Framework for Semantic Interoperability

1 Executive Summary

In order to conduct successful coalition operations, it is of the utmost importance that interoperability can be established between heterogeneous Command, Control and Intelligence (C2I) systems. This is especially true as information originating from different systems typically has different meaning. The goal is to create a shared situational awareness in the coalition, and in order to support this goal, the meaning of the information must be preserved as the information is exchanged between different systems. There must, in other words, exist semantic interoperability between the systems.

The proposed solution to this challenge from the NATO Research Task Group IST-094 ("Framework for Semantic Interoperability") is utilising formal representations of semantics (meaning) through ontologies in order to exchange not only the information, but also its meaning and intent.

This position paper outlines what the IST-094 sees as the most important issues related to semantic interoperability. This is then put into the context of NATO's needs in this area, before the proposed solution is presented and discussed.

2 The viewpoint of NATO research task group

2.1 Introduction

The recent past has shown a transition from single service operations toward coordinated joint operations, and more recently toward full coalition operations. This increasing dependence and cooperation between organizations has created an urgent need for seamless exchange of data and services between systems of different origins. Thus, it becomes important to be able to bridge over existing, heterogeneous information systems. The current approach to semantic interoperability builds mostly upon manual translation and/or transformation of the transmitted information and it is clearly non-scalable.

To conduct successful coalition operations it is fundamentally important, if not absolutely necessary, that there exists automated interoperability between heterogeneous Command, Control and Intelligence (C2I) systems. In the field of information processing, different views on the same facts, different phraseologies, methods and structures as well as different cultural aspects lead to a lack of mutual understanding even in a shared domain of applicability. This is especially true in coalition operations, where information originating from different systems typically has different meaning. The challenge is to create shared awareness through interoperability. ***This requirement means that not only information should be exchanged automatically but also its meaning and intent***.

It is our position that formal representations of semantics ("meaning") through ontologies represent an important step towards automated information interoperability. However, in addition to the use of ontologies and related tools, a consensus on a common information exchange methodology is needed. This consensus should specify the use of ontologies in the lifecycle of information systems and the recommended implementation strategy. The boundary conditions, necessary methods, and rules for their application shall materialize in a concept for a "Framework for Semantic Interoperability". The proposed framework will save the significant human resources that are allocated today to the manual interoperability tasks and, thus, it will provide a scalable solution for cooperation of multiple organizations.

2.2 Ontology Utilization

Knowledge-based solutions for semantic interoperability exploit so-called *ontologies*. Within the knowledge engineering community, ontologies are defined as *"an explicit, formal specification of a shared conceptualization."* [Gruber]. Here, *conceptualization* refers to an abstract, concept-based model of some phenomenon in the world. *Explicit* means that the type of concepts used, as well as the constraints on their use, are explicitly defined. *Formal* refers to the fact that the ontology should be machine-readable. *Shared* reflects that an ontology captures consensual knowledge, that is, the knowledge accepted by a group. For detailed background on ontologies see [W3C, IST-075], and other relevant literatures.

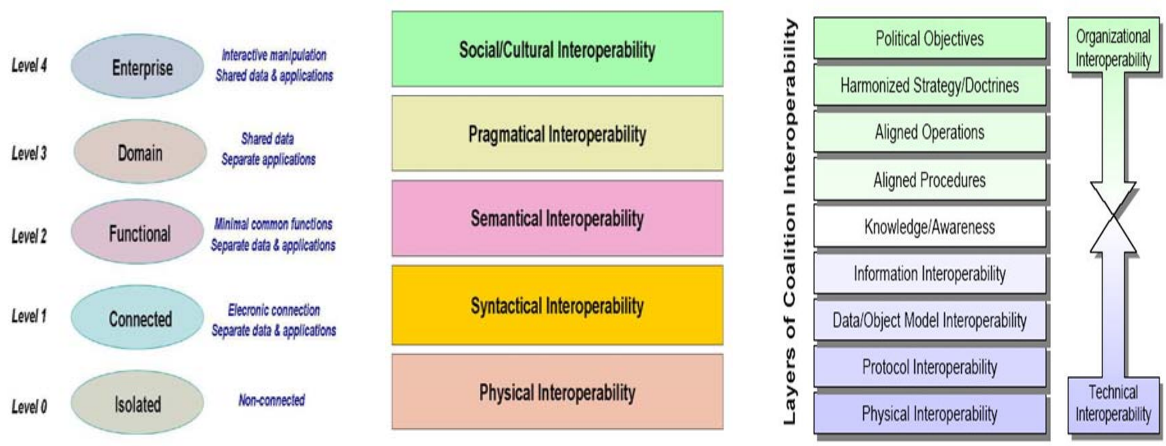
Many terms used in natural languages have several distinct meanings. In an ontology lexicon, one constrains the semantic interpretation of these terms, and provides formal definitions. This is called ontological commitment and means mapping between ontology terms and their intended meanings. The major task here is to determine precisely what meaning the term has.

More recently, ontologies have become recognized as an emerging mechanism for dealing with semantic interoperability of information systems. This is entirely aligned with the recently recognized fact that semantic understanding and interoperability is a key challenge for organizations and their systems to successfully and competitively provide their services. By specifying the conceptualization in terms of an "agreement" on meaning between the parties involved, the ontology becomes a reification of an agreement on knowledge.

There are several approaches for integrating ontologies into military systems. Ontologies can be used as system interface components to improve the communication between different systems. This is a viable approach if the systems in question operate with different and incompatible data models; a common situation within coalition operations. In such a case, direct communication (e.g., by exchanging data) is not possible. However, since ontologies provide meaning to the concepts, to the attributes, and to the attribute values used in the respective data models, the communication between the systems can be shifted toward a communication between the systems' ontology components and thereby exploit the flexibility and adaptivity of ontologies.

2.3 Levels of Interoperability

Interoperability is more than only the technical compatibility of systems. In a Network Centric Warfare scenario, the C2IS of all engaged elements must be connected (physical interoperability), exchange data in such a way that automatic processing is possible (syntactic interoperability), exchange information and guarantee identical interpretation (semantic interoperability), cooperate and realize situational awareness (pragmatic interoperability) that assures the coherent cooperation of all participating actors (social/cultural interoperability). Whether further levels should be established above social/cultural interoperability (operations, doctrines, politics, see part C in figure below) is a question of requirements. In most cases, these levels are not essential.



A) LISI – Five Levels of Interoperability Maturity[LISI]

B) IST-075 – Levels of Interoperability

C) LCIM – Levels of Conceptual Interoperability Model [LCIM]

Figure 1: Three different approaches defining levels of interoperability

During the past decade, several attempts have been made to divide interoperability into different levels or stages. Figure 1 shows an overview of different approaches to defining levels of interoperability and illustrates the spectrum of results.

Without going into details, we can state that each interoperability level in the above models represents increased capabilities over the previous level. However, the common understanding in all models is that somewhere in the middle levels the interoperability changes its characteristic. Everything below a certain level, *the semantic level,* is about physical connectivity, data exchange, message exchange, common protocols, etc. At the semantic level, the models introduce common reference models based on common ontologies, i.e., the meaning of the exchanged data is unambiguously described. For a clear definition of each level of interoperability proposed by IST-075 see the Final Report of the Task Group [IST-075].

2.4 Definition of Semantic Interoperability

Semantic interoperability has multiple interpretations, some of which we mention here. Semantic interoperability is about how to achieve a mutual understanding of the interchanged data, or share a model of what the data represent [ERCIM]. It can also be seen as the ability of two independent systems with reasoning capability to arrive at the same conclusions from the same data. According to [IEEE90], semantic interoperability is the ability of two or more systems or components to exchange information and to use the information that has been exchanged. Within our own military application domain, the US DoD [DACS] has defined semantic interoperability as the ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces, and to use the services to enable them to operate effectively together.

Although we concur with the spirit of the definitions above, we believe that our focused area, *the military C2I Systems in coalition operations,* deserves a more refined definition. To address this need, for the purpose of this paper we define semantic interoperability of computerized information systems as "*the ability of two or more computerized systems to exchange information <u>for a specific task</u> and have the meaning of that information accurately and automatically interpreted by the receiving system, <u>in light of the task to be performed</u>.*"

The definition above is very similar to the one found on Wikipedia [WIKISI]. However, there is a major and significant difference. For the RTG definition, we have removed the reference to "accurately enough to produce useful results" and replaced it with "task-orientation"[1].

2.5 Stand points

Today critical C2I information (e.g., the commander's intent, orders, doctrines and directives) flows as free text elements within messages or files. In order to process this information automatically, the free text has to be transformed into a formal structure, which represents the meaning of the text. Then the structured text must be entered into the information system.

[1] The relevance of such replacement is related to the idea that the two information systems can be vast and complex. Consequently, the mass of information that they could exchange is large. As such, it has to be expected that some limitations to semantic interoperability would arise. This is the case, for instance, if the first system tries to send to the second system some of the data that the second is not interested in or simply cannot handle. Information that is not recognized, because the target system cannot process it, will be ignored and discarded (as the human user would do).

In many cases, liaison officers perform the interface between heterogeneous systems, i.e., systems with different formal information structures. They manually convert information from one system to feed a second system. Due to their experience, they own implicit knowledge about operational facts. If it were possible to explicitly represent the knowledge of a domain that experienced experts know implicitly, this repository could be the basis for the interfaces described above. This repository might be implemented in a shared ontology and be the key tool for the interoperability of heterogeneous information systems.

Future operations will rely on direct, interpersonal exchange of information and even more on data and service-oriented cooperation. If computers were able to "understand" the meaning of the information they process, this would cause a dramatic enhancement for the benefit of information processing and decision making. Semantic technologies aim at improving machine "understanding" and thus promise to greatly increase the potential of computer-based systems and create conditions for automated interoperations of heterogeneous Command and Control (C2) Systems.

As long as the process is schematic and predefined in algorithms, computers are very powerful in processing various kinds of data. However, when decisions that require intelligent and context sensitive comprehension have to be made, the human operator is still necessary. The mass of data that is collected and conveyed by electronic means can easily be processed by the systems but when it comes to decision (transforming data into information), the human operator is still a vital component. If the operator is not supported by an automated expert system, the decision process is overloaded, and the workflow is limited by the capacity and availability of the human operator.

Semantic interoperability builds upon the ability of multiple heterogeneous systems to realize a common understanding before the actual information is exchanged (also called “schema matching”). However, conveying this meaning a priori introduces many issues. This is particularly true when considering legacy systems. In part, this is due to the historic development processes, which did not take the explication of semantics into account. For example, these systems often lack sufficient metadata descriptions that should be accessible and utilizable by other applications. Moreover, natural language barriers introduce additional complexity. Changes to the development process must be made to address these issues.

Semantic technologies must be considered as a base for a stepwise encapsulation/evolution of legacy systems towards improved joint/coalition interoperability. One major issue of most operational legacy systems is that their semantics are not properly exposed. Assuming that proper exposition of semantics can improve information interoperability, the seamless and non-intrusive adaptation of existing systems through the use of ontologies must be investigated. If each system was to take its own approach to an ontology based information system development, we could end up with a diverse set of ontologies - a similar situation to what we have today with data models.

We believe the importance of semantic information processing will increase in the future. The idea of the "semantic web" is to have information on the web defined and linked in a way that it can be used by machines – not just for display purposes, but also using it for various applications. Such applications can go beyond simple pattern matching enhanced by some syntactic rules. They allow the systems to operate on the meaning of the term. Ontologies will provide the basis onto which the semantic web will be built.

In order to achieve the necessary level of interoperability, intelligent mechanisms (integrated in knowledge based systems) are needed. These knowledge-based mechanisms have to perform semantic analysis of various information sources and bridge the semantic gap between the C2I systems. The view of our Research Task Group (RTG) is that, for this purpose, ontologies are required. Ontologies comprise data structures, relations and attributes, similar to data models. Additionally, they contain expert knowledge in the form of rules, axioms and functions determining or extending the behavior of objects and relations. Generally speaking, ontologies are knowledge representation tools that support: content extraction, explicit notation, reasoning inference, recognition of the meaning of information and flexible mediation of data and information between heterogeneous systems, such as C4IS and decision support systems.

A Framework for Semantic Interoperability covering NATO needs for semantic correct interoperability among coalitions is required. Knowledge-based mechanisms and policies are needed to flexibly bridge semantic gaps between semantically heterogeneous C2IS. This mechanism must be able to interpret the meaning of the incoming information, filter the relevant data, convert it according to the semantic restrictions of the target C2IS and store it in the database correctly. The heterogeneous C2IS remain unchanged; the software and the database of the system remains as it were initially.

Thus, in order to achieve the necessary level of interoperability additional efforts are necessary. A framework for semantic interoperability comprises intelligent mechanisms that flexibly bridge the semantic gap. On the other hand, guidelines for agreements about the purpose of the systems compound as well as an operational workflow and a development process are required.

We claim that the problem should be treated in three different layers as follows:

1. A *Life Cycle of Knowledge Based Semantic Interoperability (LC of KBSI)* should be established covering political, economical, organizational, and ethnical aspects of the *Knowledge Based Semantic Interoperability (KBSI)* as well as non-functional requirements such as reliability, performances, security, fault tolerance, and scalability.

2. A *Semantic Interoperability Development and Execution Process (SIDEP)* creating conditions for integration of the systems in question should be developed. SIDEP will specify the goal for the integration, e.g. a multinational coalition. ROE, SOP, CONOPS, as well as a deeper understanding of what resources and entities are involved in a specific context (military operation or mission), and their behaviors, relationships and needs for interaction should be clarified (i.e. create an overall picture of the business model). “How" the activity should be performed will not be addressed here and is left to Semantic

Interoperability Framework (SILF[2]), but only “what” and "why” should be done is addressed here.

3. A *Semantic Interoperability {Logical} Framework (SILF)* will exploit the emerging power of semantic technologies, including ontologies, to improve interoperability between any pair of information sources (denoted as systems A and B). SILF covers information operations, ontology operations, references to upper ontologies (the Common Ground), and transition rules in order to transfer information from A to B by utilizing a mediation engine. Thus, SILF comprises middleware communication facilitators, i.e. Semantic Mediators.

LC of KBSI (1) is understood to be outside of the scope of this task group, while SIDEP (2) and SILF (3) are under development. While SIDEP is under construction and in its initial stage, SILF is more mature and will be presented in next section.

[2] During initial considerations how to establish SI, the concept of a *Logical Framework for SI (SILF)* was created. Nowadays, the concept of a concrete Framework for SI envisaged. Hence the word *Logical* was removed – but the acronym SILF was kept because of better pronounceableness.

3 NATO Group and its proposed solution

3.1 NATO's need – The driver of this work[3]

The need for interoperability, as argued in pervious chapter, is motivated by the future multinational, multi-service and network centric operations. Consequently, there is a need for concentration on semantic issues to enable information interoperability in such operations. In each of these cases, disparate operational entities and their supporting systems will need to interoperate on a level higher than simple message exchanges, which is regularly the case today. To take this important step the following long-term goals are required:

- It is necessary to harmonize the purpose, construction, maintenance, and extensions of knowledge bases for these (parts of) domains where an information exchange is or could be required. The application of semantic tools and methods may be essential for this harmonization process as well as for providing cost effective semantic interoperability amongst participating nations. Further research on that aspect is necessary.

- It is necessary to avoid or at least mitigate future heterogeneity (like our current situation; e.g. incompatible logic data models), by cooperation among and fusion of existing ontologies and knowledge bases.

- It is necessary to develop methods and techniques in the network centric context, which do *not* require presence of a-priori, centralized ontologies and data dictionaries. This is because of the inherent dynamic character of the network and the fact that participating operational entities and systems cannot always be determined a-priori.

The goals above are beyond the scope of SILF.

3.2 NATO's RTO – The organization behind the working group

The Research & Technology (R&T) Organisation (RTO) is the single focus in NATO for Defense Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defense research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers.

RTO performs its mission with the support of an extensive network of several thousand experts from all countries that are engaged in NATO. It also ensures effective co-ordination with other NATO bodies involved in R&T activities. These bodies are made up of national representatives as well as generally recognized 'world class' scientists. They also provide a communication link

[3] The networking and information infrastructure (NII) is the supporting structure that enables collaboration and information sharing amongst users and reduces the decision-cycle time. This infrastructure enables the connection of existing networks in an agile and seamless manner.
This leads to Information Superiority, which is the ability to get the right information to the right people at the right time. NATO defines information superiority as the operational advantage derived from the ability to collect, process, and disseminate an uninterrupted flow of information while exploiting or denying an adversary's ability to do the same. [http://www.nato.int/cps/en/natolive/topics_54644.htm]

to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. [RTO]

3.3 IST-094 – The group behind this work

The total spectrum of NATO research and technology activities is covered by seven bodies, one of which is the Information Systems Technology (IST) Panel. A technical team, IST-075 Research Task Group (RTG) 034, was formed by the IST-Panel in September 2006 to research on problems involving semantic interoperability. The group was created to explore solutions to NATO nations need for semantically correct interoperability by means of knowledge based systems, and concluded its work at the end of 2009 [IST-075]. In order to achieve a common view and describe the challenge, the NATO group IST-075 conceived a framework, called SILF - Semantic Interoperability Framework, intending to provide a generic approach to SI[4].
A continuation NATO group IST-094 (Research Task Group 044) was created in the end of 2009 to proceed with this activity for the period 2010-2012. The main objective of this new group is to further research on the different elements of SILF, try to complete the framework and come up with such a detailed specification of the SILF, which can serve as a basis for an appropriate proof-of-concept demonstration.

3.4 SILF - Semantic Interoperability Framework

In order to ensure semantic interoperability, an architecture is needed which includes a pairwise (?) set of common ontologies between communicating parties, which both can understand and use. Such is always implied by actors who exchange data (otherwise communication is impossible), but in this architecture it is made explicit. This allows each data message between communicating parties to be provided with references to one or more of the ontologies according to which the message should be interpreted. In terms of high-level architecture, SILF is a middleware that supports semantic interoperability between heterogeneous information systems that need to communicate with each other. SILF applies knowledge-based techniques, using ontologies, for mediation purposes.

3.4.1 Assumptions and Preconditions

The application of SILF assumes that the lower levels of interoperability has have already been achieved and exists between the concerned systems. This means that the systems are connected (physical interoperability is established) and that they can exchange data in such a way that automatic data processing is possible (syntactic interoperability is also established). It also assumes that semantic descriptions of systems can be obtained or created in some way. These descriptions can more or less automatically be (partly) derived from the systems, but in order to achieve the necessary quality of the descriptions the process normally requires human intervention. Given the semantic description of each system, the ***task-relevant*** concepts should be identified.

It is important to note that the starting point for SILF is that existing systems have a need to share information in order to be able to interact in some kind of coalition. This must also be done without performing major changes to the existing systems, and without any requirements of knowing the other systems' intention beforehand. Nations will unlikely change their C2 systems in order to be able to interact with other nations. Nor is it likely that they want to adapt

[4] see footnote No.2

their C2 systems every time a new nation will integrate. The optimum for each C2 system is of course to "talk and listen" in their own language. In addition, the general situation is that of a sender creating a data message without knowing in advance who the receiver will be.

3.4.2 Brief description of SILF and its main components

The basic idea of SILF is to insist on having a semantic description of all of the information to be exchanged and then take advantage of a number of existing and emerging semantic technologies, mainly ontologies, to improve interoperability.

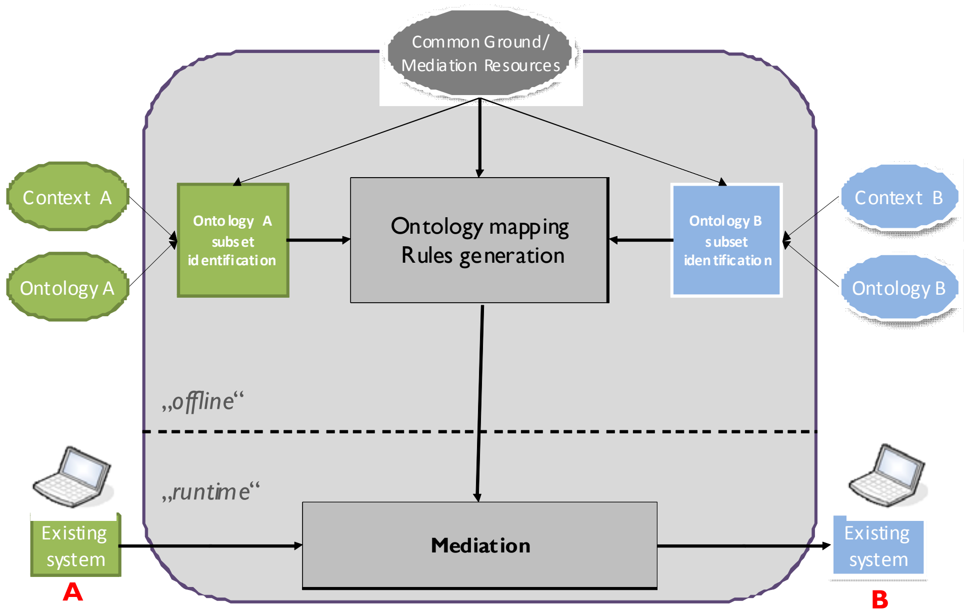


Figure 2: An overall view of SILF

Figure 2 shows an overall view of SILF which can be described as follows. In runtime, SILF mediates an exchange of information between systems (e.g., systems A and B), which do not necessarily know each other. Furthermore, the assumption is that the systems information structures are different and therefore the exchange of information cannot happen painlessly. This means that to make the communicated information correctly interpreted in accordance with the semantics of system B a translation is required for all task-related data messages sent by system A. In the offline phase, a number of ontology mapping operations take place in order to define and produce the rules necessary for these translations. Input to these ontology operations and translations are not only task-relevant subsets of semantic descriptions for systems A and B, but also links to shared mediation resources in the "Common Ground" (CG) reference ontology.

The most important components of SILF according to Figure 2 are as follows.

- *Common Ground / Mediation Resources:*
  The main purpose of Common Ground (CG) is to provide common references for the semantic descriptions supplied by independent systems, in order to produce accurate

ontology mappings. The idea here is that a relevant portion of "all knowledge" available in the world, either exist or can be made available in machine-readable form. If this available machine-readable knowledge proves to be useful, reliable and validated for military use, it can be placed in CG to support SILFs ontological activities. The CG is created and updated offline.

- *Ontology subset identification Module:*
  The output of this offline module will be the subset of relevant concepts and relations in each system ontology based on the Mission Description and the Task Ontology (if available).

- *Ontology Mapping and Rules Generation Module:*
  This offline module within SILF provides services for ontology matching operations that identify similar concepts across ontologies and otherwise harmonize and align ontologies. These ontological operations will lead to generation of predefined rules for relating and translating between concepts in the exchanged data messages.

- *Mediation Module:*
  This runtime module will use a set of collaborative software programs that, given a set of explicit translation rules created by ontology alignment operations in the previous step, converts a data message from a form which is interpretable by system A into a form which can be understood by system B. It is important to note that the structure of the message is converted without loss of semantics.

- *Semantic Descriptions / System Ontologies:*
  While semantic descriptions of the current systems interaction abilities are strictly speaking beyond the scope of the SILF architecture, we describe them briefly nonetheless since they are central to any application of SILF. A semantic description specifies, among other things, the permitted syntactic message structure as well as the intended message meaning (via references to ontologies). However, we note that SILF will derive the intended meaning not only using the semantic descriptions, but also using common concepts in the CG. In addition, the so called "Terms of interest” are used by SILF when deriving the intended meaning. For more details on this and on SILF in general the interested reader is directed to [IST-075].

3.4.3 The Operational Workflow of SILF

The process within SILF that leads to the physical exchange of data messages (information) can be divided into the four following phases:

1. The *Pre-Deployment (Preparation) phase* has the purpose to describe and expose semantic descriptions for each system.
   It is an "off-line" phase, where the military organizations accommodate their system by new capabilities required for knowledge based semantic interoperability according to SILF. All necessary information about the participants in the communication is collected or created in the form of semantic descriptions (ontologies) available to SILF. The information required by SILF is primarily descriptions of what each system can send/receive, and not their internal algorithms.

2. The *Configuration phase* (also done offline) is triggered by a conflict and it will result in a set of translation rules that will bridge mismatches between the relevant concepts. This requires the identification of the mission-relevant parts in the ontology of each system. Free-text task descriptions are converted into task ontologies.
   One aspect is the mapping of local descriptions to the previously described and/or common concepts of Common Ground (CG). By connecting these concepts to the "well-known" concepts in the domain that already exists in the CG, more information about the properties, limitations, aspects and relationships to other concepts can be achieved.
   The second aspect is the customizing/alignment of differing descriptions of the two communicating systems by using the CG in order to harmonize between parts of ontologies from both systems. In other words, an attempt is made to identify and analyze potential correspondences between what system A can send and what system B can receive. The result of ontology alignment operations is used to define the transformation that must be performed on the information to make the recipient able to interpret the contents in a semantically correct way.

3. The *Operational phase* (done in runtime) shall transform data messages in accordance with the explicit translation instructions generated by the ontology alignment operations.
   It is the only online phase from a military perspective where the configuration is completed and the SI tasks are executed with the support of SILF realizing the data exchanges between the involved systems.
   Here the application of translation rules takes place based on the instructions created in phase 2. This step is about transforming the message that SILF receives from system A and deliver the result to system B.

4. The last phase, *Post-Operation*, (done offline) is mostly about analysis and evaluation of the results to be able to propose improvements for future uses.

The above operational workflow of SILF is a description from an information system perspective which mainly explains the inner life cycle of SILF. In which order and how SILF succeeds to do its job has been in focus here. Viewed as a system in use from a military perspective, SILF life cycle consists of four phases *Preparation, Configuration, Operation,* and *Post-Operation*.
These four phases are exhaustively described in [IST 075].

3.5 Open issues

Given the SILF and SIDEP ideas above, there are several issues which require further investigation (in general, e.g.):

- It is not clear if the interoperability of ontologies also guarantees the interoperability of systems which use those ontologies – this also requires further investigation.

- We need to identify what other components (methods, algorithms, tools, languages, inference engines, etc.) would be needed within the framework to facilitate the interoperability between C2I systems.

- The *interoperability between two ontologies* is different from *ontology-based interoperability between two C2I* (or any information) systems.
- For interoperability between two C2I systems using ontologies, we have several open issues, such as how to extract the relevant information, how to exchange, etc. Thus a closer analysis or a proof of concept case study is required and justified.
- For interoperability between ontologies, we could make use of available methods, tools, algorithms to create, map, align, dynamically manipulate, maintain and version ontologies.
- What are the limitations of knowledge based methods/ontologies and how to identify them?
- For which kind of applications does it makes sense to use knowledge based systems?

Finally, to provide a more balanced judgment we also have to do self-criticism investigations e.g.:

- How is/appears SILF compared to existing "frameworks"?
- What other “frameworks" already exists?
- Why they do not last out?
- How does SILF differ from them?
- What are the specific advantages SILF offers?
- What kind of Framework is SILF?

4 Literature

[Gruber] Gruber, T. R. (1991). The Role of Common Ontology in Achieving Shareable, Reusable Knowledge Bases. Principles of Knowledge Representation and Reasoning: Proceedings of the Second International Conference, San Mateo, Morgan Kaufmann, 1991.

[W3C] http://www.w3.org/

[IST-075] Final Report of Task Group IST-075, NATO Research and Technology Organisation, RTO-TR-IST-075 AC/323(IST-075) TP/315, July 2010

[LISI] Levels of Information Systems Interoperability, C4ISR Architecture Framework Version 2.0, C4ISR Architectures Working Group Final Report, 30 MAR 1998.

[LCIM] Tolk, A. and Muguira, J.A. (2003). The Levels of Conceptual Interoperability Model (LCIM). Proceedings IEEE Fall Simulation Interoperability Workshop

[ERCIM] Solvberg, Hakkarainen, Brasethvik, Su, Matskin and Strasunskas at the European Research Consortium for Informatics and Mathematics, http://www.ercim.org

[IEEE90] IEEE Standard Computer Dictionary: A Compilation of IEEE Standard Computer Glossaries. New York, NY: 1990

[DACS] US DoD – The Data & Analysis Center for Software http://www.thedacs.com/databases/url/key/42

[WIKISI] Semantic interoperability http://en.wikipedia.org/wiki/Semantic_interoperability

[RTO] NATO's Research & Technology Organization http://www.nato.int/structur/rto/rto.htm