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Structural-Parametric Synthesis of Multi-Agent UAV-based SMR Monitoring system: an Ontology Approach

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***Abstract* — The article is devoted to the synthesis of multi-agent unmanned aerial vehicle (UAV) -based small modular reactor (SMR) monitoring system (MAUAV-SMRMS) as part of overall monitoring system of SMR. The features of SMR operation are analysed and the main monitoring tasks that can be performed by UAVs are highlighted. An ontological model of the domain area of SMR UAV-based monitoring has been developed and researched. The ontology classes and properties are described. The place of ontology in the problems of systems synthesis is shown. The main features of the utilization of the ontology for the MAUAV-SMRMS structural-parametric synthesis for inspection and monitoring components of SMR are presented and discussed. The possibility of automated knowledge growth in ontologies is discussed.**

Keywords* — *unmanned aerial vehicle, small modular reactor, monitoring system, multi-agent system, ontology

I. INTRODUCTION

Nowadays, the use of SMR is considered as the main direction for increasing power generation capacities, replacing outdated capacities, and generating electricity in hard-to-reach regions. SMRs are recognized as objects of increased danger, and high safety and security requirements are imposed on them [1]. Unmanned aerial vehicles are recognized as a flexible tool, the use of which provides to improve the safety and security of the SMR. There are general approaches of UAV use, that target this aim:

- Inspection and Monitoring components of SMR [2].
- Deploying Ad Hoc networks in case of damaging wired communications [3].
- Utilizing UAVs as part of physical protection system [4].
- Deploying UAVs to quickly assess the area involved in the emergency. and provide situational awareness. For instance, UAVs can be used for surveying and mapping the terrain of SMR's site area and around this area to evaluate accident consequences [5,6].

There are two modes to define ways for utilizing MAUAV-SMRMS: normal and post-accident. The main specialty of utilizing MAUAV-SMRMS in post-accident mode is performing tasks as a reserve system in cases of damaged main systems, for instance, deploying wireless connections in case of damaged wired ones. Also, for this mode, it is necessary to take into account the negative impact of the radiation on the UAV equipment and the possibility of performance degradation as a result of such impact.

The tasks of monitoring, inspecting, security and Emergency Response for SMR belong to the tasks of covering areas. UAVs equipped with cameras, sensors, and other instruments can be used to perform routine inspections and monitoring of SMR's components and SMR's site areas. They can provide a detailed observation of the components and systems of the SMRs and SMRs' site, which can be deployed on wide areas, detect any anomalies or malfunctions, and help identify potential problems before they escalate. In addition, UAVs can be used for perimeter security and surveillance of SMRs as part of a physical protection system. They can observe the area over and around the reactors' site area, and detect any suspicious activity, intruders, or potential threats.

The tasks of deploying flying wireless networks are related to the tasks of point coverage. UAVs can carry equipment to perform collecting/transmitting data from SMRs and monitoring stations to the SMR control room/center.

When performing these tasks, it is necessary to take into account the sizes of the SMRs' site, specification of the UAVs and their payload, requirements for the format of representation of data on the results, frequency of information update, duration and dependability of mission; and conditions: day/night, simple/complex weather conditions.

The variety of tasks, the uncertainty and variability of the conditions for their implementation determine the use of a multi-agent approach when creating monitoring systems. The information model of multi-agent systems uses ontologies that allow describing the composition, state, and interaction between the components of a multi-agent system.

The paper considers the use of ontology as the basis for the structural-parametric synthesis of the MAUAV-SMRMS, which allows performing various missions, taking into account the real situation and requirements. The results of the use of ontology in this case are:

- Type of UAVs and their payload.
- The necessary composition of the UAV support subsystem.

The rest of the paper is structured as follows.

The next section considers the existing studies concerning tasks of structural synthesis and utilization of ontologies for these goals.

In section III low-level ontology of MAUAV-SMRMS is developed.

Section IV provides an example of utilizing the ontology for the MAUAV-SMRMS structural-parametrical synthesis for Inspection and Monitoring components of SMR.

Section V presents the main results of the work and highlights the next steps of research.

II. State-of-the-Art

Approaches to the synthesis of complex systems, including the use of ontologies, are considered in many works.

Jumaah et al. [7] propose an approach to developing a UAV-based PM2.5 monitoring system with a detector comprising four Arduino sensor modules.

In work [8] general algorithms to justify the structure and composition of UAV-based monitoring systems considering the requirements and limitations of missions are described.

The paper [9] presents a comprehensive summary of the state of the art of ontology-based systems engineering, as well as illuminating a roadmap for future directions.

In [10] multi-source observed data are generally characterized by their syntactic, structural, and semantic heterogeneities. A key challenge is the semantic interoperability of these data. In this context, an ontology-based system that supports environmental monitoring, which implemented and evaluated using quality metrics, was proposed.

Also, supply chain ontology as an important medium for solving information system interoperability problems. To inform future supply chain ontology research, the paper [11] sets out to review and analyse existing supply chain ontology models.

In paper [12], nine basic interaction patterns among decisions were identified and an ontology to define the knowledge associated with these interaction patterns was proposed and discussed. Key advantages of the ontology include that we can capture both the vertical and horizontal interactions between decisions in a decision-based design process, and we can design flexible, reusable, and executable decision workflows for designing complex systems using the ontology.

The paper [13] considers the complexity of the decision-making process for experts in various topics in the problem of initial processing of unstructured information. This problem of Big data requires the latest solutions that provide a structural reflection and integrative use of information descriptions under consideration by experts. It takes the process of information and analytical evaluation and decision-making beyond one subject area and raises questions about the ontological consideration of the problem itself. The ontological principles of such consideration are based on multiple hyperproperties of information for the realization of the categories of integration, systematicity and continuity, as well as the implementation of structures and their functionality reflection and transformation. For this, there is the ontology of the problem of rational choice based on means of a ranking of alternatives on a set of indicators. It provides the creation of a system designed to solve the ranking problem based on the ontological model of the subject area.

The paper [14] proposes an ontology for interoperability assessment. The main objective of such an ontology is to provide a sound description of all relevant concepts and relationships regarding an interoperability assessment. Inference rules are also provided for reasoning on interoperability problems. To evaluate the proposed ontology, a case study based on a real enterprise is presented.

The approach to the development of a computer system for automated construction of the basic ontology is presented in [15]. The mathematical support of the functioning of intellectual agents of activity planning on the basis of ontologies was developed, which allowed for the formalization of their behaviour in the space of states. Using ontologies allows us to narrow the search way from the initial state to the state of the goal, rejecting irrelevant alternatives.

Work [16] presents a definition of the form of correspondence of factors modelling technological activity: “process” and “resource” factual frames that can be processed by artificial intelligence methods, and possible forms of of relationships for factors of technological activity: “process” and “resource” concepts with concepts characterizing processes, namely: “representation”, “data”, “information”, “knowledge”, necessary for the formation of an ontology.

In [17] ontologies have been advocated as a mechanism to address these problems, as they can support the model-based transition and formalize the domain knowledge. However, manually creating ontologies is a time-consuming, error-prone, and tedious process. Little has been known about how to automate the development and little work has been conducted for building systems engineering ontologies.

In [18] attention has been paid to the development of ontology-based solutions, which are meant to tackle issues from inconsistency to semantic interoperability and knowledge reusability. This paper looks into how the available technology, models, and ontology-based solutions might interact within the manufacturing industry environment to achieve semantic interoperability among industrial information systems. Through a systematic literature review, this paper has aimed to identify the most relevant elements to consider in the development of an ontology-based solution and how these solutions are being deployed in the industry.

Thus, most of the considered studies suggest approaches of ontology utilization for only the back-bones of complex systems, but do not consider how to use this ontology for synthesis systems to perform specific tasks in real conditions.

III. Ontology model of MAUAV-SMRMS

Situational creation of the structure of complex systems for specific tasks can be taken care of for a large number of different solutions in a specific object area. A promising direct formalization of such knowledge is the development of ontologies.

Ontology is a formalized representation of knowledge about a single subject area (environment, world), an appendage for automated processing. It chooses a language for describing the subject matter of the problem of synthesis and includes machine-interpretation of the main formula to understand and understand between them.

The Resource Description Framework (RDF) allows writing machine-interpreted statements in the form of subject-predicate-object triples, called RDF triples. The stinks can be varied with different syntaxes, among them - RDF/XML, Turtle, N-Triples, JSON-LD, RDFa, and HTML5 Microdata.

Such RDF triples are machine-interpretable and, with strict rules, can be used to derive new statements based on those formulated by automated reasoning. But complex domains require even more representational capabilities, such as property cardinality restrictions, domain and range restrictions, and enumerable classes, which led to the Web Ontology Language (OWL), which is specifically designed to create web -ontologies with a rich set of modelling constructors and eliminates the limitations of developing RDF ontologies.

Each OWL ontology consists of RDF triples that define concepts (classes), roles (properties and relationships), and individuals [https://www.w3.org/OWL/].

There are top-level ontologies, which define a general fundamental description of the field of application, subject field ontologies, and application-level ontologies. The lower the level, the more complete the description the ontology contains.

The MAUAV-SMRMS ontological model should describe the structure and interaction of the constituent elements of the system when performing various tasks in various conditions.

The following hierarchy of classes is used in the ontology:

- Mission type:
  - Inspection and Monitoring of SMR;
  - Deploying Ad Hoc networks;
  - Security;
  - Emergency Response:
    - Dose rate measurement;
    - Radiation sources location;
- Mode:
  - Normal;
  - Post-accident;
- Performing unit:
  - Simple UAV;
  - Custom UAV;
- Support unit:
  - Automatic battery maintenance station (ABMS);
- Payload:
  - Camera;
  - FLIR;
  - Radiation dosimeter;
  - Network equipment.
- Environment conditions:
  - Day;
  - Night.

This list of classes and subclasses can be expanded depending on the features of the monitoring system.

A description of the object properties defined in the ontology is presented in Table 1.

TABLE I. DESCRIPTION OF THE OBJECT PROPERTIES DEFINED AT THE ONTOLOGY

Domain	Properties	Range
UAV	perform	Mission type
ABMS	maintenance	Simple UAV; Custom UAV
Simple UAV	has	Camera; FLIR; Network equipment; Radiation dosimeter
Camera; FLIR; Network equipment; Radiation dosimeter	deployed	Custom UAV
Inspection and Monitoring	use	Camera; FLIR
Deploying Ad Hoc networks	use	Network equipment
Security	use	Camera; FLIR
Emergency Response	use	Radiation dosimeter
Camera	used	Day
FLIR	used	Night
Inspection and Monitoring; Deploying Ad Hoc networks; Security	performed	Normal
Radiation sources location	performed	Post-accident
Dose rate measurement	performed	Normal; Post-accident

The table contains descriptions of only object properties that are used in the ontology. If individuals are added to the ontology, then the Data Type properties that describe them will be used to describe them. For example, a UAV is described by such Data Type properties as:

- flight endurance;
- •maximum permissible wind speed;
- payload;
- Data Transmission Protocol.

Protégé software was used to create ontologies.

The ontograph of the developed domain ontology for MAUAV-SMRMS shown in Fig. 1.

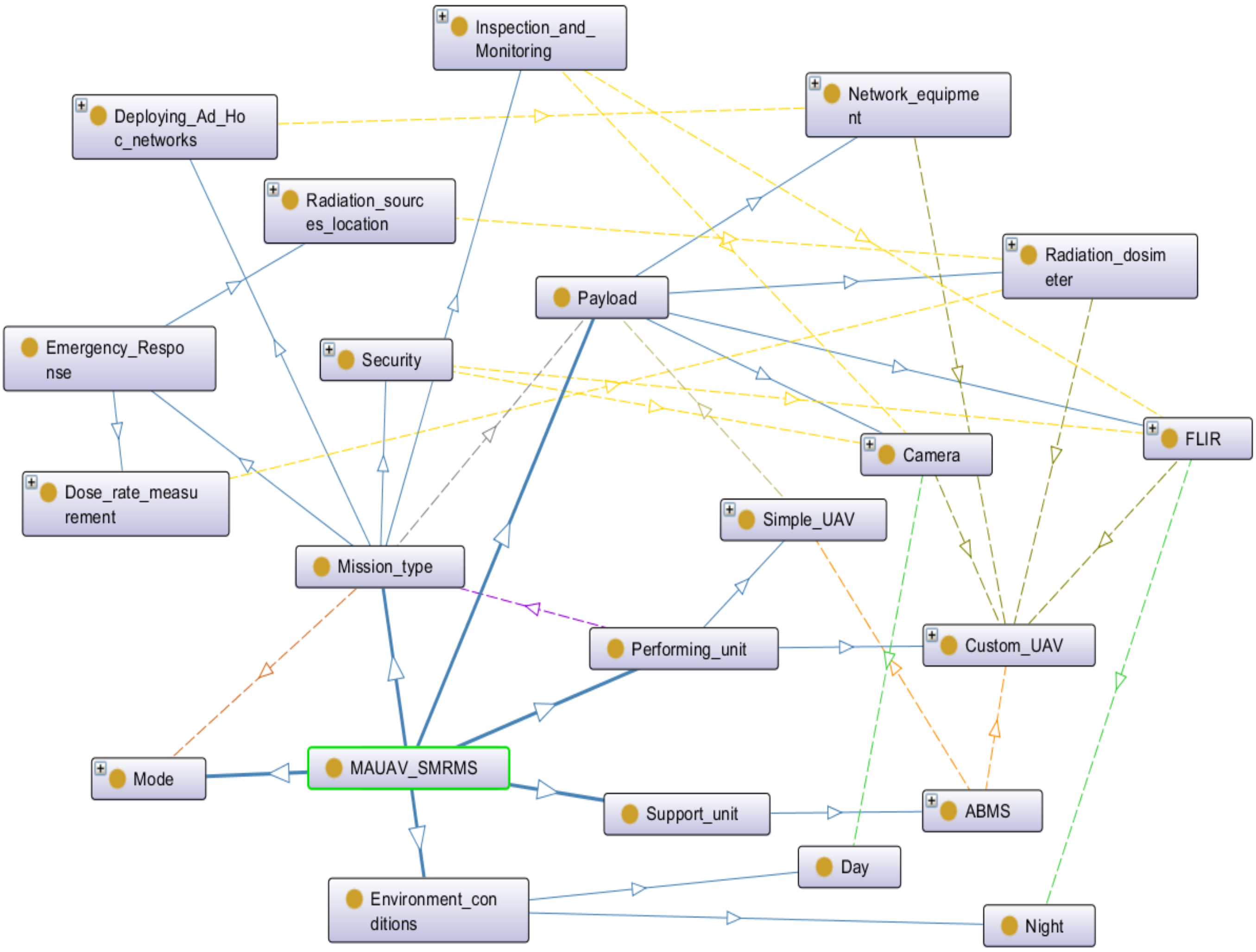

Fig. 1. The ontograph of the developed domain ontology for the MAUAV-SMRMS.

The use of the ontology to form the composition of UAV groups is carried out by transforming the mission task into a SPARQL query. The result of the request is a list of UAVs with a payload and ABMS for the specified UAVs, if necessary. If it is necessary to add data and knowledge to the ontology, SWRL rules can be used.

The place of ontology in the process of structural-parametric synthesis of MAUAV-SMRMS shown in Fig. 2.

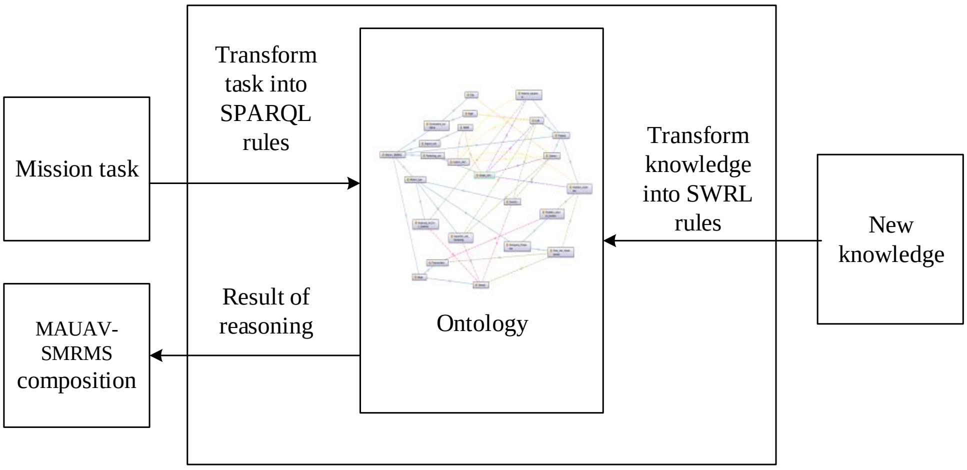

Fig. 2. The use ontology for structural-parametrical synthesis of MAUAV-SMRMS

IV. Example of the use onthology for structural-parametric syntesis of MAUAV-SMRMS

Let's consider the use of ontology for the selection of UAVs and the equipment necessary to perform a task at least 0.8 hours, at night in wind conditions of more than 10 m/h.

To clarify the ontology (Fig. 1), let's add individuals to following classes:

- Simple UAV;
- ABMS;
- Payload.

The OWL codes of the added individuals for Simple UAV, Payload and ABMS classes are shown in Fig. 3, Fig. 4, and Fig. 5 respectively.

```
<!-- http://www.semanticweb.org/user/ontologies/2023/7/ims#Simple_UAV_1 -->
  <owl:NamedIndividual rdf:about="http://www.semanticweb.org/user/ontologies/2023/7/ims#Simple_UAV_1">
    <rdf:type rdf:resource="http://www.semanticweb.org/user/ontologies/2023/7/ims#Simple_UAV"/>
    <ims:dataTransmissionProtocol
      rdf:datatype="http://www.w3.org/2001/XMLSchema#string">Mavlink</ims:dataTransmissionProtocol>
    <ims:flightEndurance rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.5</ims:flightEndurance>
    <ims:maxWind rdf:datatype="http://www.w3.org/2001/XMLSchema#int">10</ims:maxWind>
    <ims:payload1 rdf:datatype="http://www.w3.org/2001/XMLSchema#string">Camera1</ims:payload1>
  </owl:NamedIndividual>
    <!-- http://www.semanticweb.org/user/ontologies/2023/7/ims#Simple_UAV_2 -->
  <owl:NamedIndividual rdf:about="http://www.semanticweb.org/user/ontologies/2023/7/ims#Simple_UAV_2">
    <rdf:type rdf:resource="http://www.semanticweb.org/user/ontologies/2023/7/ims#Simple_UAV"/>
    <ims:dataTransmissionProtocol
      rdf:datatype="http://www.w3.org/2001/XMLSchema#string">DSM</ims:dataTransmissionProtocol>
    <ims:flightEndurance rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.75</ims:flightEndurance>
    <ims:maxWind rdf:datatype="http://www.w3.org/2001/XMLSchema#int">12</ims:maxWind>
    <ims:payload1 rdf:datatype="http://www.w3.org/2001/XMLSchema#string">FLIR1</ims:payload1>
  </owl:NamedIndividual>
    <!-- http://www.semanticweb.org/user/ontologies/2023/7/ims#Simple_UAV_3 -->
  <owl:NamedIndividual rdf:about="http://www.semanticweb.org/user/ontologies/2023/7/ims#Simple_UAV_3">
    <rdf:type rdf:resource="http://www.semanticweb.org/user/ontologies/2023/7/ims#Simple_UAV"/>
    <ims:dataTransmissionProtocol
      rdf:datatype="http://www.w3.org/2001/XMLSchema#string">MavLink</ims:dataTransmissionProtocol>
    <ims:flightEndurance rdf:datatype="http://www.w3.org/2001/XMLSchema#float">1.0</ims:flightEndurance>
    <ims:maxWind rdf:datatype="http://www.w3.org/2001/XMLSchema#int">15</ims:maxWind>
    <ims:payload2 rdf:datatype="http://www.w3.org/2001/XMLSchema#string">Camera2</ims:payload2>
   </owl:NamedIndividual>
```

Fig. 3. Individuals of “Simple_UAV” class.

```
<!-- http://www.semanticweb.org/user/ontologies/2023/7/ims#ABMS_1 -->
  <owl:NamedIndividual rdf:about="http://www.semanticweb.org/user/ontologies/2023/7/ims#ABMS_1">
    <rdf:type rdf:resource="http://www.semanticweb.org/user/ontologies/2023/7/ims#ABMS"/>
  </owl:NamedIndividual>
  <!-- http://www.semanticweb.org/user/ontologies/2023/7/ims#ABMS_2 -->
  <owl:NamedIndividual rdf:about="http://www.semanticweb.org/user/ontologies/2023/7/ims#ABMS_2">
    <rdf:type rdf:resource="http://www.semanticweb.org/user/ontologies/2023/7/ims#ABMS"/>
  </owl:NamedIndividual>
  <!-- http://www.semanticweb.org/user/ontologies/2023/7/ims#ABMS_3 -->
  <owl:NamedIndividual rdf:about="http://www.semanticweb.org/user/ontologies/2023/7/ims#ABMS_3">
    <rdf:type rdf:resource="http://www.semanticweb.org/user/ontologies/2023/7/ims#ABMS"/>
  </owl:NamedIndividual>
```

Fig. 4. Individuals of “ABMS” class.

```
<!-- http://www.semanticweb.org/user/ontologies/2023/7/ims#Camera_1 -->
  <owl:NamedIndividual rdf:about="http://www.semanticweb.org/user/ontologies/2023/7/ims#Camera_1">
    <rdf:type rdf:resource="http://www.semanticweb.org/user/ontologies/2023/7/ims#Camera"/>
  </owl:NamedIndividual>
   !-- http://www.semanticweb.org/user/ontologies/2023/7/ims#Camera_2 -->
  <owl:NamedIndividual rdf:about="http://www.semanticweb.org/user/ontologies/2023/7/ims#Camera_2">
    <rdf:type rdf:resource="http://www.semanticweb.org/user/ontologies/2023/7/ims#Camera"/>
  </owl:NamedIndividual> <!-- http://www.semanticweb.org/user/ontologies/2023/7/ims#Dosimeter_1 -->
  <owl:NamedIndividual rdf:about="http://www.semanticweb.org/user/ontologies/2023/7/ims#Dosimeter_1">
    <rdf:type rdf:resource="http://www.semanticweb.org/user/ontologies/2023/7/ims#Radiation_dosimeter"/>
  </owl:NamedIndividual>
  <!-- http://www.semanticweb.org/user/ontologies/2023/7/ims#FLIR_1 -->
  <owl:NamedIndividual rdf:about="http://www.semanticweb.org/user/ontologies/2023/7/ims#FLIR_1">
    <rdf:type rdf:resource="http://www.semanticweb.org/user/ontologies/2023/7/ims#FLIR"/>
  </owl:NamedIndividual>
  <!-- http://www.semanticweb.org/user/ontologies/2023/7/ims#FLIR_2 -->
  <owl:NamedIndividual rdf:about="http://www.semanticweb.org/user/ontologies/2023/7/ims#FLIR_2">
    <rdf:type rdf:resource="http://www.semanticweb.org/user/ontologies/2023/7/ims#FLIR"/>
  </owl:NamedIndividual>
  <!-- http://www.semanticweb.org/user/ontologies/2023/7/ims#LiFi_1 -->
  <owl:NamedIndividual rdf:about="http://www.semanticweb.org/user/ontologies/2023/7/ims#LiFi_1">
    <rdf:type rdf:resource="http://www.semanticweb.org/user/ontologies/2023/7/ims#Network_equipment"/>
  </owl:NamedIndividual>
```

Fig. 5. Individuals of "Payload" class.

To determine the components of the monitoring system to the ontology, a SPARLQL query is used, the view of which is shown in Fig. 6.

As a result of the request, a list of payloads, which are used when performing a mission in night conditions, UAVs that have this payload and can fly at a wind speed of more than 10 m/s, and ABMS to service UAVs with flight duration shorter than 0.8 hours, is formed.

The results of the SPARLQL query are presented in Table. II.

```
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 ims: <http://www.semanticweb.org/user/ontologies/2023/7/ims#>
SELECT ?payload ?UAV ?ABMS
WHERE {
?payload rdf:type :Payload.
?UAV :has ?payload
FILTER EXISTS {?payload :used ?Night}
FILTER EXISTS ((?UAV :maxWind > 10))
?ABMS :maintenance ?UAV
FILTER EXISTS ((?UAV :flightEndurance < 0.8))
OPTIONAL {?UAV :dataTransmissionProtocol ?protocol}
```

Fig. 6. SPARLQL query.

TABLE II. COMPOSITION OF MAUAV-SMRMS AS THE RESULT OF SPARLQL QUERY

Payload	UAV	ABMS	Protocol
FLIR_1	Simple_UAV_2	ABMS_1	DSM
FLIR_1	Simple_UAV_2	ABMS_2	DSM
FLIR_1	Simple_UAV_2	ABMS_3	DSM

Considering the specifics of the task, it requires the use of FLIR, which is used at night. In the ontology, there is only one individual of the Simple_UAV class – "Simple_UAV_2", which has FLIR_1 and can fly at a condition with wind speed of more than 10 m/s. Individual "Simple_UAV_2" has a flight time of 0.75 hours, which is less than the time specified for completing the task - 0.8 hours, therefore the involvement of ABMS is necessary. Due to the uncertainty of which ABMS can maintain this UAV, three results are returned with a combination of all ABMS class individuals: "ABMS_1", "ABMS_2", "ABMS_3".

V. CONCLUSION AND FUTURE WORK

The main monitoring tasks of SMR that UAVs can perform are as follows: Inspection and Monitoring components, Deploying Ad Hoc networks, Security, and Emergency Response.

The main features of the utilization of the ontology for the MAUAV-SMRMS structural-parametric synthesis for inspection and monitoring components of SMR are presented and discussed. The possibility of automated knowledge growth in ontologies is discussed.

The ontology model of the MAUAV-SMRMS with classes and properties is developed and explored. The utilization of the ontology makes it possible to provide the structural-parametric synthesis of the MAUAV-SMRMS

An example of using the ontology for the MAUAV-SMRMS structural-parametrical synthesis for inspection and Monitoring components of SMR is given and analyzed.

This is demonstrated that ontology allows providing a synthesis of a multi-agent system for specific mission requirements and limitations by SPARLQL query. But the most exact result requires the more fuller ontology description.

The next research steps can cover the development of SWRL rules for the automation implementation of new knowledge into ontology.

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