Towards Engineering Drones' Semantic Trajectories as Knowledge Graphs

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Abstract

The information related to the movement of vehicles can be enriched with data beyond latitude, longitude, and timestamp, enhanced with complementary segmentations, constituting what is called a *semantic trajectory*. Semantic Web (SW) technologies have already been used for the modeling and enrichment of semantic trajectories. In this paper, we present our work-in-progress regarding the engineering of semantic trajectories of drones as knowledge graphs (KG). Particularly, the work is motivated by a use case that focuses on UAV (Unmanned Aerial Vehicles) drones with a mission to document specific regions/points of interest (a petrified forest in GeoPark). This research work aims to develop a) a methodology for the engineering of *semantic trajectories as KGs* (STaKG), b) a toolset for the management of KG-based semantic trajectories and c) a repository of semantically annotated GIS recording missions and the corresponding produced documentation records. In this paper, we present work-in-progress related to a) the STaKG engineering methodology, b) the STaKG management toolset for supporting the methodology, c) the semantic model for representing knowledge related to drones' semantic trajectories and the related documentation recordings.

Keywords[1]

Geoinformatics, drone, knowledge graph, semantics, trajectory

1. Introduction

Today, geospatial data is vital for emerging research and development areas such as the one of autonomous/unmanned vehicles. The next generation of spatial knowledge graphs will integrate multiple spatial datasets with the large number of general datasets that contain geospatial references e.g., weather data, points and regions of interest (POI/ROI). Geospatial Linked Data (GLD) enables a web-based, interoperable geospatial infrastructure. Geospatial information systems benefit from Linked Data principles in building the next generation of spatial data applications e.g., autonomous vehicles, delivery, surveillance, and documentation drones. This paper presents an approach for managing GLD, especially for building next-generation spatial applications in the domain of UAV drones. The aim of this paper is to present the proposed approach and the in-progress implementation of a semantic model and a toolset for the engineering of drones' semantic trajectories as KGs.

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The segments of an object's movement track, which have been defined based on the interest that they present for some application (e.g., a drone's movement in an area for a given recording mission), are called *trajectories* of the moving object [1]. A trajectory can be i) enriched with additional data (beyond latitude, longitude, and timestamp information), and/or ii) enhanced with several complementary segmentations, constituting a *semantic trajectory* [2]. In terms of deployment, a semantic trajectory may be useful for applications that require the interpretation of the trajectory of a moving object (e.g., points or regions of interest that a drone has documented).

Semantic Web (SW) technologies have been used for the modeling and enrichment of semantic trajectories, since they facilitate the modeling and interlinking of data that could enhance a trajectory of raw movement data, as well as the segmentation of the trajectories themselves, based on semantic data, in a standardized and meaningful way [2, 3]. *Knowledge Graphs* (KGs) incorporate semantic models (in many cases they can be considered as populated ontologies in the form of directed graphs) utilized for the structured and formal representation of heterogeneous data, as well as for reasoning with multiple integrated views of it [4, 5].

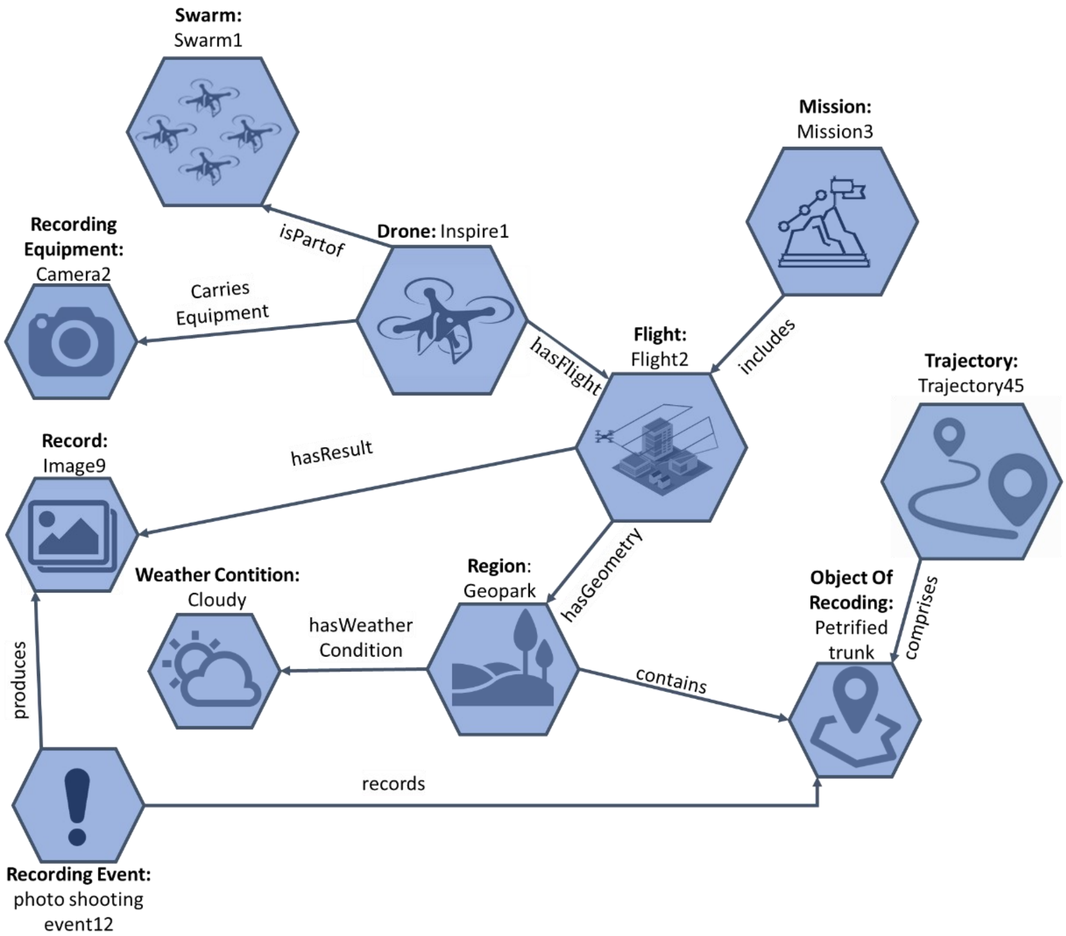

Figure 1. Example KG representing knowledge related to a drone trajectory followed during a documentation mission in the GeoPark of Lesvos island.

Motivated by use cases related to drones' mission to document (with photos recording events) specific regions and points of interest such as the GeoPark of petrified forest in Lesvos island, our research aims to develop a KG-based approach for transforming trajectories of drones (usually operating in a swarm) - and particularly, UAV (Unmanned Aerial Vehicles) drones - into semantic trajectories that can be effectivele managed, visualized, and analyzed. A snapshot of the use case is depicted in Figure 1 in the form of a simplified KG. The main objectives of the approach are to facilitate i) the modeling of semantic trajectories of drones and swarm of drones, their flights and recordings per mission (e.g., volume and frequency of recording episodes), ii) the visualization and analysis of semantic trajectories, iii) the retrieval of semantic information of flights/missions (e.g., drone position, recording position, episodes' date/time, weather data), and, iv) the retrieval of records (e.g., photos) which have been produced during different recording events of trajectories related to a flight/mission, based on parameters such as the type or location of recording events (e.g., nearby recording positions, photograph recording, the object of interest that has been recorded, etc).

Based on the aforementioned objectives, this research aims to contribute a) a methodology for the engineering of drones' semantic trajectories as KGs (STaKG), b) an integrated toolset for the management of KG-based drones' semantic trajectories, and c) a repository of semantically annotated GIS recording missions and the corresponding produced documentation records. Specifically in this paper, we present work-in-progress related to a) the proposed STaKG methodology, b) the under-development STaKG management toolset for supporting the methodology, c) the developed semantic model for representing knowledge related to drones' semantic trajectories and the related documentation recordings.

The remainder of the paper is structured as follows: Section 2 presents related work. Section 3 presents the proposed methodology for engineering drones' semantic trajectories as KGs. In Section 4, the architecture and technological choices for the toolset that supports the proposed methodology are presented. In Section 5, the developed semantic model and the expected results of the work-in-progress implementations, are discussed. The paper concludes with a discussion summarizing the research work conducted so far.

2. Preliminaries and Related Work

According to recent discussions, a KG is "a very large semantic network that integrate various and heterogeneous information sources to represent knowledge about certain domains of discourse" [6] or "a graph of data intended to accumulate and convey knowledge of the real world, whose nodes represent entities of interest and whose edges represent relations between these entities" [4]. Additionally, "a knowledge graph acquires and integrates information into an ontology and applies a reasoner to derive new knowledge" [3], a definition that shows the close relation of KGs to the exploitation of reasoning. More particularly, if the KG builds up quantified statements, ontologies or rules are required in order to provide more expressive and standard representation of knowledge, while deductive methods can be used to entail further knowledge. Inductive methods can also be used in order to extract additional knowledge from a KG, based on simple or quantified statements [4].

Santipatakis et al. [1] propose the datAcron ontology for representing semantic trajectories at varying levels of spatiotemporal analysis. Mobility analysis tasks are based on a wealth of disparate and heterogeneous sources of information that need to be integrated. The proposed ontology, as a generic conceptual framework, tackles this challenging problem. The experimental results in Air Traffic Management domain demonstrate that the proposed ontology supports the representation of trajectories at multiple and interlinked levels of analysis.

Gao et al. [7] proposed a representation of semantic trajectories that considers domain knowledge, in addition to spatiotemporal data, to achieve improved retrieval of semantic trajectories. The developed method proposes a tree-shaped hierarchical network that detects ROI in a set of trajectories, in order to replace those trajectories with sequences of the detected ROI. The ROI sequences are transformed, based on the geographical and semantic trajectory features, to continuous vectors. The model measures similarities among the vectors and emphasizes on the context of trajectories to extract semantic relations among target objects.

3. Engineering drones' semantic trajectories as knowledge graphs

Ontologies constitute the backbone of KGs since they provide the formal and explicit semantics that KGs need for the effective modeling of linked data in the Web of Data. *Ontology engineering methodologies* (OEMs) define specific methodological phases, processes, and tasks for the engineering of ontologies, including feasibility analysis, identification of goals, requirements specification, implementation, evaluation, and maintenance. Those steps present - to some extent - an analogy to KG building steps. As suggested by related work [5], the ontology and the KG that is built on top of it, can both be developed following the general principles and similar/analogous tasks and steps of an OEM (e.g., DILIGENT [8], HCOME [9]). In this direction, our work borrows and adapts principles and tasks of a collaborative and iterative OEM to support KG engineering, involving stakeholders of different expertise related to KG development, enrichment, and maintenance, in a continuous, iterative, and collaborative manner. The proposed methodology, namely *Semantic Trajectories as Knowledge Graphs* (STaKG) methodology, is mainly based on the *Human-Centered Collaborative Ontology Engineering Methodology* (HCOME) [9] and to its latest updates to support ontology modularization and bias issues. In addition, we borrow princeples from other related KG engineering approaches [6, 10] and merge with the ones of HCOME. STaKG methodology constitutes a hybrid (human-center/top-down and data-driven/bottom-up), collaborative and iterative approach for supporting STaKG lifecycle: i) specification, ii) development, iii) evaluation and exploitation.

Figure 2: Phases and processes of STaKG methodology (ST refers to a *Semantic Trajectory)*.

The three phases of STaKG methodology are briefly described below (and depicted in Figure 2):

- The first phase includes the specification of the involved stakeholders of the engineering team (who is doing what), as well as the aim, scope, and requirements in terms of data, semantic annotations, segmentations of the trajectories, and the model that will capture the required knowledge.
- The second phase includes the creation of the explicit knowledge related to the STaKGs, i.e., the extension and specialization of reused semantic trajectory models (e.g., an extension of existing semantic trajectory ontology) based on the requirements of the first phase. It also includes the creation of instance data i.e., spatiotemporal and contextual data about the recorded trajectories. In the same phase, storage, publishing, retrieval, and visualization of the STaKGs are included.
- The third phase includes a) the evaluation of the quality of the modeled STaKGs, in terms of correctness, completeness, and bias, b) the cleaning and enrichment of the STaKGs. Enrichment refers to the discovery and linking to additional/extenral knowledge sources

(e.g., from the Web). In the same phase, deployment and maintenance procedures are included.

The deployment of STaKGs involves a set of services according to the proposed STaKG methodology. These services may be useful to a number of different use cases. A key set of the deployment services suggested by the methodology are:

- *visualization* in terms of geographic maps and events or phenomena timelines e.g., provide a geographic map that visualizes different flights of a drone in the form of a semantic trajectory (i.e., with the related data-recording episodes) during a specific mission,
- *analysis* based on spatiotemporal semantics e.g., analyze the duration and recording results of a specific flight of a drone in a specific area of interest,
- *comparison* of semantic trajectories e.g., compare (in terms of spatiotemporal criteria) the semantic trajectories of two recording episodes for the same ROI/recording space,
- *merging* of two semantic trajectories of flights that occur in the same recording mission of a specific drone,
- *splitting* and *refinement* of a semantic trajectory to specific episodes e.g., further splitting the recording episodes of the trajectory of a drone to sub-episodes of camera-shooting position set at up-shooting-departure for the next shooting position,
- *discovery* of previously unknown behaviors of moving entities (behavior analytics) where there is no *a priori* knowledge for the behavior, e.g., discover types of flights of drones based on the flight-behaviors/patterns followed by their operators,
- *behavior detection/reasoning*, which refers to the recognition of an already known moving behavior of a moving entity. For instance, based on the semantic trajectory of a drone and the carried equipment, recognize the aim of the flight or the mission (e.g., surveillance flight vs scientific flight),
- *evaluation* in terms of spatiotemporal information and its correlation with other contextual data e.g., evaluate the expected efficiency (e.g., duration, altitude) of a flight or mission based on the environmental conditions of the flight or mission (e.g., high efficiency cannot be expected during bad weather conditions).

4. The STaKG management toolset

To support STaKG methodology with an engineering environment, we have designed a management toolset based on state-of-the-art technology for Linked Data and KGs. Its interconnected components exchange data through a pipeline process (see Figure 3) that involves a) preprocessing of position/movement data (data cleaning, data compression), b) the enrichment of raw trajectories for the engineering of semantic trajectories (semantic segmentation, semantic annotation, utilization of application domain and geographical data), c) conversion of ST to KGs (ST management, retrieval), d) analysis of STaKG to recognize semantic behaviors (classification, clustering, aggregation, comparison of STaKGs).

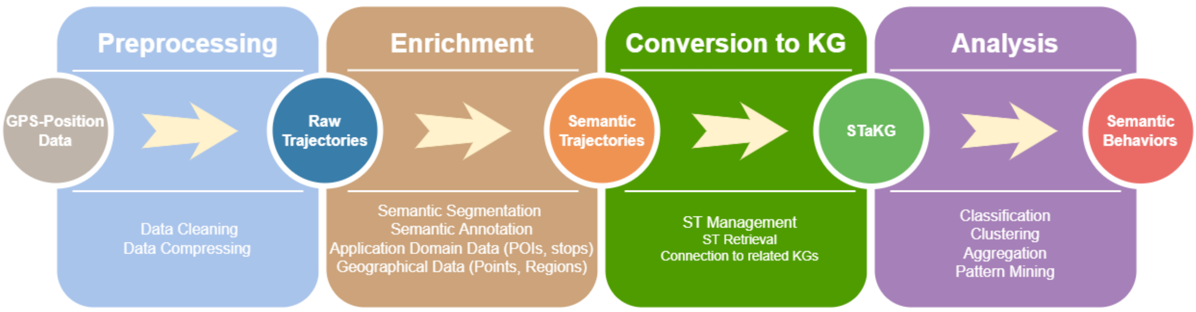

Figure 3. STaKG pipeline processing

The high-level architecture of the designed toolset (see Figure 4) includes: a) a tool for raw trajectory data cleaning and RDFization based on automated/semi-automated mapping to related semantic models, utilizing specialized tools (OpenRefine [11], Karma [12]), b) a tool for trajectory data summarization and their enrichment with recording metadata, weather data, and structured data of POI/ROI shape files, c) a tool for semantic trajectory management (split, merge, combine, analyze), and d) a web-based tool for semantic trajectory browsing and visualization. The tools described in (b), (c), and (d) will be developed using GRAND [13] technology stack which includes GraphQL, React.js, Apollo, Node.js, and Neo4j. Furthermore, a graph database, namely Neo4j [14], supports the web-based tool, and stores the managed data (semantic trajectories, GIS recording missions, and produced records). Especially for RDF store technology, although noteworthy alternatives exist, specialized in spatiotemporal RDF data storing, e.g., Strabon RDF store [15], Neo4j was selected due to its integration in the GRAND technological stack, as well as due to the integrated graph analytics solutions that it provides.

A high-level architectural design of the interconnected tools of the STaKG toolset, and the related exchanged data, is depicted in Figure 4.

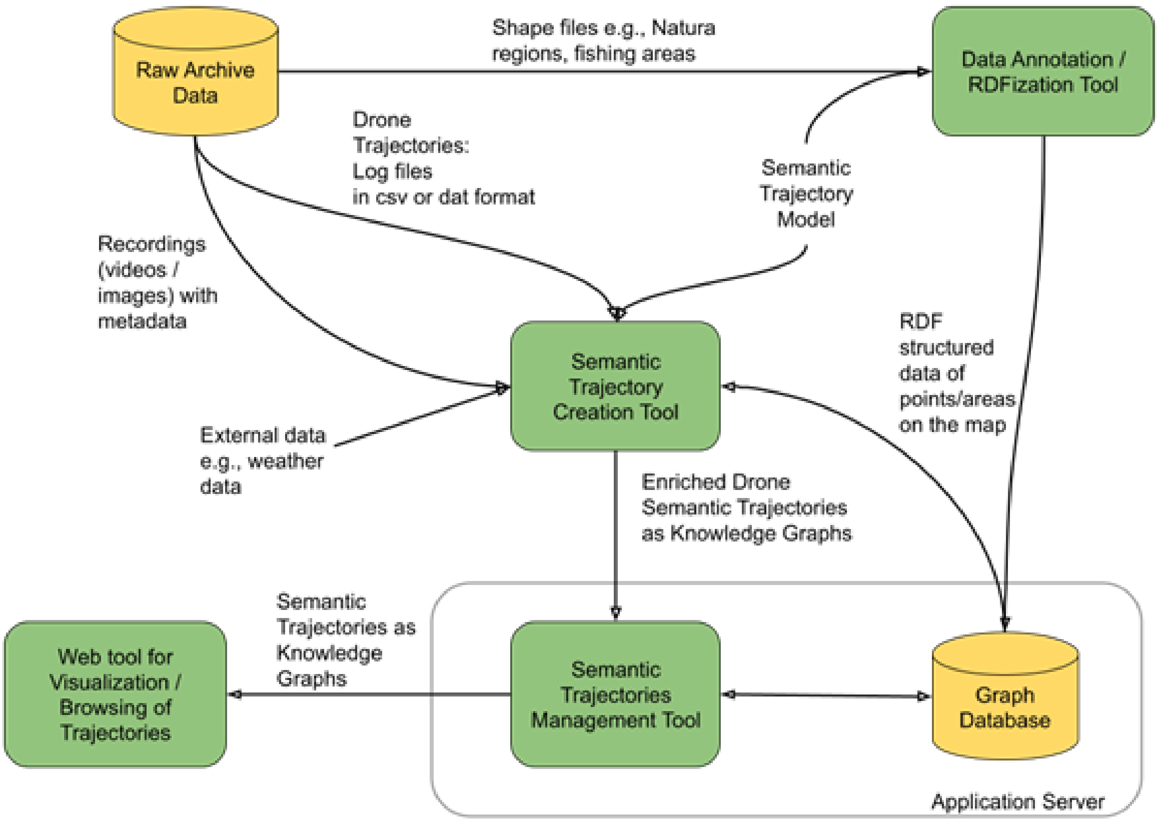

Figure 4. STaKG toolset high-level architecture and data exchange.

5. Implementation and expected results

In the motivated use case of our work, the data and knowledge that the underlying model of a STaKG aims to capture is derived from five different -though interlinked- thematic domains: i) trajectory information, ii) drones' flight and mission information, iii) recording events and resulted records, iv) geographical information of regions/points of interest, and v) weather conditions. The data related to the five thematic domains, are:

- *flight data,* derived from flight log files which are written records of a flight automatically generated by a drone. Flight log files contain flight details concerning flight planning information along with time-stamped movement of the drone and on-board sensor data (e.g., longitude, latitude, altitude, timestamp of different positions). Flight log files are usualy stored (usually in CSV format) at the native application of a device (remote control, mobile phone, or tablet) and on the drone's pilot application.

- *equipment data,* which are the data reported by the flight operator, describing the characteristics of a drone (e.g., model, serial number, software type). Those data are documented after the in-situ survey using drone data management software (namely, Drone Logbook).
- *recording/mission data*, which are the data reported by the flight operator in the context of the mission planning procedure (e.g., the purpose of the mission, the category of the mission, the area of the mission, the equipment to be used). Those data are documented by experts right after the mission, using drone data management software (namely, Drone Logbook).
- *records data (aerial and terrestrial)*, which are the metadata of the files (photos, videos, lidar data) acquired during the flight mission (e.g., longitude, latitude, date, time of the recording) or/and metadata of the processed/final records. Those data are provided either by exif files of the records or directly from the records.
- *geographic names and elements*, which are data about the POI/ROI that the objects of interest are located and the drone's mission occurs.
- *weather data*, which are data (e.g., temperature, humidity, wind velocity) recorded by weather monitoring devices or systems, and they are dynamically collected from external (Web) services or/and in-drone sensors, based on the time and location of the mission that is recorded.

For the development of the semantic model that is required to represent knowledge related to StaKGs, existing related models have been studied, such as the *datAcron* [16]*, Dronetology* [17], and the *W3C Geospatial Ontologies* [18]. These models were selected based on our previous experience in related work, as well as on searching ontology repositories (LOV [19] and ODP [20]) using terms such as *trajectory, drone, weather, recording, record*. At this point, the *datAcron* ontology has been selected for reusing the main conceptualization of the semantic trajectory and aviation. The *Dronetology* ontology has been recently proposed and designed as an application ontology focused on Wireless Sensor Networks and Unmanned Aerial Systems (WSN-UAS) domain with limited requirements, i.e., to support an ontology-based path planning adaptation system, which is integrated into the UAS payload providing autonomous flight replanning [21]. On the other hand, the datAcron ontology covers two domains that are included in the scope of the semantic model under development: *semantic trajectories* and *air traffic management*. The ontology is reused by its direct import. The datAcron ontology directly imports the ontologies: i) DUL (DOLCE+DnS Ultralite ontology) [22], which is a simplification of parts of the DOLCE Lite-Plus library, ii) SKOS [23] (Simple Knowledge Organization System), which is a data model for sharing and linking *Knowledge Organization Systems* (e.g., classification schemes, authority files, subject headings) via the Web, iii) SOSA/SSN [24] (Sensor, Observation, Sampler, and Actuator/Semantic Sensor Network), which describe the context of sensors and actuators activity (including systems of sensors and actuators, observations, procedures, subjects, samples etc.), iv) SF (Simple Features Geometry) [25], which extends GeoSparql and defines *Simple Feature* geometry types (a set of standards for the specification of geographic features used by geographic information systems [26]), v) GML [27] (Geography Markup Language), which is an RDF encoding for the transport and storage of geographic information, and vi) GeoSparql [28], which is an ontology for spatial information, while it includes SPARQL extension functions and RIF rules supporting queries and reasoning.

The primary objectives of the semantic model under development are to i) exploit the existing ontologies, ii) model the aforementioned data and knowledge, and iii) bridge the different thematic domains which are required for our use case. At this stage, a first draft version of the semantic model (Onto4drone [29]) has been developed (version 1.0.0) and it is available in OWL. It is directly based on the datAcron ontology, and indirectly on the DUL, SKOS, SOSA/SSN, SF, GML, and GeoSparql ontologies. The model was developed following the HCOME collaborative engineering methodology, supported by Protege 5.5 (for personal space engineering), and WebProtege (for shared space engineering) tools respectively. In addition, Google docs and Meet have been used for further collaborative engineering tasks.

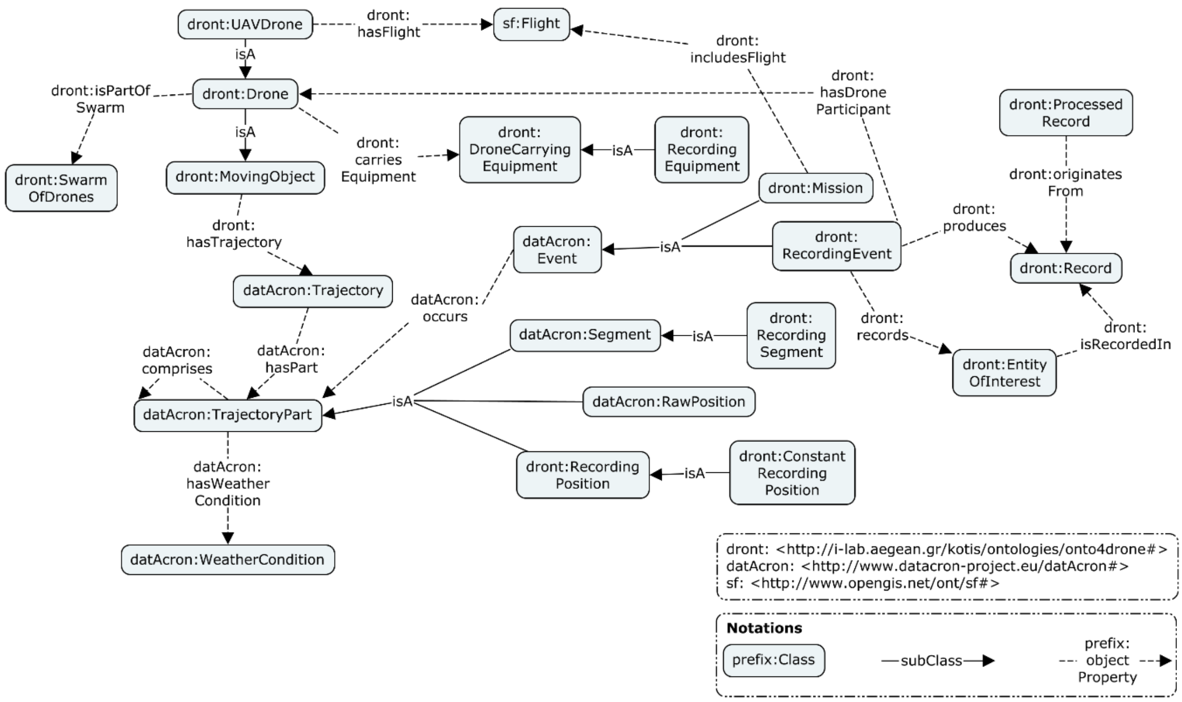

Figure 5: Basic concepts and relations of the STaKG semantic model representing drones and recording episodes.

The basic concepts and relations of the model which were first specified and afterwards implemented in the Onto4drone ontology, are briefly presented in Figure 5 in the form of a concept map. The first version of Onto4drone includes classes, object properties, and data properties based on the motivated use case, as well as some basic restrictions (see Figures 6-8). For example, a representative restriction is the one that defines that a *RecordingEvent occurs in* at least one *RecordingPosition* or in a *RecordingSegment*. Additionally, a number of individuals have been added in order to evaluate the engineered model at this initial stage.

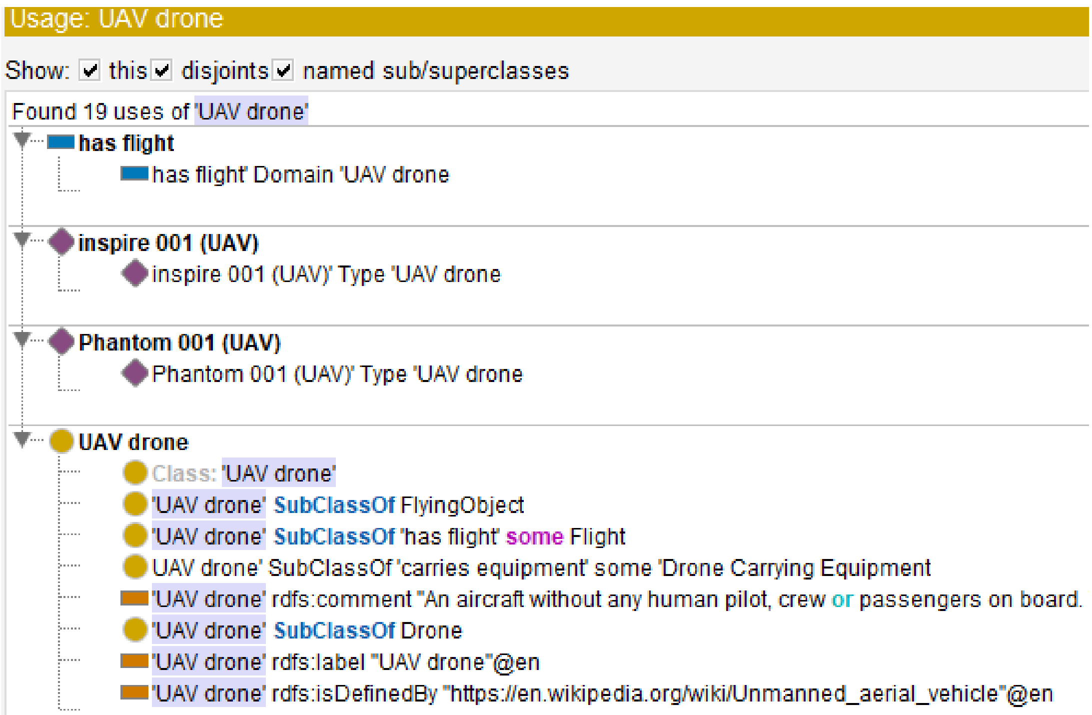

Figure 6: The object properties, individuals, restrictions, and annotations of the class *UAV Drone* of the Onto4drone ontology (version 1.0.0).

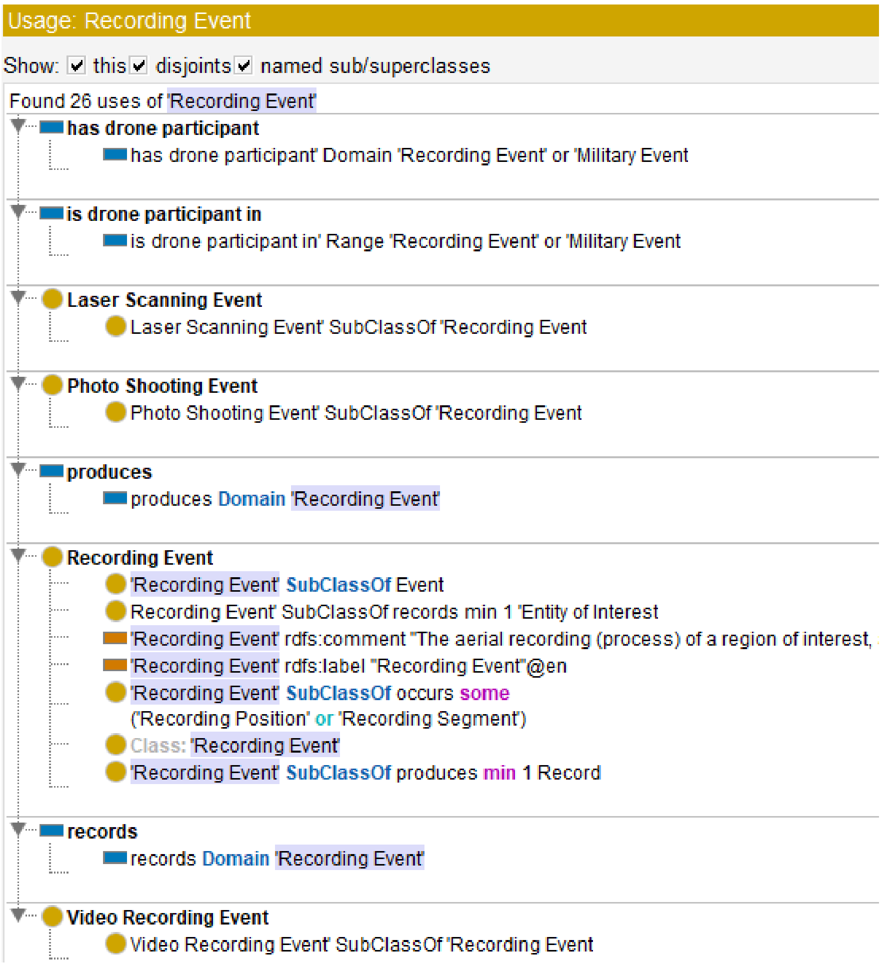

Figure 7: The object properties, individuals, restrictions, and annotations of the class *Recording Event* of the Onto4drone ontology (version 1.0.0).

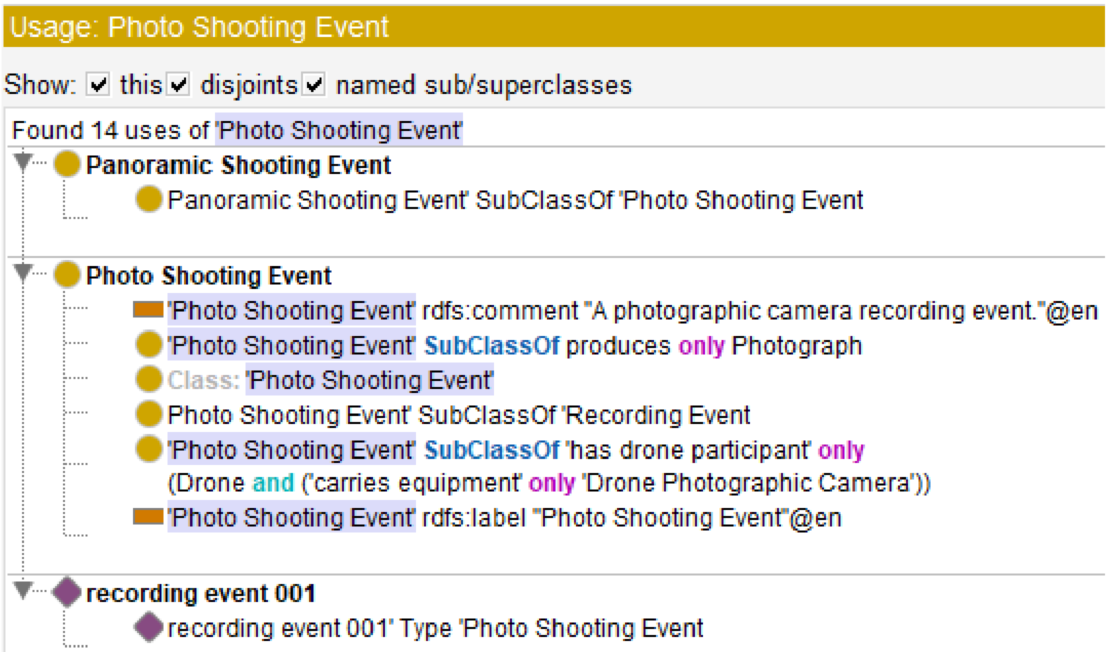

Figure 8: The object properties, individuals, restrictions, and annotations of the class *PhotoShootingEvent* of the Onto4drone ontology (version 1.0.0).

Figures 9 and 10 depict example SPARQL queries used for evaluation purposes (aligned to the competency questions specified in the Specification phase of the STaKG methodology). For instance, "*which flights of a specific mission results in records that include a specific object of interest*" or "*what are the weather conditions at specific recording points while recording an object of interest*".

Next steps of our work towards the development of the Onto4drone semantic model include further exploitation of GeoSparql classes and object properties, as well as the addition of axioms and/or rules which will support inferences useful for the segmentation of trajectories based on our use case, e.g., a *position of the trajectory of a drone* is inferred as a *recording position* if a *recording event* has been occurred there.

SPARQL query:

```
#which flights of mission1 resulted in records that include the object of interest, pertified trunk
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX dront: <http://i-lab.aegean.gr/kotis/ontologies/onto4drone#>
PREFIX datacron: <http://www.datacron-project.eu/datAcron#>
PREFIX opengis: <http://www.opengis.net/ont/sf#>
PREFIX sosa: <http://www.w3.org/ns/sosa/>
SELECT * WHERE {
                    dront:m_001 dront:includesFlight ?flight .
                    ?flight sosa:hasResult ?records .
                    dront:petrifiedTrunk dront:isRecordedIn ?records.
                    }
```

flight	records
flight 001 of mission 001	photograph 001
flight 002 of mission 001	point cloud 001

Figure 9: Example query "which flights of mission1 resulted in records that include a specific object of interest, namely, a petrified trunk".

SPARQL query:

```
#what are the weather conditions and temperature at the recording points while recording of the object of interest,
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX dront: <http://i-lab.aegean.gr/kotis/ontologies/onto4drone#>
PREFIX datacron: <http://www.datacron-project.eu/datAcron#>
PREFIX opengis: <http://www.opengis.net/ont/sf#>
PREFIX sosa: <http://www.w3.org/ns/sosa/>
SELECT DISTINCT ?position ?weather ?temperature WHERE {
                    dront:petrifiedTrunk dront:isRecordedIn ?record.
                    ?rec_event dront:produces ?record.
                    ?rec_event datacron:occurs ?position.
                    ?position datacron:hasWeatherCondition ?weather.
                    ?weather datacron:reportedMaxTemperature ?temperature
        }
```

position	weather	temperature
position 002	weather condition 002 of position 002	"24"^^<http://www.w3.org/2001/XMLSchema#int>
position 001	weather condition 001 of position 001	"25"^^<http://www.w3.org/2001/XMLSchema#int>

Figure 10: Example query "what are the weather conditions and temperature at the recording points while recording a specific object of interest, namely, a petrified trunk".

Eventually, the engineered STaKGs using the proposed methodology, model and toolset, are expected to constitute a GLD knowledge base available for a) utilization by drone-related applications, and b) the deployment of related services which will facilitate the work of epxerts/stakeholders. First and foremost, the STaKG knowledge base will be exploited for advanced map-based visualization of trajectories, flights, missions, recording events, timelines, and records e.g., a geographic map that visualizes different flights and individual photographic records of a drone in the form of a semantic trajectory, along with the related data-recording episodes recorded during a specific mission. Additionally, the STaKG knowledge base will be exploited for management and analytics tasks, such as the merging of two or more STaKGs that are related to the same recording mission, as well as the splitting and refinement of a STaKG to specific episodes e.g., splitting the recording episodes of the moving trajectory of a drone to sub-episodes of camera-shooting position set at up-shooting-departure for the next shooting position.

6. Conclusion

This paper presents a KG-based approach for transforming trajectories of drones into semantic trajectories managed by an integrated toolset. To this aim, the paper presents the proposed STaKG methodology, a hybrid, collaborative, and iterative methodology of engineering STaKGs, used in all phases of STaKG engineering. In addition, the paper presents a semantic model for representing STaKGs. Finally, the paper presents the architecture and the implementation choices of a management toolset (its implementation is a work-in-progress) based on state-of-the-art technology for Linked Data and KGs, which will support the STaKG methodology. Eventually, the KG-based semantic trajectories which will be formed as a structured, meaningful, and enriched output (a STaKG knowledge base), are expected to constitute the base for the deployment of management services which includes visualization, merging, splitting, and refinement of STaKGs, facilitating the work of experts in the Geoinformatics domain.

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