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AN ONTOLOGY FOR THREAT MODELING AND SIMULATION OF SMALL UNMANNED AERIAL VEHICLES

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ABSTRACT

Low, Slow and Small Unmanned Aerial Vehicles (LSS UAVs) are one of the fastest-growing threats for national defense, security and privacy. A NATO task group performed a study to identify the elements necessary to define LSS models applicable for the development of necessary countermeasure to potential threats in the future. The goal of this project is to utilize this data collected by the NMSG-154 study to generate a Web Ontology Language (OWL) ontology for LSS threat modeling. The LSS ontology will form the basis for a metamodel for a domain-specific language (DSL) based on the parameters identified. This DSL will eventually be used to generate specific simulation scenarios to model potential threats caused by small drones.

Keywords: ontology, domain-specific language, UAV, LSS

1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs), or drones as they are more commonly known, have become readily available in the mainstream for personal use and hobby flying. These Low, Slow, Small (LSS) vehicles are usually programmable, which allows the user to modify behavior to include harmful intent (NATO MSG-154 2018). The rapid evolution and widespread availability of this technology has made defense against the LSS threat a real worldwide concern (Stalinsky 2017). The primary LSS threat comes from three classes of minor UAVs, which are Micro, Mini and Small. This is because these UAVs can get very close and can avoid being recognized early enough to trigger an appropriate response. The easiest way to test potential scenarios of such threats and appropriate responses in a safe environment is to use experimental frameworks (Hodicky 2016) and to follow existing standards and best practices recommended in the domains of modeling and simulation (M&S) and of autonomous systems (Hodicky 2017). This project intends to use a domain-specific language (DSL) to allow for scenario-based simulation of LSS threat models based on the categorization and discussion provided in the NMSG-154 study (NATO MSG-154 2018).

DSLs are computer languages tailored to a specific application domain. As a result, DSLs are often more expressive for that particular domain, offering ease of use. This allows domain experts, who may not be familiar with programming and general-purpose programming languages, to use a DSL to express ideas and concepts in their domain, which is commonly not possible otherwise (Bettini 2016).

In order to describe a domain-specific model, a metamodel needs to be defined first. A metamodel is, in general terms, an object-oriented model. It is composed of metaclasses, which are composed of properties. A property is either an attribute (an instance of a standard datatype) or a reference to another metaclass (Bousse, Mayerhofer, Combemale, and Baudry 2017). An indispensable part of the modeling approach is a strong semantical basis for the model which incorporates the behavioral parts of the model and their connection with the structure (Harel 2001).

A common approach for modeling requires the utilization of ontologies (Jafer, Chhaya, and Durak 2017). Ontologies describe the important ideas in the form of keywords and hierarchical relationships, which are specific to a given domain and essentially provide a vocabulary for that domain (Yao and Zhang 2009). Developing an ontology for any domain requires a detailed analysis of that domain. Ontology development is primarily a definition and categorization process (Chan 2004). Ontologies bridge the gap between people and systems, as they describe domain relationships and objects in an easily understood manner while maintaining the ability to be machine interpretable. Ontologies allow both people and computers to understand and derive new knowledge about the domain in question (Putten, Wolfe, and Dignum 2008). Therefore, ontologies can be used as a starting point for further development as a domain expands or the ontology embraces new or additional concepts (Hilera and Fernández-Sanz 2010).

An ontology provides a quick and simplified description of a DSL, abstracting language's technical details, while highlighting key terminology and specifics. Once an ontology is built, it is a simple process to generate the language's metamodel and establish relationships among related concepts. Generating this ontology is the first task in this project.

2. NMSG-154 STUDY

This work uses the NMSG-154 study as a basis for categorization of important terms and parameters related to LSS threat modeling. The MSG-154 derived its activity from dedicated NATO Industrial Advisory Group (NIAG) Studies to Counter LSS (NATO NIAG Study SG-170 2013; NATO NIAG Study SG-188 2015; NATO NIAG Study SG-200 2017), where specific technologies for detection and neutralization were identified. The NMSG-154 study performed a categorization of UAVs based on the physical characteristics and other capabilities of individual drones (Proietti, Goldiez, Farlik, and Di Marco 2017), which is essential to developing measures to counter threats from the specific UAVs. The aim of the study was to take into account the variety of the commercially available LSS aerial platforms in order to define LSS models from different points of view (Proietti, Goldiez, Farlik, and Di Marco 2017).

2.1. NSMG-154 Tasks

The study identified several parameters that can be used to model LSS UAVs. The work was broken down into several work packages. The first task was the categorization of LSS to summarize the different characteristics and parameters that build upon existing classification systems.

The next task was the physical modeling to model behavior during flight, including the flight profile, navigation algorithms, flight duration and impact physics among other flight characteristics. Detectability, intelligence and tactics modeling were included to create a full picture of an LSS flight, the threats posed by it and to determine the best response to counter any such threat. The first task of categorization was completed and summarized by Proietti et al. (2017) and their summary has been used as the basis for this work.

2.2. Model Definition Categories

The main categories identified for model definition were (Proietti, Goldiez, Farlik, and Di Marco 2017):

- typology, which defined certain model parameters such as the modes in which the drone can operate;
- the material used to manufacture the drone;
- flight parameters and performances;
- the kind of propeller used;
- reference to NATO Classification;
- the type of navigation system used;
- the remote controller characteristics (if any/available);
- the payload, considering both own sensors and possible hazards.

These model categories each have several parameters identified within the study. These parameters form the starting point of the ontology for small UAV threat modeling. A sample of parameters has been shown in Table 1. It is important to note that this study provided a non-exhaustive list of parameters that can be used to model LSS threats. The parameter list can be expanded in accordance with the technical development of drones as well as with the level of fidelity required in modeling.

Table 1: Selected Parameters for LSS Categorization (Proietti, Goldiez, Farlik, and Di Marco 2017)

Category	**Parameter**
Typology	Fix Wing
	Rotary Wing
	Flapping Wing
Dimension	Length
	Wingspan (fix wing)
	Height
	Weight

3. ONTOLOGY DEVELOPMENT

The ontology was developed by first categorizing the parameters and separating them into a hierarchical collection of terms with definitions. The relationships between these terms was then determined in order to obtain a collection of related terms for LSS UAV modeling. These parameters have originally been described by the NSMG study (NATO MSG-154 2018) but have been formalized for use in simulation and as part of a UAV body of knowledge in this work. This ontology was published in the OWL format for direct conversion into a metamodel for a DSL.

The important terms in the ontology are discussed here.

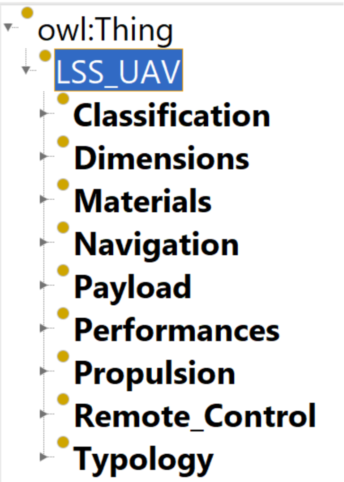


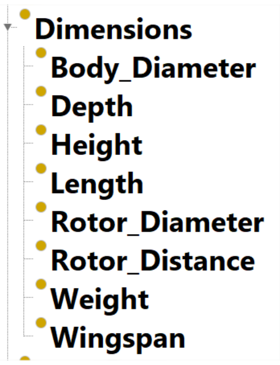
Figure 1: High-Level View of LSS UAV Ontology

The primary categorization yields the classes shown in Figure 1. Each category has multiple subcategories which have a definition for the metamodel. The subcategories are shown in this section.
Classification refers to NATO classes for UAVs and can be seen in Figure 2. This classification occurs on the basis of the weight of the UAV as well as its purpose (Fahlstrom & Gleason 2012).

- Classification
  - HALE
  - MALE
  - Micro
  - Mini
  - Small
  - Tactical
  - UCAV

Figure 2: Terms in Classification Category

All dimensions needed to accurately model the shape, size and aerodynamics of the UAV are recorded in the Dimensions category as shown in Figure 3.



- Dimensions
  - Body_Diameter
  - Depth
  - Height
  - Length
  - Rotor_Diameter
  - Rotor_Distance
  - Weight
  - Wingspan

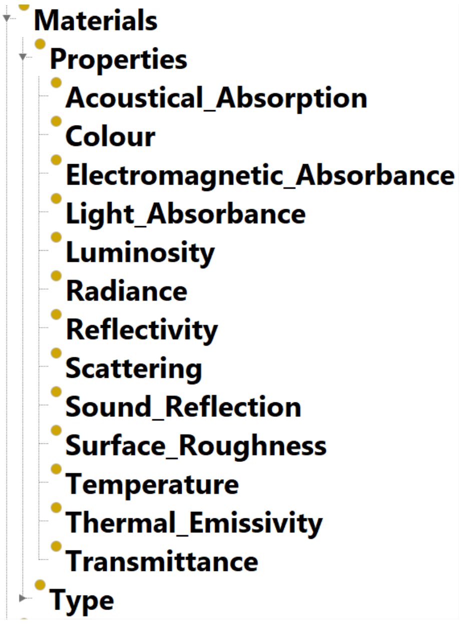
Figure 3: Terms in Dimensions Category

The material the UAV is made out of defines the characteristics of the UAV and imposes limits on its performance. Thus, it is an important parameter in the modeling of the vehicle. The category consists of the type of material being used and the properties of the material, as can be seen in Figure 4.

- Materials
  - Properties
  - Type

Figure 4: Terms in Materials Category

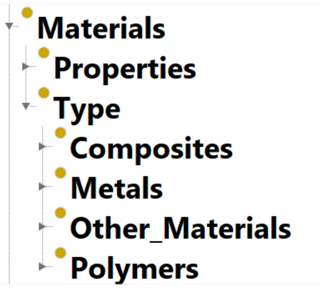
The material properties are off several types such as its color, temperature, luminosity and thermal emissivity, to name a few. A full list of the parameters considered for modeling is shown in Figure 5.



- Materials
  - Properties
    - Acoustical_Absorption
    - Colour
    - Electromagnetic_Absorbance
    - Light_Absorbance
    - Luminosity
    - Radiance
    - Reflectivity
    - Scattering
    - Sound_Reflection
    - Surface_Roughness
    - Temperature
    - Thermal_Emissivity
    - Transmittance
  - Type

Figure 5: Properties included in Subcategory of Materials

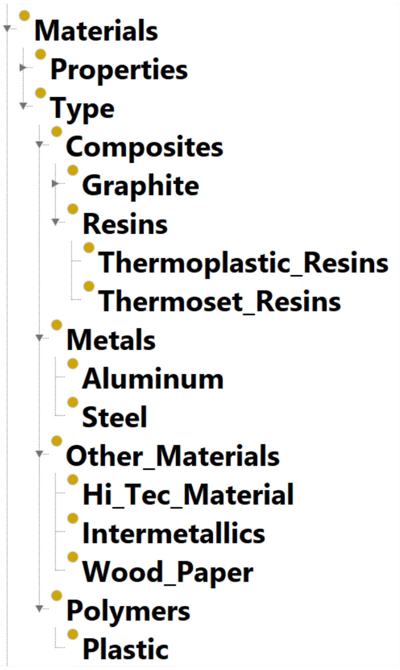
In addition to the properties, the type of material is recorded too, so the properties can be automatically populated. The types are first subdivided into the following categories: composites, metals, polymers and other materials. This subcategory listing is shown in Figure 6.



- Materials
  - Properties
  - Type
    - Composites
    - Metals
    - Other_Materials
    - Polymers

Figure 6: High-Level Types of Materials

The specific type of materials the UAV is made out of are covered under the subcategories. This includes the materials that UAVs are currently made from, and also lists other materials they could be made out of in the future to allow for accurate modeling. These types of materials can be seen in Figure 7.



- Materials
  - Properties
  - Type
    - Composites
      - Graphite
      - Resins
        - Thermoplastic_Resins
        - Thermoset_Resins
    - Metals
      - Aluminum
      - Steel
    - Other_Materials
      - Hi_Tec_Material
      - Intermetallics
      - Wood_Paper
    - Polymers
      - Plastic

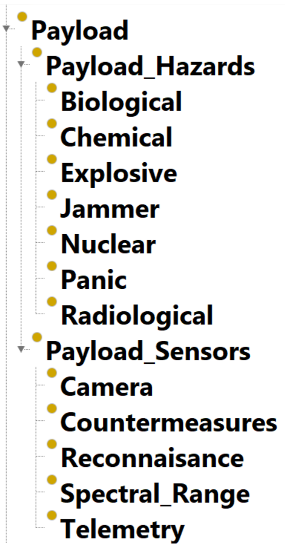
Figure 7: All Possible Types of Materials

The type of navigation capabilities of the UAV dictates the maneuvering and performance, and needs to be accounted for in the modeling of the systems. The more redundancy in the systems, the more accurate it usually is (NATO MSG-154 2018). The type of systems present in the UAV can be seen in Figure 8.

- Navigation
  - Artificial_Intelligence
  - GPS
  - GSM
  - INS
  - Navigational_Support_System
    - Collision_Avoidance
  - Remotely_Piloted
    - RF
    - Tethered
  - Visual

Figure 8: Terms in Navigation Systems Category

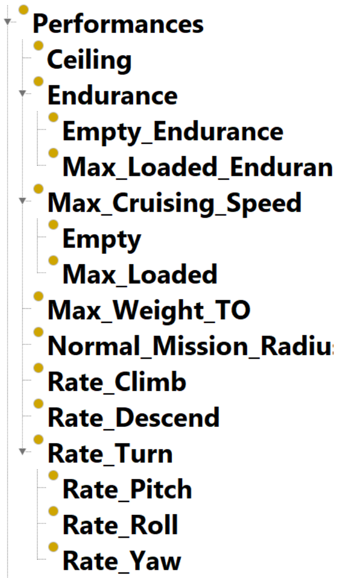
Each UAV carries some equipment and sensors onboard. This is categorized as the payload and is considered to be of two types in the modeling process. One is the set of sensors that convey flight data and could possibly be jammed or manipulated. The other type is some sort of offensive mechanism to engage any forces. The hazardous material could be of various types and the danger posed by each type can be simulated based on the type of hazard load. Those types being considered during modeling have been shown in Figure 9.



- Payload
  - Payload_Hazards
    - Biological
    - Chemical
    - Explosive
    - Jammer
    - Nuclear
    - Panic
    - Radiological
  - Payload_Sensors
    - Camera
    - Countermeasures
    - Reconnaisance
    - Spectral_Range
    - Telemetry

Figure 9: Terms related to Payload

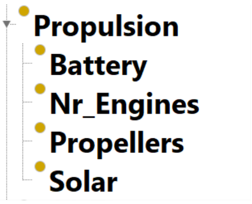
The performance parameters of the LSS are used to model its flight characteristics and behavior. The keywords for this category can be seen in Figure 10.



- Performances
  - Ceiling
  - Endurance
    - Empty_Endurance
    - Max_Loaded_Enduran
  - Max_Cruising_Speed
    - Empty
    - Max_Loaded
  - Max_Weight_TO
  - Normal_Mission_Radiu
  - Rate_Climb
  - Rate_Descend
  - Rate_Turn
    - Rate_Pitch
    - Rate_Roll
    - Rate_Yaw

Figure 10: Performance Parameters of LSS

The propulsion characteristics are discussed in the form of engines, propellers, battery and solar capabilities of the vehicle. These terms can be seen in Figure 11.



- Propulsion
  - Battery
  - Nr_Engines
  - Propellers
  - Solar

Figure 11: Propulsion Parameters of LSS

Since the vehicle is unmanned, a thorough simulation requires the modeling of the remote-control parameters. These can be seen in Figure 12.


Remote_Control
Frequency
Max_Distance
Max_Power
Method
Route_Planning

Figure 12: Remote Control Properties

The UAV type can be defined simply by a few type names. These are shown in Figure 13. Several physical properties and shapes of the UAV are determined by the type name listed.

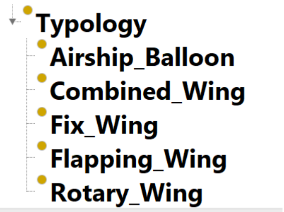

Typology
Airship_Balloon
Combined_Wing
Fix_Wing
Flapping_Wing
Rotary_Wing

Figure 13: Terms in Typology Category

4. METAMODEL DEVELOPMENT

The metamodel was developed using Ecore in Eclipse Modeling Framework (EMF). The Ecore format is basically a subset of UML Class diagrams. This Ecore model of the class definition is the metamodel, which describes the structure of the model and provides a template for the generation of individual models (Jafer, Chhaya, Durak, and Gerlach 2018). The metamodel includes all data items and the relationships between them. A metamodel is then further utilized to construct a model, which is a concrete instance of this structured data.

The metamodel generated based on the ontology has been broken up into two halves so that the text can be read. It has not been expanded fully as it consists of the same elements as present in the ontology. This metamodel is shown in Figure 14 and Figure 15.

The first half of the metamodel can be seen in Figure 14. The LSS UAV is the parent entity and has all the properties described in the rest of the metamodel. As per the ontology, it has a *Typology* class which is a category type, enumerated by the elements in the ontology under that category. The dimensions of the UAV are described in the *Dimensions* class. The *Materials* class has a materials type enumeration, which contains the names of the materials shown in Figure 7 and also a class of material *Properties*. The *Performance* data of the UAV is recorded in a separate class.

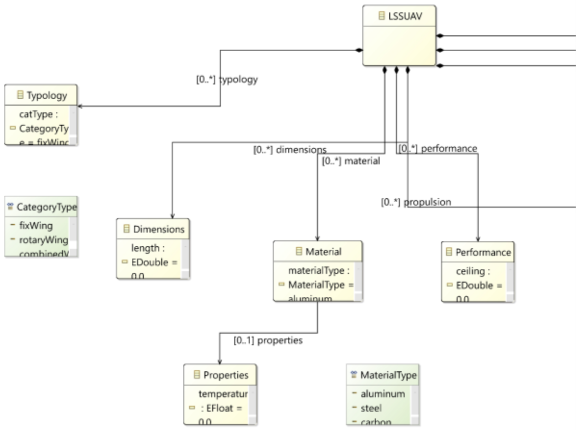


Figure 14: Metamodel Details, part (a)

The second half of the metamodel can be seen in Figure 15. This includes the *Navigation* properties of the UAV as well as the *RemoteControl* capabilities. The payload is also described in this section as per the parameters identified in the ontology. The NATO *Classification* is also covered in the form of an enumeration.

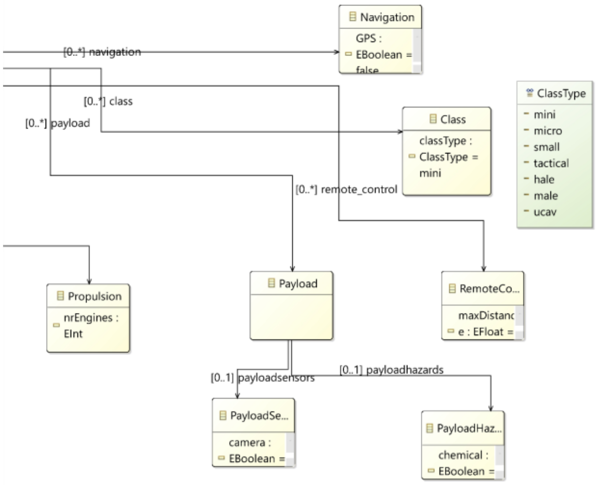


Figure 15: Metamodel Details, part (b)

This metamodel uses the parameters identified by the MSG-154 (NATO MSG-154 2018) to describe the properties of a UAV. Once the LSS vehicle can be modeled, it can be used in a simulation to assess the threat posed by it on any type of environment.

5. CONCLUSION AND FUTURE WORK

This paper discusses the results of the categorization task of the NMSG-154 task group. The work here expands upon the data found during the task and used the results to develop an ontology for modeling LSS threats which affect safety and security. The ontology developed was used to generate a metamodel for a DSL.

The DSL can describe a UAV and its properties and parameters. A specific model of a UAV generated using this metamodel can then be used in a simulation to understand its behavior in various situations. Being able to model the physical properties of a UAV is the first step towards simulating its behavior. Using the data presented in by the NMSG-14 task group, a more formalized metamodel was generated, which can actually be used for such modeling and scenario generation, and ultimately for simulation of the threats posed by these vehicles.

The next task is to use the DSL for scenario generation of LSS threats. Executing specific scenarios in a simulation can enable us to understand the risks posed by the UAV and to prepare a plan to counter the threat appropriately.

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