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Concept of Operations as a Boundary Object for Knowledge Sharing in the Design of Robotic Swarms

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ABSTRACT

Designing a swarm of autonomous robots for commercial, military, or other purposes is a challenging engineering and human factors design effort. The challenges argue in favor of practices and tools for better integration of different engineering disciplines and for the advancement of communication between stakeholders with different interests. The Concept of Operations (ConOps) approach is widely used in Systems Engineering for this purpose. A ConOps is a high-level description of how the elements of a system and entities in its environment interact in order to achieve their stated goals. This paper will present the development of a ConOps for a swarm of autonomous robotic vehicles in the military domain to demonstrate how autonomic robotic swarms can be deployed in different military branches in the future. The proposed ConOps can be considered as a boundary object in the design, validation, or procurement of an autonomous robotic swarm system. We also propose that the ConOps should be maintained throughout the system life-cycle as an overview description and definition of overall goals and policies.

1. Introduction

In this paper, we will focus on boundaries and barriers within and between key parties in the military and other safety-critical domains that hinder collaboration and communication in engineering projects. We propose that a specific set of knowledge objects is needed that help stakeholders cross these boundaries and create a common understanding. A term that has been coined to describe the barriers that hamper knowledge sharing and collaboration is the ‘knowledge boundary’ [7]. As the term suggests, it prevents the exchange of information between groups of experts coming from different domains or whose interests diverge. Knowledge boundaries may lie, for example, between buyers and vendors [16] and different personnel groups in an organization (e.g., [4], [6], [27]). Knowledge boundaries expose potential difficulties in communication, but at the same time, they provide the potential for interaction and continuous boundary crossing and joint efforts at the boundary [8]. Knowledge boundaries do not necessarily match with organizational boundaries, and knowledge boundaries also exist within an organization and between engineering domains. Boundaries may also change during a long project: some boundaries may disappear while others appear. For example, in military engineering projects, a complex and dynamic set of knowledge boundaries typically emerge between different stakeholders that have to be managed and settled in some way Fig. 1.

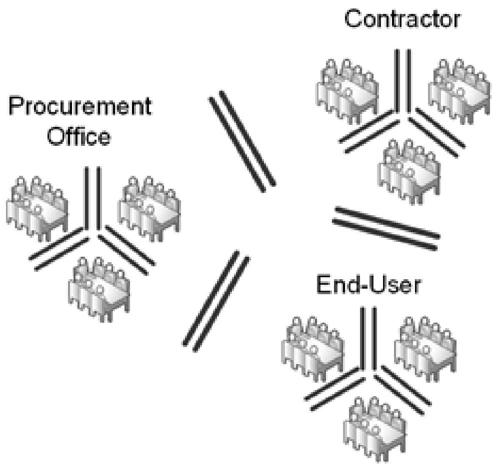

Fig. 1. Double lines illustrate the knowledge boundaries within and across the typical main parties in military engineering projects. “Contractor” refers to a supplier of munitions or service; “Procurement office” to the logistics command of the defense forces; and “End-user” to a regiment of soldiers deploying the final product or service

In order to amend various problems caused by knowledge boundaries, we need shared representations and objects that mediate the interaction between and among stakeholders presenting multiple perspectives and supporting cross-disciplinary communication between experts of different domains in design projects. We propose that these kinds of representations play an important role in interactions among people in many domains.

The objective of the paper is twofold: First, to demonstrate that a special kind of design artifact called a Concept of Operations (ConOps) can be considered as a boundary object that can be used in knowledge exchange between different stakeholders; second, to demonstrate that a specific ConOps developed in our project can be used in boundary crossing purposes in the military domain, and especially it can be used to describe and organize the interaction between human operators and a swarm of autonomous or semi-autonomous robots.

1.1. Knowledge Sharing Objects

Knowledge-sharing objects are collaboratively created, maintained, and used artifacts. Since they support collaborative activities and common knowledge creation and exploitation across communities of practitioners, through them, actors can cross or break down knowledge boundaries. Knowledge-sharing objects are, for example, communication tools and information-sharing platforms that are commonly known and thus can be effectively utilized for purposes of knowledge exchange.

As the term suggests, knowledge-sharing objects are aimed at supporting knowledge exchange between people. The underlying idea behind the term is that specific objects and artifacts are needed in knowledge exchange if there are challenges in communication and cooperation between people. These challenges may emerge if people come from different domains or they have conflicting interests so that they have no common vocabulary and understanding, and/or they have partly differed aims and objectives.

1.2. Boundary Objects

A boundary object is a related term to a knowledge-sharing object. They are abstract or physical artifacts that are positioned in the intersections between organizations and which in some way have the capacity to play a mediating role between organizations and support communication and cooperation, and also fulfill the informational requirements of all parties [24]. According to this view, boundary objects are, thus, mediating artifacts between several systems of activity. Some examples of boundary objects include various kinds of plans, instructions, guidelines, agreements, and contracts between stakeholders. Typically, they are paper-based documents with text and graphical illustrations, but digital technologies enable us to present them in a more dynamic and engaging manner. However, there is also another meaning of boundary object, mainly advocated by the cultural-historical activity theory, according to which it should be viewed as a shared problem space promoting shared activity between stakeholders [1]. We use the term in a general sense, and our view is, thus, in line with both of the above-mentioned interpretations.

For example, while negotiating project contracts, stakeholders have to work with others who have different opinions, perspectives, and backgrounds and who, thus, may have a different vocabulary for describing their views [16]. Therefore, there is a need for the establishment of a common ground and a shared understanding between stakeholders. Without shared understanding, negotiations about project contracts will fail. The negotiators have to understand the nature of existing boundaries and other knowledge-sharing objects in order to be able to solve emerging problems. Koskinen and Mäkinen [16] propose that a bid and tender can be considered as a weakly structured boundary object. During and after tendering and contracting, a series of negotiations are arranged, and after the negotiations, the final project contract is completed. The contract can be considered as a strongly structured boundary object including multiple views and can be considered as a collective reality of all partners. The study by Koskinen and Mäkinen [16] showed that one of the reasons for failures in contracting is the lack of boundary objects during project contract negotiations. As suggested by [5], boundary objects can actually promote the development of a partnering relationship in the contracting phase, that is, commitment to cooperate in order to achieve common business objectives.

Boundary objects help to clarify and smooth the design process, create and deploy new knowledge, and support problem-solving and decision-making. In order to support knowledge exchange and promote knowledge creation, these artifacts have to possess some characteristic features. Boundary objects have to establish a shared language so that their structure and content are easily comprehended by different users. Objects also have to be open for the addition of new features and for the update so that they can represent new aspects of the domain that may have been ignored earlier. On the other hand, the objects have to be underspecified to such a degree that they enable fruitful communication between people that do not have a common professional background and do not have the same level of competence in the target domain. In order to reach these objectives, a special concern must be paid to the correct level of abstraction of the artifact and to the correct level of rigidity [6]. The correct level of abstraction refers to the level of detail that has been represented in the artifact [6]. Rigidity refers to underspecified and redundant features of artifacts that, instead of considering them as serious flaws that prevent understanding and communication, make them more understandable and sharable [6].

1.3. Categorization of Shared Representations

There is a continuum of shared representations and boundary objects from abstract to more tangible. Visual layout diagrams vary from functional layouts to detailed layouts and CAD models [28]. Typical boundary objects are various storyboarding tools and visual analytics environments. Even though most of the knowledge-sharing objects are still paper-based or presented in conventional 2D digital media, there are also available collaborative visualization techniques such as collaborative problem-solving environments, virtual and augmented reality environments, and online games [2] [11]. According to [2], objects enabling visualization may act as effective boundary objects and promote negotiations, provided that they enable participants to make multiple interpretations and promote real-time communication.

2. Concept of Operations as a Knowledge-Sharing Tool Between Domains in Systems Design

2.1. Concept of Operations as a Boundary Object Facilitating Design and Innovation in Different Domains

Fairley and Thayer [9] coined the term ‘ConOps’ in their paper in 1997, and the desired format and contents of a ConOps document have been determined in IEEE standard 1362 [12]. According to one definition, ConOps is a high-level knowledge artifact describing how the elements of a particular system and entities in its environment interact in order to achieve the stated goals of the system [28]. It is also characteristic of ConOps to emphasize the end-user perspective and human-technology interaction aspects. That is, it is described how the end-user will interact with the new system in selected scenarios. ConOps documents are developed for design and innovation in many domains such as military, health care, traffic control, space exploration, financial services, and different industries such as nuclear power, pharmaceutical, and medical [28]. We propose that a Concept of Operations could be used as a boundary object that supports collaboration and promotes integration in the design of complex military systems such as an autonomous robotic swarm system.

Since ConOps is a high-level description, technical details are omitted from it. Or rather, the level of detail should be optimized: on the one hand, the description should be accurate enough to fully explain how the proposed system is planned to operate; on the other hand, it should be general enough to promote discussions across domains and disciplines.

Typically, a ConOps is considered a transitional design artifact is playing a role in the requirements specification activity during the early stages of the design process and which has of no use in the later stages [28]. We, however, propose that the ConOps should be updated and maintained throughout the system life-cycle as an overview description and definition of overall goals and policies [28]. In fact, the ConOps should support communication and collaboration and provide a basis for discussions about the target system at all stages of the development process [14]. The ConOps can also be considered a much-needed tool for better integration of Human Factors Engineering into Systems Engineering. Since, in many cases, design activities aim at the upgrade of the current system with a new one, the ConOps document describes the end-state vision and the path that leads to the end-state. High-level objectives can, thus, be expressed in the form of changes in system capabilities [28].

ConOps documents exist in many forms: They are typically textual descriptions embedded with graphical illustrations trying to describe the essential features of the proposed system, such as objectives, processes, and main system elements [28]. According to our literature review, most of the ConOps documents contain at least the following information [28], [18]:

- overall goals and constraints of the system or activity;
- the business or production processes to be carried out;
- characteristics of the environment and interfaces to external entities;
- main elements of the system (incl. human-system interface);
- main system functions and work items;
- operational states and operating modes;
- allocation of responsibilities and tasks to the system elements;
- operational scenarios;
- high-level user needs and requirements;
- analysis of the system (advantages/disadvantages/ alternatives).

ConOps developers should make efforts to establish a shared language with a structure and content accessible to stakeholders coming from different domains. ConOps should, thus, demonstrate the behavior of the system in order to build up a shared view of its dynamics and, at the same time, facilitate communication and negotiation about its characteristics with other stakeholders [18].

ConOps documents have several features common to boundary objects. To the degree they are considered as living documents that are updated throughout the system life-cycle, they are open to the addition of new features. They also should be underspecified to be able to provide a common framework for effective communication and innovation. The level of detail should also be appropriate to foster a fluent dialogue between experts coming from different domains.

Even though ConOps has been considered a valuable tool in systems engineering, as Mostashari et al. [18] have proposed, it has often been difficult to convince systems engineers of its value. It has been seen as an additional burden to systems engineering processes rather than a useful tool. One possible reason is that ConOps has typically been a long textual document, which has been developed once at the beginning of the design process. During a long project, it has easily become outdated so that it no longer reflects the requirements and challenges of the development process. Therefore, in order to make the ConOps artifact valuable for the development project, it must be a living, collaboratively generated document that utilizes graphical visualization and simulation techniques for demonstration purposes [18].

2.2. Promotion of ConOps Development

To provoke boundary crossing and knowledge exchange through ConOps, tools, techniques, and practices are needed to facilitate ConOps development. First, there is a need for specific and deliberate practices to promote the development of ConOps artifacts. Mostashari et al. [18] have proposed a three-stage process: In the conceptual stage, stakeholders' interests are surveyed, and the desired future state is outlined; in the specification stage, the desired future capabilities are specified; and in the design and implementation phase, the system architecture and the implementation and management plan are determined.

Second, technical tools are needed to facilitate the development process and to illustrate the results. There is an emerging trend to shift from a textual ConOps to that based on images and visualizations. For example, Thronesbery et al. [26] have developed a storyboard tool and graphical model-based approach for enhancing ConOps operations and lowering boundaries between different stakeholders. When considering development processes, these tools can help bridge the gap between human factors and requirements/systems engineering. The storyboard tool is based on a software concept that helps authors to indicate descriptive information related to the ConOps work [26]. It creates links between use cases and information categories and supports collaboration with all stakeholders. Korfiatis et al. [15], in turn, presented a method utilizing graphical models and game-like simulations in an initial concept engineering system prototype. The idea is to visualize and increase stakeholders' involvement in the ConOps creation phases. The authors suggested that the graphical model-based approach can be developed further for an automatic generation of textual ConOps and data analysis based on graphical concept engineering.

2.3. Some Relevant Examples of ConOps

ConOps documents come in different forms, but at the system level, a ConOps document typically illustrates the key system elements and their workings, stakeholders, tasks and functions, and goals and requirements. For example, the ConOps for International Space Weather Information system for aviation describes the basic requirements for space weather information to meet the operational needs of main aviation personnel [13]. The ConOps, answering the critical 'why, who and how questions, consists of two graphical presentations, one describing the system concept and another showing a usage scenario of the proposed system [14]. The other similar example of ConOps utilization comes from the Air Traffic Management context [3]. The ConOps for Air Traffic Management defines the roles of traffic and terminal controllers, flight crews, and airline operations centers, and it aims to illustrate the operational usage of the system from different users' points of view.

Next, we present some examples of ConOps artifacts for unmanned robots relevant to our own work and evaluate them in terms of to what degree the end-user's perspective and human-robot interaction issues are taken into account. Stark et al. [25] studied and presented a model of ConOps for Unmanned Aerial Systems (UASs). The idea of the UAS ConOps is that the flying drones in UAS should be fully utilized and integrated with the National Airspace System (NAS) consisting of the airspace and all the technical systems and services of the U.S. in order to enable the fluent flow of air traffic. The ConOps aims to develop and set standards for airworthiness, flight operations, and operator certification issues. Airworthiness standards regulate different categories of airplanes (i.e., normal, utility, acrobatic, and commuter airplanes). NATO has made its own standard for UAV-system military airworthiness [20]. In the NATO STANAG requirements, autonomous control is classified into four different levels, of which Level 1 is the fully autonomous mode, and Level 4 is a remotely piloted control mode. The air safety section, in turn, considers failure conditions (minor, major, hazardous and catastrophic) and how the UAS can tolerate these conditions. Levels of handling qualities are divided into four different levels: satisfactory, acceptable, controllable, and uncontrollable. A ground control station (GCS) where UAVs are operated and monitored is an essential element of airworthiness. One example of a GCS screen is also described and illustrated in detail. Stark et al. presented different ways to enhance air safety for small UAV-based systems. These safety enhancement methods include definitions and action suggestions related to fault tolerance, sense and avoid aspects, and risk mitigation. Flight operations in the UAS ConOps are divided into two sections: First, mission planning focuses on describing flight and process phases needed, and the mission plan outcome indicates objectives and requirements related to the flight mission and its phases. In addition, mission planning defines, for example, flight paths, emergency landing, and standby locations. Second, mission control focuses on monitoring the mission progress and how the planned flight phases are realized. Operators in the UAS ConOps play a key role when considering integration to NAS. Insufficient human-drone system interaction can lead to accidents and mission failures. Training certifications, clear procedures and manuals, and documentation are essential elements for ensuring the comprehensive realization of human-factor issues.

Pratt et al. [21] demonstrated the utilization of the ConOps approach in autonomy recommendations for an unmanned aerial system in crisis management operations. The ConOps work helped them to define sufficient distances and needed control and navigation protocols for unmanned aerial vehicles with cameras to survey the damaged urban environment. Their study suggested that multiple-camera UAVs should have three flight team members with different roles: mission specialist, pilot, and flight director. One of the challenges was that since the three team members had different views of the same scene, it was difficult to combine information received from different viewpoints and thus maintain situation awareness at the team level. Finally, the ConOps defines autonomy levels for different stages and team member responsibilities in system supervision and camera-view controls.

Tran [29] presented the concept of a Multidimensional Rescue Robot Swarm (MRRS) robot system for helping rescue teams in searching and identifying victims in urban disaster areas. The system is based on network devices (computers, antennas, and routers), field devices (notebooks and remote controllers), and robot swarms. The main goal is that the system would map hazards and risks of the operating environment while searching and detecting living persons in the area. Finally, the MRRS helps to plan and execute rescue plans. The rescue robots suggested for the system should be capable of operating in challenging environments and in hard conditions, and they should be equipped with advanced sensor and camera solutions. Large robots can carry small robots for special tasks or for entering areas where large robots are not capable of entering. These small special robots, such as lizard-like robots, should have advanced forms and movement methods. Also, UAV robots and ship-like and submarine-like robots can supplement the robot system. The MRRS approach considers typical ConOps goals and topics. Tran has divided stakeholders into active (primary) and passive ones. The primary stakeholders consist of rescue team personnel, victims, and the environment. The passive stakeholders are actors like system designers and maintenance personnel, system purchasers, a department of rescue officials, and funding instances.

In Tran's report, other MRRS ConOps areas are defined as follows: mission description, including mission statement which defines the main goal of the system (e.g., the operator can send commands and monitor progress normally), and stakeholders' acceptance and needs (listing user requirements and needs related to the system); operational scenarios, including normal operational circumstances and abnormal operational situations (i.e., the system is in an error state, or the operator uses the manual mode for driving the robots); key constraints and risks (incl. cost and budget, schedule, technical, financial, liability and operational risk); operational architecture (incl. system mode and state, functional decomposition and composition, IDEF0 model to model system functions, quality function deployment, and system physical viewpoint); and organizational and business impact [29]. Very little is, however, said about how the operator monitors and controls the robots during the rescue mission.

One thing that can be learned from these examples is that the ConOps of robotic systems comes in many different forms, but all of them are typically quite lengthy textual documents, including some Fig.s and tables. This also means that much time is needed to read the document and familiarize oneself with its content. Hence, it is not necessarily an easy task to apply it as a knowledge-sharing object at the boundary of domains. By applying data visualization techniques to ConOps design, it is possible to make the ConOps more illustrative and easier to comprehend.

Human-robot interaction issues are addressed in all three ConOps documents at a general level, but only two of them describe in more detail the interfaces through which operators interact with the robots and view the scenes received from the robot camera.

3. Concept of Operations as a Boundary Object in Safety-Critical Domains

3.1. Supporting Knowledge Sharing and Boundary Crossing Between Domains and Stakeholders in Safety-Critical Domains

As a higher-level document facilitating the development of common understanding, a ConOps document can also, in the military domain, play a role as a boundary object. There are complex knowledge boundaries between different engineering domains and various players in the military domain, and how these boundaries are crossed has a large impact on the success of the project. Shannon and Weaver ([22]; see also [6]) have identified three main types of knowledge boundaries: syntactic, interpretive, and practical, and three processes to manage interaction across these boundaries: transfer, translation, and transformation. At the syntactic level, the stakeholders strive to reach a common vocabulary and a common set of concepts in order to understand each other [6]. Possible misunderstandings are caused by lexical issues, and they can be solved by representations that help the stakeholders to build a common vocabulary and language for transferring knowledge across the boundary. At the interpretive level, representatives of the Defence Forces and contractors may interpret a particular phenomenon differently, which may hamper their ability to collaborate and communicate. Knowledge objects are needed that help people create common meanings, translate perspectives and prevent misunderstandings [6]. At the practical level, stakeholders have different interests and aspirations, and therefore more ‘stronger’ shared representations are needed that help people to negotiate their interests and transform their knowledge [6]. For each level, a different kind of ConOps is needed in Fig. 2. In Fig. 2, the triangles and distances become larger when moving from the syntactic level to interpretive and practical levels because the uncertainties and novelties between stakeholders increase.

Fig. 3 depicts the three different types of knowledge objects that should be generated from the source (“Master ConOps”) [6]. The textual draft ConOps developed according to existing ConOps standards and guidelines should be sufficient at the syntactic level. However, since at the interpretive and practical level, ConOps has to be able to support learning and mediate negotiation between stakeholders, artifacts that work at the syntactic level do not suffice. At the interpretative level, graphical visualizations are thus, needed that help stakeholders develop a common understanding of the target system and coordinate their efforts in an interactive way. At the practical level, simulations and virtual models provide new knowledge of the proposed system that helps stakeholders to negotiate specific aspects of the design and transform their knowledge base.

For example, regarding a ConOps for a robotic swarm, the draft should describe the general design principles, the operational environment, general operational functions, allocation of responsibilities, and operator behavior in different mission states; at the semantic level, the textual document should be complemented and enriched by virtual models of the robotic swarm around which people can navigate; and at the practical level, in order to support the negotiation and consolidation of conflicting interests a real-time simulation of robotic swarms may be required [17].

To sum up, ConOps should promote communication and collaboration by providing a common frame of reference for relevant stakeholders. It should, in some way, help stakeholders to focus on some critical aspects of the total system by drawing their attention to those parts of the system. The

ConOps should also help arrange certain aspects of knowledge in such a way that specific relationships and interdependencies within the system can be identified and taken under negotiation, and novel combinations of the knowledge can be articulated and discussed.

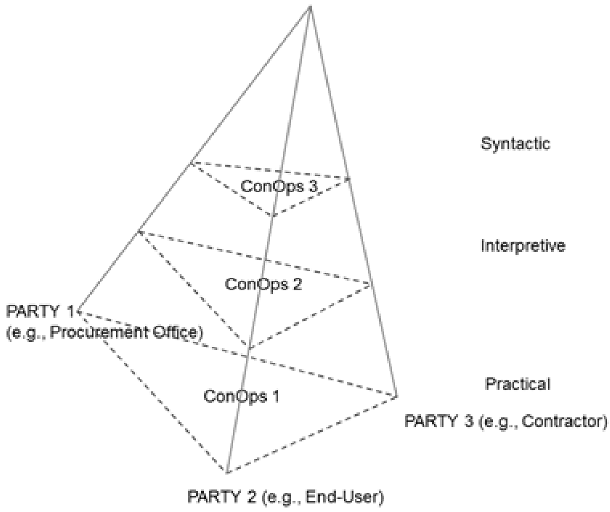

Fig. 2. Three levels of ConOps in the interaction between the procurement office, contractor, and end-user. The uncertainties and novelties between actors become larger when moving from the syntactic to the practical level, and therefore "stronger" ConOps tools are required. Modified from [6].

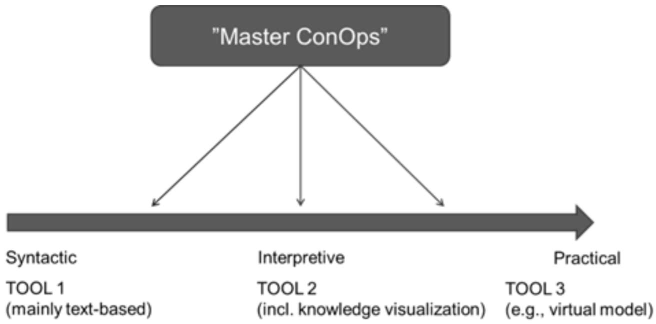

Fig. 3. Three types of ConOps are generated from the 'Master ConOps.'

4. Demonstration of Roboconops Development

4.1. Knowledge Elicitation Methods and Materials

In the RoboConOps project, the main aim was to develop a ConOps for a swarm of autonomous robotic vehicles for the military domain in order to clarify how autonomic robotic swarms can be deployed in various military branches (i.e., Air Force, Navy, and Ground Forces) in the future (i.e., by 2030).

4.1.1. Research Setting and Approach

Several methods were used in the development of the ConOps: literature reviews, workshops, advisory group meetings, theme interviews, and inquiries. Visualizations, system architecture sketches, and animations were produced on the basis of the theme interviews. The following topics, among others, were addressed in the interviews: the role of autonomous systems in capacity building, possible use cases, main actors in missions, level of autonomy and intelligence required, impact of autonomous systems at the strategic, tactical, and operative level, a collaboration between manned and unmanned systems, system and payload requirements, monitoring and control concepts, safety and security issues, and competence and training requirements. Possible usage scenarios were suggested in interviews, and they were discussed and further specified in workshops.

4.1.2. Data Collection and Analysis

Representatives of the Finnish Navy, the Air Force, the Ministry of Defense, and the Helsinki Police Department were interviewed in the Spring and Summer of 2016. Audio recordings of the interviews were transliterated after each interview and analyzed and organized according to interview themes.

There were two workshops with the Navy and Air Force in the Autumn of 2016, in which three experts from the two military branches (the Navy and the Air Force) attended and in which the preliminary versions of the ConOps were presented and discussed. The Ground Forces concept was discussed in the advisory group meetings, including participants from the Finnish Defence Research Agency and from the industry. The advisory group meetings were arranged throughout the year 2016 (four meetings in total). Both in workshops and in advisory group meetings, preliminary versions of the ConOps were discussed. In addition, there were two larger seminars in the Autumn of 2016 in which the results of the project were presented.

The outcomes of the workshops and advisory group meetings were analyzed by three human factors experts. The results were categorized and classified in tables where main military-branch-specific results were presented in such a way that differences between them could be easily identified.

4.2. RoboConOps Development

The RoboConOps is a kind of source ConOps from which more specific ConOps artifacts can be derived to cross the knowledge boundaries at the syntactic, semantic, and practical levels. The starting point was the special challenges for the successful implementation of robotic swarms that were identified in discussions with military experts. Some of the most important challenges were the following:

- how autonomous robotic swarms could be exploited in military operations;
- how to integrate an autonomous robotic swarm into existing manned systems and operating procedures;
- how to combine the robotic swarms for a joint operation;
- how and to what degree the swarm has to be tailored in order to meet special requirements of the different military sectors;
- how to choose the proper level of swarm autonomy for different military sectors and operations;
- how to determine operator roles and responsibilities, required skills and competencies, and communication requirements for each operation exploiting robotic swarms.

The question of swarm autonomy is related to a question of the dynamic balance between human and autonomous system, that is, how the authority, control, and responsibility is divided between a human agent and a robot at different phases of the mission (e.g., [10], [19], [23], [30], [31]). The answer to the autonomy question has an impact on human-robot-interaction-specific requirements, such as user interface solutions needed in control concepts and human operator roles and tasks when planning, executing, and debriefing missions with robot swarm systems.

The iterative ConOps development process included the following main stages:

- background and motivation of the ConOps;
- iterative drafting of the ConOps;
- introduction of the ConOps.

In the following, we will briefly outline the main contents of each stage.

4.2.1. Background and Motivation of the ConOps

It is essential that in the ConOps development, a dedicated project group with managerial and operative experience is identified and actively involved. In the RoboConOps project, the general aim was to outline the motivation and background of the initiated RoboConOps development and take a broad view of the military operations in each branch through interviews and workshops.

The first and necessary step to take before the new ConOps can be accomplished is to view the operation from an evolutionary perspective, that is, how a particular operation has been developed throughout the times. Reviewing the past and current situation may help to define the aimed/pursued future situation. The project group is involved in discussing the meaningful operative concepts, experiences, and change agents (e.g., trends and strategies) that have shaped and transformed the operation over time. As a result, a shared understanding of operative goals and bases can be created.

4.2.2. Iterative Drafting of the ConOps

After taking an evolutionary perspective, the ConOps development process focuses on analyzing and elaborating on the different elements of a future operation and the operative organization the new solution will be part of.

a. Iterative drafting of the ConOps

After taking an evolutionary perspective, the ConOps development process focuses on analyzing and elaborating on the different elements of a future operation and the operative organization of the new solution will be part of.

b. Design of the ConOps

Simultaneously with the ConOps definitions, the first sketches of the system architecture, descriptions of user interaction with the system, and conceptual illustrations and animations are drafted. A high-level description of how the elements of the system and its environment may communicate and collaborate in order to achieve the stated goals is created and matured.

c. Evaluation of the ConOps

Throughout the ConOps development process, it is important to expose the design specifications, that is, the design rationale and ideas, to critical feedback from relevant stakeholder groups. Interviews and workshops were arranged to evaluate the RoboConOps solutions together with domain experts of the three main military branches. The identified critical usage scenarios are exploited when exploring and reflecting on how RoboConOps can be employed.

4.2.3. Contents of the RoboConOps

Text, conceptual illustrations, and animations are used to describe how the three military branches are going to leverage robot swarms in the future. Drawings are used to illustrate how different stakeholders collaborate and cooperate, and animations demonstrate how military-branch-specific mission scenarios progress step by step and how operators and robot systems act and interact at different phases of a mission. At a later stage of the project, also simulations will be designed and produced, which would enable to prevent and solve more fundamental misunderstandings and differences of opinions between stakeholders. Together with expert workshops, this co-design process familiarized researchers with the main characteristics of different operating environments.

The main contents of each branch-specific RoboConOps are the following:

- description of the mission goal;
- critical scenario description, including, e.g., main stages of the mission, operator tasks, and activities;
- main system requirements, including user needs and key performance requirements, and possible limitations;
- system structure at the general level, including system interfaces, system architecture, and the most important devices and payload;
- human-system interaction, including the level of autonomy and user interface solutions.

Three representative scenarios were developed, one for each of the main branches of the Defence Forces, that is, coast guarding at the littoral zone by the navy, air surveillance by the Air Forces, and support for the urban troop operations. The scenarios were fictional stories, and they describe possible situations in the future year 2030 when robotic swarms are key players in military operations. The scenarios defined the main and secondary goals of the RobonConOps system for each military branch, and therefore both normal and demanding operating situations are described in the scenarios. In our view, representative scenarios are critical in knowledge sharing and boundary crossing between domains and military branches.

Performance requirements for the proposed system were based on the theme interviews and the workshops held together with domain experts. Most of the requirements focus on issues such as level of autonomy, data collection and tracing procedures, swarm navigation, human-robot interaction, operational robustness, weather-proofed, and serviceability [17].

Overall, three system architectures were generated, and all of them consist of some common elements such as robot nodes of the swarm, internal and external communication system, sensors and actuators, target, environment, and control center in Fig. 4. In the coast guarding system architecture, the idea is that underwater sensors and surveillance unmanned air vehicles (UAVs) monitor surroundings and send possible alarms and notifications to the swarm operation center. Cargo UAVs carrying unmanned underwater vehicles (UUVs) or surface vehicles (USVs) can supplement, for example, unknown object detection and survey missions. The operators in the command-and-control center formulate and design the missions, control possible actions and make contact with other stakeholders if necessary. The air surveillance system architecture consists of different UAV types, such as cost-effective and large-swarm mini-UAVs, long-range surveillance UAVs, and multifunctional UAVs. It is also possible that manned aircraft are included in the system architecture. In addition, urban troops are elements of the system architecture, and they are equipped with a fixed sensor and camera network, surveillance UAVs, cargo UAVs, and multifunctional unmanned ground vehicles (UGVs).

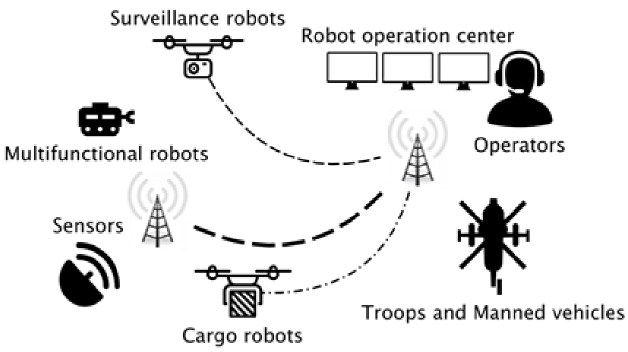

Fig. 4. Example of RoboConOps system architecture

The RoboConOps is divided into three lower-level ConOps documents related to the three military branches under consideration (i.e., Air Forces, Navy, and Ground Forces). There are considerable differences between the three ConOps. Some of them are listed in Table 1. The nature and length of missions in different military branches vary a lot. Air Forces execute carefully planned reconnaissance missions that can be over in minutes. On the other hand, in the coastal-guard context patrolling is continuous, and possible search, observation, and tracking of an unknown underwater object can last for hours or even days. Technical requirements for the design of robotic vehicles and robot swarms are also different. Air Force's unmanned vehicle system aims to control and saturate airspace with a large number of cost-effective devices. In the Navy scenario, unmanned vehicles need to endure harsh operation environments for a long duration of time. Also, possible active civilian traffic is a challenge for the coastal guard operation. In urban environments, unmanned vehicles need to operate in outdoor and indoor conditions and among civilians in populated and built areas. An appropriate and acceptable level of autonomy is also different for different military sectors. The level of autonomy scale created by Sheridan and Verplank [23] was utilized in the characterization of human-robot interaction. The level of autonomy is highest in the Navy scenario, in which swarms of autonomous vehicles conduct long-term patrolling in a wide-range area, and they need to react quickly for possible unknown objects. The level of autonomy was defined to be lowest in Ground Forces operations, where operators play a more cooperative and active role during mission execution by monitoring and controlling the swarm through mobile user interfaces. Also, the robots' swarms need to cooperate actively with human troops in Ground Forces operations.

Table 1. RoboConOps level

Content	Air Forces	Navy	Ground Forces
Purpose	Area recce etc.	Submarine hunting etc.	Urban recce etc.
Reqs.	Airspace control and saturation	Maintenance-free and resilience	Indoor navigation ability
Challenge	Airspace mgmt.	Winter conditions, civilian traffic	Buildings, civilians
Element	UAV	UUV/USV/UAV	UGV/UAV
Level of autonomy	Quite high	Quite high	Moderate
Staff	A pair of operators	Operator & Int. Officer	Field operator & comm. center
User Interface	Workstation-based	Workstation-based	Mobile

Three control concepts for supervising the autonomous robotic vehicles were also developed and presented for three military branches. Each of the control concepts describes the purpose, requirements, challenge, elements, level of autonomy, staff, and user interface of the robotic systems.

The control concepts describe operator roles in detail level and how they are connected to the technical system and to other actors related to each military branch's operations. The idea of Air Force and Navy scenarios was that two operators monitor and supervise autonomous swarms with a workstation-based user-interface setup. In Air Force's control room, one operator makes plans for missions for the autonomous swarms, monitors the mission progress, and reacts to possible exceptions. The other operator has an intelligence officer role, and he/she makes plans for missions together with the other operator, builds a common operational picture, and analyzes and shares gathered reconnaissance information. The Navy scenario also has two operators in the command-and-control center. The first operator monitors the sensor network and the status of the robotic swarm and analyzes possible alarms and unknown object information. The other operator is in charge of special missions, and he/she supervises robotic swarms in special tasks and communicates with troops and manned vehicle units if necessary. The basic structure of the control concept for the Navy is depicted in Fig. 5. In-Ground Force operations and operators are split into different locations. One operator controls robotic vehicles in a workstation-based operation center, makes plans and introduces missions to swarms, and monitors their progress. The other operator is located in the battleground and directly co-operates with the swarm through a mobile user interface. He/she assigns such tasks as building investigation and clearing missions to the swarm. Because he is on-site, he can also analyze and supplement received intelligence data.

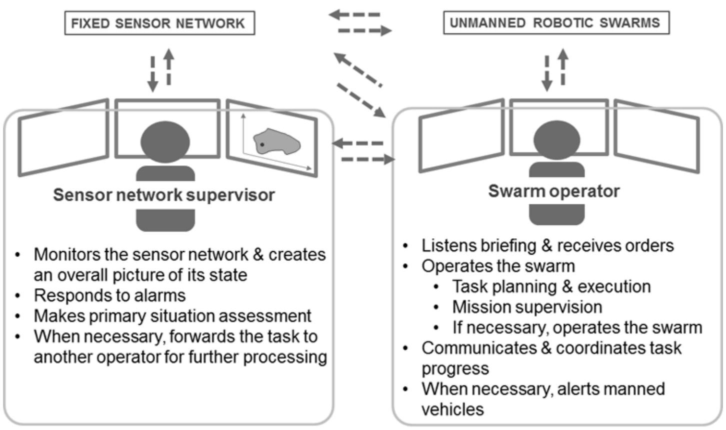

Fig. 5. Control concept for a swarm of robotic vehicles.

5. Discussion: Conops as a Boundary Object in Military Domain

As said, ConOps should play an important role in knowledge sharing and boundary crossing between expert and stakeholder domains. We propose that the RoboConOps could play a role as a master ConOps that could be tailored to mitigate misunderstandings and differences of opinions at the syntactic, interpretive, and practical levels in Fig. 6. The critical stakeholders in the RoboCobOps are 1) researchers/consultants who are studying and inventing future solutions and developing new technological applications, 2) military managers who have opinions on how the Defence Forces shall be developed and how the limited financial resources are spent in an optimal fashion, and 3) military staff who are interested in how their missions are executed efficiently. There is always some fear of the collapse of the status quo and of emerging communication problems or conflicts between stakeholders. The professionals in the field also have some worries about losing jobs with the introduction of semi-autonomous or autonomous robot systems. Even though the problems accumulate at the practical level, they apparently cut across the three levels, and therefore effective boundary objects are needed, on the one hand, to help stakeholders to reconcile discrepancies and negotiate their interests, and, on the other hand, help them to solve misunderstandings regarding the details of the technical system.

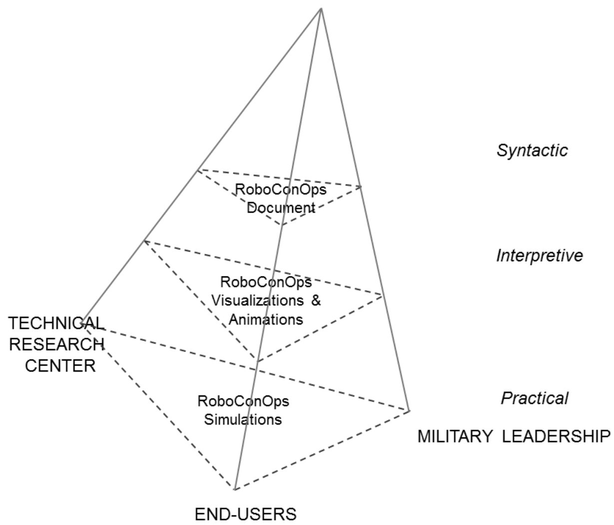

Fig. 6. Three levels of RoboConOps.

Firstly, since there are some suspicions about autonomous robotic systems in the Defence Forces, the ConOps might play an important role in overcoming possible misunderstandings and resistance. It could help officers to negotiate their doubts, interests, and aspirations at the practical level. The ultimate goal is that it could help to transform their awareness of autonomous systems and robotic swarming. Secondly, the ConOps should help to reconcile possible controversies at the interpretive level. During the design process, the ConOps could promote the recalibration of trust towards autonomous systems and better consideration of ethical and legislation issues regarding autonomous systems in military missions. Ethical and legislation issues were essential topics in workshops, and it was considered that the ultimate control of autonomous robotic swarms must rest with the human operator. At a more specific level, the ConOps makes it possible to visualize many critical engineering issues, such as communication within a swarm, goal setting and adjustments during a mission, and problems and opportunities in the remote control.

The ConOps approach makes it possible to understand and disclose motivations and possible barriers to use among different user groups. The ConOps also helps to determine different modes for swarm management according to their complexity [17]. In the lowest level of complexity, one operator executes one mission by monitoring and controlling one specific robot swarm, and in the highest level of complexity, multiple robotic swarms, operators, and troops from different military units operate in the same area and accomplish joint missions. Even though technological and human factors issues are seldom a critical bottleneck for the deployment of autonomous swarm robot systems, they are highly important from the end user's perspective, and they must also be adequately addressed in the ConOps. A fluent interaction between human operators and a swarm of robots means specific requirements for the operator and the system. The operator must be aware of the system and mission status, and user interfaces must be designed to present situation-aware information in the right manner. On the other hand, the system must adapt to different situations and react to operator actions.

5.1. Requirements for ConOps as a Knowledge-Sharing Object

As suggested above, boundary crossing does not always occur without problems. A ConOps as a boundary object should stimulate communication and knowledge sharing and, thus, foster mutual understanding among stakeholders. However, despite its positive effects, its real value is not necessarily recognized, and the ConOps is quite easily marginalized and placed at the periphery in system design and in tendering and contracting. One possible argument is that we do not need a ConOps, since we already have other similar kinds of documentation which is more familiar to us. Or the value of a ConOps is recognized, and it is developed at the beginning of a project, but it is not able to be properly exploited, and it plays a quite marginal role in design work or in contracting.

In order to fulfill the above-mentioned promises, ConOps as a boundary object should effectively promote communication and coordination at the boundary of domains. By using the terminology suggested by [1], there should be a communicative connection between diverse practices at the boundary, and the ConOps should support the translation of knowledge from one domain to another and promote the automatization and routinization of boundary crossing. A ConOps as a boundary object should also promote perspective-taking and making. That is, on the one hand, it must make explicit one’s understanding and knowledge of a particular topic, and on the other hand, enable looking at oneself through the eyes of other perspectives. A ConOps should also promote the transformation of one’s practices based on the confrontation with a deficiency or a lack forcing the parties to reconsider their existing practices and initiate some changes.

In order to achieve these objectives, the ConOps has to be underspecified to the degree that it enables effective communication among actors that do not know each other and/or who do not share the same level of knowledge and competence in a particular domain [5]. In addition, its granularity has to be carefully determined so that the level of detail is adequate and what is considered to be worth being represented is actually represented. It is possible that a more extensive use of data visualization techniques in ConOps design will promote these endeavors in the future.

5.2. Benefits of our Approach

One of our main propositions is that a ConOps can be thought of as a boundary object: It has similar functions as many other boundary objects; that is, it fosters boundary crossing and knowledge creation, and it can be investigated by similar means as other boundary objects. On the other hand, it can be argued that even though a ConOps has some commonalities with a boundary object, they are two different things. The main difference between them is that a ConOps is typically much more strongly structured than a boundary object, which is often quite malleable and plastic. Clearly, a boundary object is a more general term, and there are all kinds of boundary objects that have very little in common with ConOps artifacts. However, what is common to both of them is that they act as a common ground for further discussions between stakeholders – and for our purposes, these similarities are more important than their differences.

One of the benefits of examining ConOps as a knowledge-sharing object is to collide with different mindsets and ways of thinking. Literature on ConOps design has been quite a technology and design-oriented, whereas discussions of knowledge sharing and boundary crossing have been taking place in journals and other forums focusing, for example, on learning, knowledge management, and organization studies. Our conviction is that something new and fruitful may emerge from this collision of views and ideas, and hopefully, our paper is a modest argument in favor of this view.

5.3. Future Aims

Future work aims to fine-tune our approach for ConOps development to better utilize it in the design of autonomous systems and in the optimization of human-robot interaction for autonomous systems. Our aim is also to establish a ConOps service, which would enable us to build a strong foundation for design projects and to define a ConOps development process that would be a commonly shared standard of activity and, thus, may lead to successful project completion. The cornerstone of our approach is that ConOps must be sensitive to the levels of knowledge boundaries so that different kinds of ConOps artifacts can be derived from the master ConOps for different purposes.

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