS Applications

OpenGIS® Implementation Standard for Geographic
information - Simple feature access - Part 2: SQL option, p. xvi
Simple Features © 2010 Open Geospatial Consortium, Inc.

https://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CCQQFjAA&url=https%3A%2F%2Fportal.opengeospatial.org%2Ffiles%2F%3Fartifact_id%3D25354&ei=H808VNaEHenKygOWgoHAAw&usg=AFQjCNGzi96ntHCbcZZxRl-Q3iZH8adovQ&bvm=bv.77412846,d.bGQ&cad=rja

Possible Basic Ontology for GIS Applications



SPARQL Protocol And RDF Query Language

- SPARQL is a query language for RDF, closely related to RDF triples (subject–predicate–object expressions)
- SPARQL is able to define variables
- The basic concept of SPARQL is the matching of SPARQL triples to RDF subgraphs
- This matching can be further constrained through SPARQL specific structures
- How to connect semantic models representing geographical data to a query language making this concept accessible for GIS application?

→ GeoSPARQL

Basic Structure

- SPARQL has the following basic structure

```
SELECT ...
WHERE
{
   ...
}
```

- The SELECT clause specifies the variables that are part of the query result
- The WHERE clause provides the basic graph pattern to be matched against the data graph

GeoSPARQL

Consists of:

- An RDF/OWL vocabulary for representing spatial information
- A set of SPARQL extension functions for spatial computing
- A set of RIF (Rule Interchange Format) rules for query transformation

GeoSPARQL – Basic Classes

- Spatial Object

```
geo:SpatialObject a rdfs:class, owl:class;
  rdfs:isDefinedBy  <http://www.opengis.net/spec/geosparql/1.0>;
  rdfs:label        “Spatial Object”@en;
  rdfs:comment      “This class represents everything that can have a
                    spatial representation. It is super class of
                    Feature and Geometry.”@en .
```

- Feature

```
geo:Feature a rdfs:class, owl:class;
  rdfs:isDefinedBy  <http://www.opengis.net/spec/geosparql/1.0>;
  rdfs:label        “label”@en;
  rdfs:subClassOf   geo:SpatialObject;
  rdfs:disjointWith geo:Geometry;
  rdfs:comment      “This class represents the top level feature type.
                    This class is equivalent to GFI_Feature defined in
                    ISO 19156, and it is super class of all feature types.”@en .
```

- Geometry
  - Are all Spatial Objects that are no features (see above)?
  - GeoSPARQL further specifies a Geometry Class Hierarchy

Properties of geo:Feature & geo:Geometry

- geo:Feature
  - geo:hasGeometry
  - geo:hasDefaultGeometry
- geo:Geometry
  - geo:dimension
  - geo:coordinateDimension
  - geo:spatialDimension
  - geo:isEmpty
  - geo:isSimple
  - geo:hasSerialization

Definition of Topological Relation

- GeoSPARQL specifies three sets of topological relation types based on a simple (GeoSPARQL own) definition, Region connected calculus (RCC8), and Dimensionally Extended nine-Intersection Model (**DE-9IM**, Egenhofer), but is not restricted to those.

- Relation Name:
  - Equals
  - Disjoint
  - Intersects
  - Touches
  - Within
  - Contains
  - Overlaps
  - Crosses
- Relation URI:
  - Geo:sfName
- Domian/Range
  - Geo:SpatialObject

Query Functions Based on Topology

- Some Boolean query functions defined for the *Simple Features* relation family
- Multi-row intersection patterns should be interpreted as a logical OR of each row
- Each function accepts two arguments (geom1 and geom2) of the geometry literal serialization type specified by *serialization* and *version*.
- Each function returns an xsd:boolean value of **true** if the specified relation exists between geom1 and geom2 and returns **false** otherwise

- Query Function

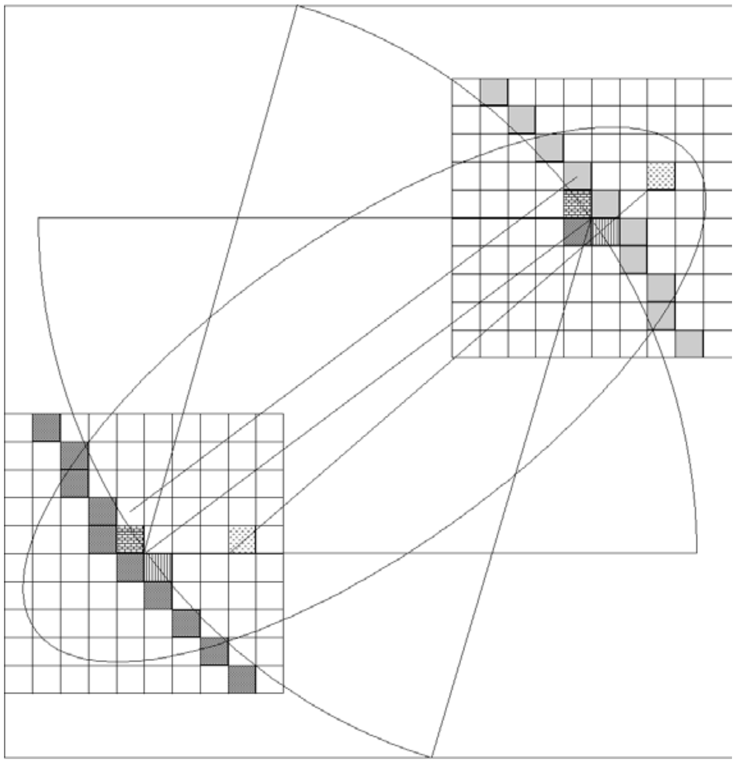
Geof : sfName (geom1: ogc : geomLiteral,
geom2 : ogc : geomLiteral
) : xsd : boolean

OGC GeoSPARQL - A Geographic Query Language for RDF Data

Uncertainty Visualization Truck Scenario

To reduce uncertainty in the localization and orientation task, we will assume that a rack-body truck has two independent GPS sensors located at the front and at the back of the truck. The distance between these sensors is assumed to be d = 20 meters–the average length of a truck according to European directives.
To compute the GPS-position of the truck with the highest probability, we

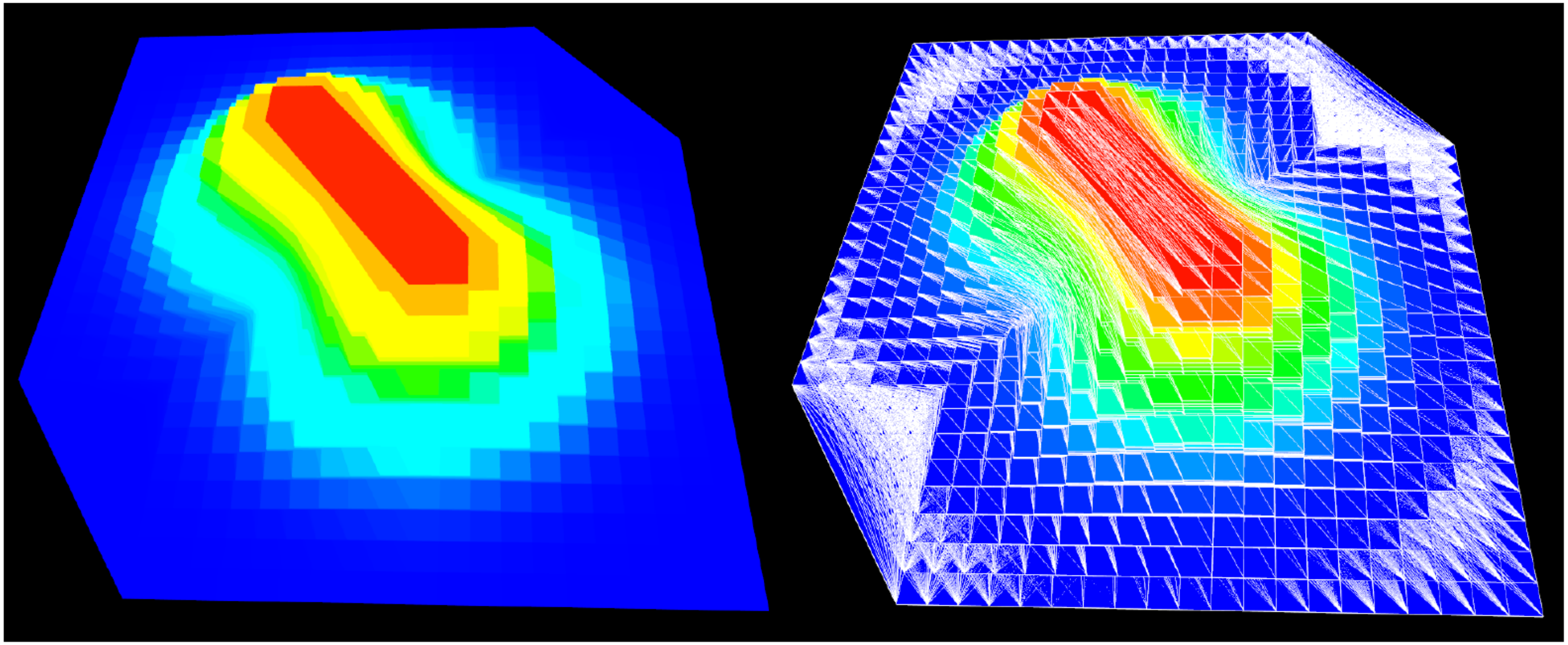
(a) compute all possible combinations of the focal elements and their distances,
(b) find all focal elements with 20 meters $\in \boldsymbol{d}$,
(c) normalize all possible combinations, and
(d) find the maximal masses describing the most probable position–here, a line with two uncertain endpoints.



[2]

Roughly speaking, the grid approach using 2DIBPAs is similar to the Riemann integral concept using upper and lower sums. In our example, we ask for inner and outer domains *I* and *O*, which contain all possible orientations of the truck with a given high probability, and alignments enclosed by a contour *C* situated in the shape $S := O \setminus I$.

Uncertain GIS Query Based on DST

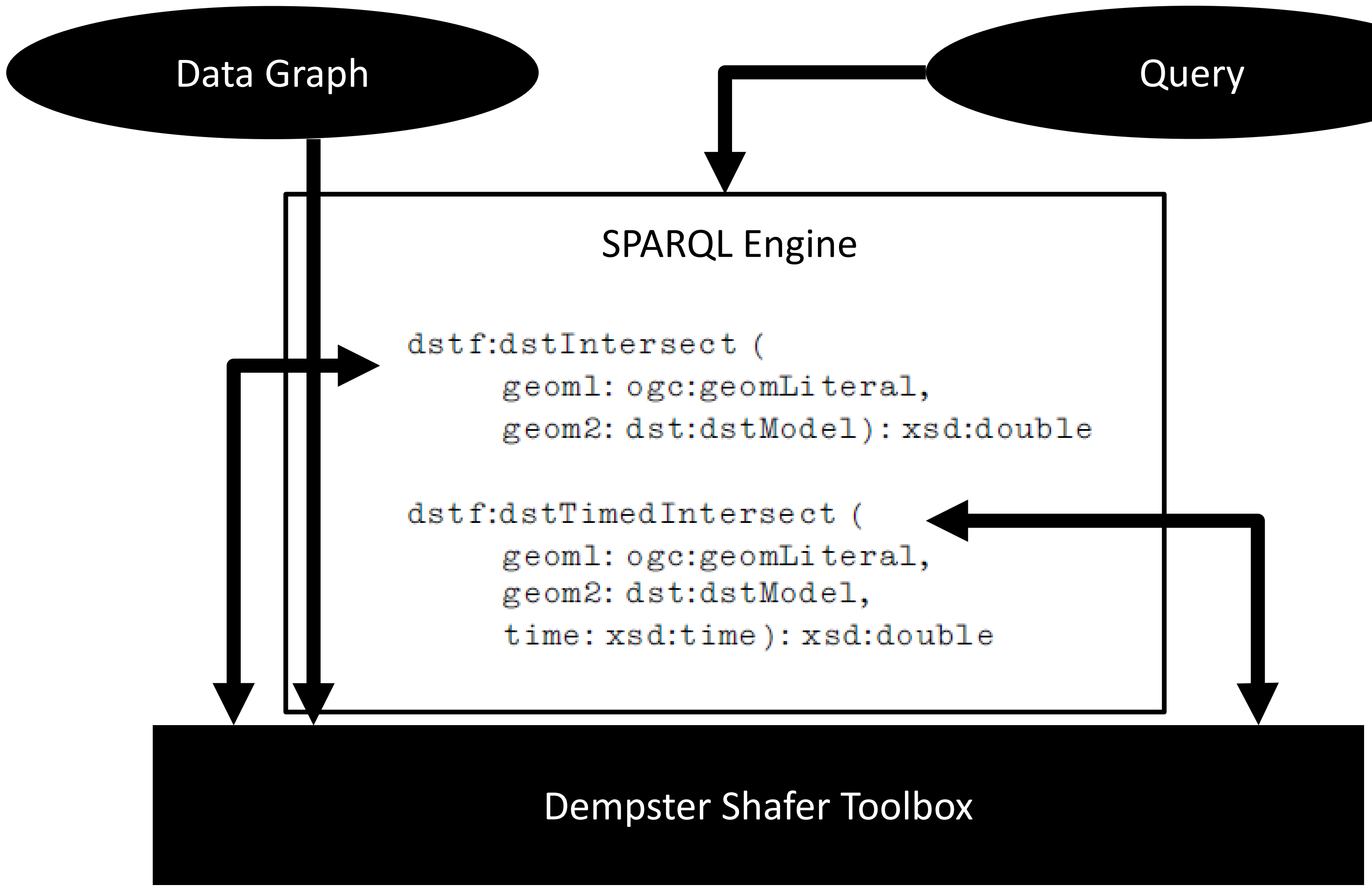


Graphical representation of the solution set describing possible locations and orientations of a truck. [2]

Extended GeoSPARQL for Uncertain GIS

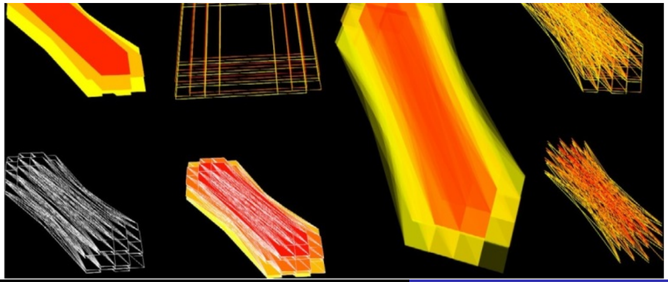
```
dst:hasUncertainGeometry a rdf:Property;
rdfs:subPropertyOf  geo:hasGeometry,
                    geo:hasDefaultGeometry;
rdfs:isDefinedBy     <http://inf.uni-due.de/dst>;
rdfs:label          "has uncertain geometry"@en;
rdfs:comment        "Connects a feature to a
                    geometry with an uncertain
                    geometry."@en;
rdfs:domain         geo:Feature;
rdfs:range          geo:Geometry.

dst:hasCertainGeometry a rdf:Property;
rdfs:subPropertyOf  geo:hasGeometry,
                    geo:hasDefaultGeometry;
rdfs:isDefinedBy     <http://inf.uni-due.de/dst>;
rdfs:label          "has certain geometry"@en;
rdfs:comment        "Connects a feature to a
                    geometry with
                    an exact, thus certain
                    geometry."@en;
rdfs:domain         geo:Feature;
rdfs:range          geo:Geometry.
```

Extended GeoSPARQL for Uncertain GIS



Truck Example

```
<rdfs:Class rdf:about="http://example.org/Truck#Vehicle">
  <rdfs:subClassOf rdf:resource="http://www.opengis.net/ont/geosparql#Feature"/>
</rdfs:Class>
<!– Instances from GPS tracks –>
<!– Truck A - TA–>
<ex:Vehicle rdf:about="http://example.org/Truck#TA">
  <dst:hasUncertainGeometry rdf:resource="http://example.org/Truck#TAGeom"/>
</ex:Vehicle>
<geo:Geometry rdf:about="http://example.org/Truck#TAGeom">
  <dst:asDST rdf:datatype="http://inf.uni-due.de/dst#dstModel">
    <![CDATA[<http://inf.uni-due.de/DST/format>
      (15837FOCALS)[20.0,22.0,20.0,22.0,32.0,34.0,36.0,38.0,.0008804,.0008804;
      20.0,22.0,20.0,22.0,32.0,34.0,34.0,36.0,.0008804,.0008804;
      ...
      18.0,20.0,20.0,22.0,32.0,34.0,36.0,38.0,.0008804,.0008804;],
      LatLonEle(51.4211024,6.787125,0.0).
    ]]>
  </dst:asDST>
</geo:Geometry>
```



Different rendering techniques and visualization approaches to the (convex) hull geometries [2]

Conclusion and Further Work

- A workflow for modeling, visualizing, and querying uncertain (GPS-)localization using interval arithmetic was developed
- A first implementation was realized by J. Frez at the University of Chile
- Further refinements and a validation in projects
  - Crime prevention
  - Disaster management

References

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