Bridging Semantic Interoperability Gaps with SILF

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***Abstract*— Information exchange among coalition command and control (C2) systems in network-enabled environments requires ensuring that each recipient system understands and interprets messages exactly as the source system intended. The Semantic Interoperability Logical Framework (SILF) aims at meeting NATO's needs for semantically correct interoperability between C2 systems, as well as the need to adapt quickly to new missions and new combinations of coalition partners and systems. This paper presents an overview of the SILF framework and performs a detailed analysis of a case study for implementing SILF in a real-world military scenario.**

Keywords: ***Semantic interoperability, mediation, knowledge representation, C2 systems, ontologies***

I. Introduction and Motivation

The term "interoperability" has many definitions. A CMU report on System of Systems Interoperability (SOSI) [1] defines interoperability as "the ability of a set of communicating entities to (1) exchange specified state data and (2) operate on that state data according to specified, agreed-upon, operational semantics." According to an IEEE standard, "Interoperability is the ability of two or more systems or components to exchange information and to use the information that has been exchanged" [2]. The need for semantic interoperability has always existed in the military context. However, with the advent of automated command and control (C2) systems and the reliance on machine-readable information, semantic interoperability has become an even more important issue. Given the number of C2 systems involved in a coalition operation and the amount of information being shared, the use of liaison officers and domain experts to assist with manual interpretation and mediation tasks, which is one of the current solutions, is not a viable option when operating in accordance with the principles outlined in Connected Forces Initiative and Smart Defence.

One example of a semantic gap between military systems and units goes back to the Operation Desert Storm in 1991 [3]. In Desert Storm, an aerial observer located an enemy unit and transmitted a message with a bombing request to the supporting artillery headquarters. The artillery headquarters had forwarded the enemy location's coordinates to a Navy ship, which fired two rounds, but both missed the target by 527 meters, a distance much greater than the expected precision. It turned out that the target was missed, because the aerial observer and the artillery headquarters were using a different geo-coordinate system from the Navy and none of them was aware of this fact when processing the target location message.

A more tragic result of a semantic gap took place in the Operation Bramble Bush [4], which was an Israeli plan to assassinate the Iraqi dictator Saddam Hussein in 1992. The details of the incident were described in 2003 by the newspaper Yedioth Ahronoth and the Ynet news website [5]. The final rehearsal for the operation was supposed to include a dry run and a firing exercise. However, the same code word was set for launching an imaginary and a real missile in both stages of the rehearsal. Due to a confusion between the two stages, the code word sent by the observation post was misinterpreted by the commando unit, which fired two live rounds into the convoy simulating the target, killing five of their fellow commandos and wounding six more.

Interoperability can be defined at various levels. In [2], seven interoperability levels are presented under the framework of the Levels of Conceptual Interoperability Model (LCIM), ranging from Level 0 (No Interoperability) to Level 6 (Conceptual Interoperability). At Level 3 (Semantic Interoperability), the interoperating systems should be able to exchange a set of terms that they can semantically parse. Figure 1 shows the five interoperability levels defined in the Position Paper on Framework for Semantic Interoperability (SILF) [6]. It starts at the bottom with network connectivity and communication protocol levels. However, even if we have no network connectivity issues and we exchange messages using exactly same language syntax we may easily fail with information interpretation. This is where we move to the upper interoperability level. At the higher levels, we build our interoperability definition by adjusting the IEEE definition [2] to the military context in the era of an increasingly automated world. We define Semantic Interoperability as the ability of two or more computerized systems to exchange information for a specific task and have the meaning of that information accurately and automatically interpreted by the receiving system, in light of the task to be performed [7].

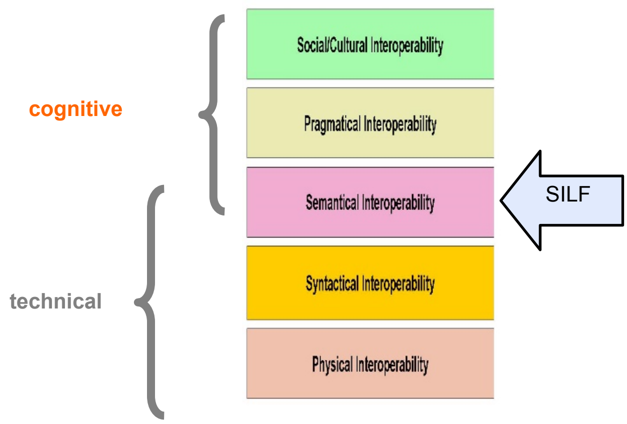

Figure 1. Levels of Interoperability [6]

Automated and accurate interpretation by the receiving system may be possible when the sender will expose its data and knowledge in an explicit manner. Ontologies seem to be a promising way of a formal specification of system knowledge. They allow constructing "smart" exchange messages that will be automatically interpreted by the receiving system. By "smart" messages, we mean messages where data elements are linked to ontological concepts (of system A and B, respectively). Before automated interpretation can take place, correspondences between the ontologies have to be defined. Such correspondences have the form of language-to-language mappings (if different ontology languages are used) or term-to-term mappings (if the ontology languages are the same but domain terms are named differently). In some cases, where the models of both A and B differ in terms of the scope or granularity of the covered domains, model transformations may be required. The SILF framework covers both aspects, mapping and transformation, which are included as part of mediation/translation rules.

NATO's Research and Technology Group IST-119 – RTG-059 (Maturing & Validation of SILF - Feasibility Study) started its activity in January 2013 for a period of three years (2013-2015). Its objectives include extending existing implementations of SILF to address a representative range of realistic use cases and evaluating SILF using a range of scientific and operational criteria. The group includes the representatives of the following nations: Germany, Israel, Norway, Poland, Spain, Sweden, Turkey, and USA. The Group Chair is Prof. Mark Last from Israel.

II. Overview of SILF and SIDEP

A. *SILF - Semantic Interoperability Logical Framework*

In order to ensure semantic interoperability between heterogeneous systems, an architecture is needed which includes a set of common ontologies between communicating parties. Such models are always implied by actors who exchange messages (otherwise communication is impossible), but in this architecture they are made explicit. This allows each message between communicating parties to be provided with references to one or more of the ontologies required for interpreting that message. SILF, initially introduced in [8] is a high-level view of such an architecture that supports semantic interoperability among heterogeneous information systems.

If each military system (that could ever be used in a Net Enabled coalition system-of-systems mash up) was engineered to work harmoniously with all other military systems, no matter in what combination or for what purpose, there would be no need for SILF. However, this Utopian situation will never be realized: individual systems are designed, implemented and acquired individually and asynchronously. Regardless of best intentions to satisfy relevant standards, budget and schedule imperatives guarantee that there will never be a situation where all such systems employ identical semantics and provide best attainable qualities of service. Furthermore, more demanding use cases that arise after standards have been compiled and the systems have been built may also lead to problematic situations. So in the real world, there will always be potential semantic mismatches that might or might not lead to operational failures. SILF is intended to provide a modicum of adaptability (that would not otherwise be present) to identify the problematic situations and, if feasible, provide a "shim" that temporarily fixes the problem for a specific enactment.

In terms of software architecture, SILF may be implemented as a middleware that provides interoperability in a communication medium and not as part of the communicating systems. SILF applies means of knowledge-based systems, using ontologies, for mediation purposes. SILF may be a single middleware separate from the communicating systems or it may consist of multiple middleware elements if common ground ontologies and mediators are distributed across the network. The SILF mediator elements may be attached to each communicating system (as an adapting layer) and in this setting, no physical and separate middleware exists. Summarizing, SILF is a framework, which can be implemented in multiple settings.

As we will try to keep our description of SILF as a concept to the level that is adequate to understand the rest of this paper, the interested reader who seeks for deeper details is referred to the Final Report of the NATO task group [7].

B. Assumptions and Conditions

The application of SILF assumes that the lower levels of interoperability have already been achieved between the systems in question. 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, however SILF enables syntax to syntax mapping as well). It also assumes that semantic descriptions of the systems can be obtained in some way. These descriptions can more or less automatically be (partially) derived from the systems metadata, but in order to achieve the necessary quality of the descriptions the process normally requires human intervention.

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

C. Main components and functions

The basic idea of SILF is to foster the use of semantic descriptions of all of the information to be exchanged between communicating systems and then to take advantage of a number of existing and emerging semantic technologies, mainly ontologies, to improve interoperability. Figure 2 shows an overall view of SILF-enabled mediation for a case of two different information systems (A and B), which need to exchange information without necessarily knowing each other’s semantics. This means, for example, that to make the communicated information correctly interpreted by system B, a mapping and transformation is required for all information that system A communicates. A number of ontology operations take place in order to define and produce the rules necessary for these transformations. Input to these ontology operations and transformations are not only semantic descriptions of systems A and B, but also references to potentially shared concepts and definitions, which will exist in the "Common Ground" (CG) (see Fig. 2).

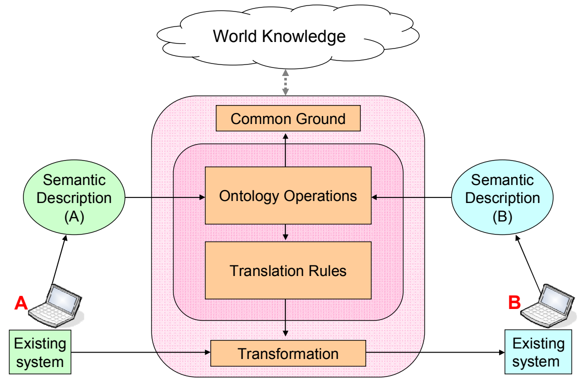

Figure 2. An overall view of SILF

The main purpose of *Common Ground* (CG) is to provide knowledge resources that will serve as 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 "the world knowledge", 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 SILF ontological activities. An ontology manager within SILF provides services for *ontology operations* that identify similar concepts across ontologies and accordingly match and align ontologies automatically rather than relying on current handcrafted solutions. *Translation rules* are the output of the mappings between concepts in systems A and B ontologies, their Semantic Descriptions and the Common Ground. *Transformation* is used to convert a message from a form, communicated by system A into a form, which can be interpreted correctly by the receiving system B.

The purpose of Common Ground is to provide shared and reusable resources that will allow SILF to set up multiple interoperability channels (A-B, A-C, C-D,..., etc.) within one operation. The CG will reduce the number of required mappings. The existing example may be MIP JC3IEDM model used as a hub model between national C2 models. However, MIP is not yet formalized in the form of ontology (that may be the future work). The example brokerage with use of common resources is also discussed in [9].

The major functionality of SILF is to facilitate the exchange of messages (information) by the help of the above-described components. The information exchange is orchestrated into a number of stages, which we have defined as the life-cycle process of SILF, namely Semantic Interoperability Development and Execution Process (SIDEP) and which is briefly described in the next sub-section.

D. SIDEP - Semantic Interoperability Development and Execution Process

We have designed SIDEP as the process of preparing and executing a semantic interoperability task between two or more C2 systems.

SIDEP guides the life cycle of a semantic interoperability task initiated by a task initiator and involving at least two actors (systems). The process consists of the following four phases: Preparation, Configuration, Operation and Post-Operation. Every phase is a distinct sub-process, having a strict position in the phase sequence. Every phase includes one or more activities, which are executed in a given order. We assume the activities to be implemented as the services of SILF. A service can be internal to SILF, or external, when consumed by an actor participating in a semantic interoperability task. Every service has input and/or output, which capture acquired and produced artefacts, respectively.

In Fig. 3, the four major SIDEP phases are depicted, together with the activities included in each stage.

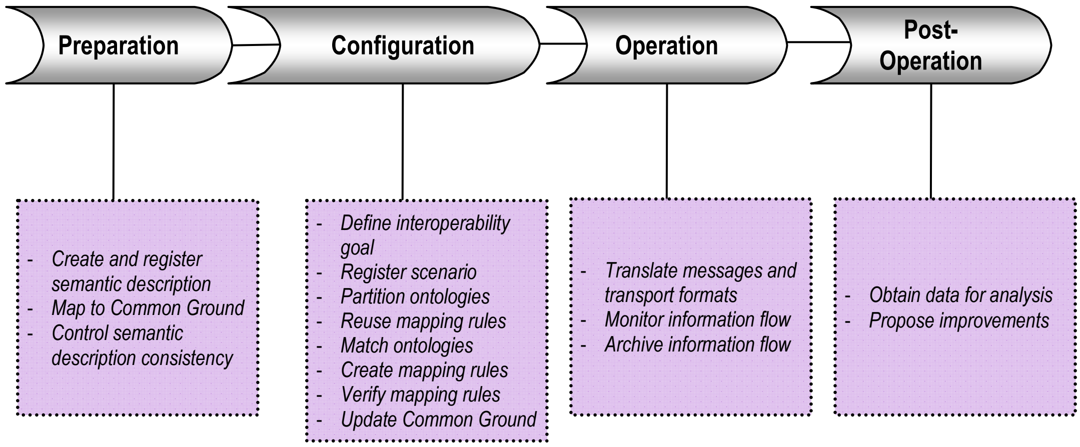

Figure 3. SIDEP phases and activities.

The Preparation is an "off-line" phase, where the military organizations accommodate their system by new capabilities required for knowledge-based semantic interoperability according to SILF. When a certain military operation and its goal have been specified, the Configuration phase will start to harmonize the semantic descriptions of the heterogeneous participating systems in the operation. The Operation phase is the only online phase from a military perspective where the configuration is completed and the SI (semantic interoperability) tasks are executed with the support of SILF realizing the message exchanges between the involved systems. The last phase, Post-Operation, deals with analysis and evaluation of the results aimed at proposing improvements for future uses. For more details on the objectives of each phase, please refer to [10].

III. The DCAS (Digital Close Air Support) Case Study

This section illustrates the application of SILF principles and methods to a Digital Close Air Support (DCAS) task. A working demonstration example was implemented by applying the ONISTT ontologies and reasoning engine [11] [12] to the semantic context and content of communication exchanges between the FAC (Forward Air Controller) and the CAS (Close Air Support) aircraft. The example shows application of SILF to preparatory and operational phases as follows:

1. An ontology of tasks, messages, tactical equipment capabilities, physical properties of the operational environment, and the like, expressed in a formal language that a computer can understand and reason over.
2. Discovery of a possible semantic gap between sender and receiver, i.e., they may exchange the same message type, but they may differ in their semantic understanding of the contents in the DCAS context.
3. Ranking of alternative interoperability solutions, for example, using a SILF mediator.
4. Implementation of mediation rules, including English explanation of rule execution traces to verify the rules are correct.
5. Application of mediation rules to translate messages between systems to ensure a semantic match sufficient to meet the goals of the DCAS mission.

This section is neither complete nor canonical with respect to applying SILF ontologies and functions. It presumes only to illustrate several aspects of a possible approach.

A. DCAS Task Description

Task Event No.	Description
1	Scout detects hostile targets that endanger tactical unit
2	Scout notifies tactical unit commander
3	Tactical unit commander passes CAS request to TACP
4a	TACP passes CAS request to ASOC
4b	TACP alerts FAC
5a	ASOC coordinates with senior ground HQ
5b	Senior ground HQ approves CAS request
6a	ASOC assigns on-call aircraft
6b	ASOC provides CAS aircraft info to TACP
6c	TACP passes CAS aircraft info to FAC
7a	FAC determines target coordinates
7b	FAC sends 9-line brief to CAS aircraft
8	CAS aircraft on-station report
9	CAS aircraft depart initial point (IP)
10	FAC terminal control of CAS aircraft
11	CAS aircraft deliver bombs on target

TACP = Tactical Air Control Party
ASOC = Air Support Operations Center
FAC = Forward Air Controller

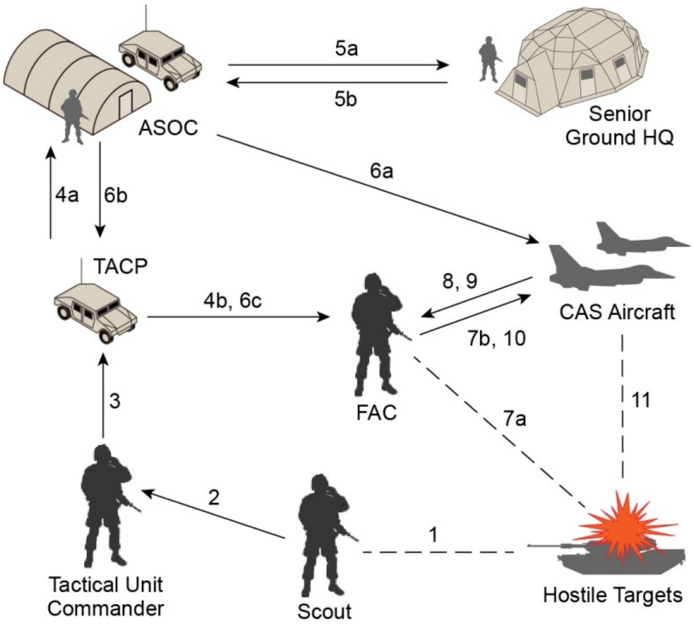

Figure 4. CAS

The DCAS event flow is shown in Figure 4. In voice-based CAS, Communication Event number 7b, the FAC sends a 9-line brief to the CAS Aircraft. Digital CAS replaces the voice 9-line briefing with a VMF (Variable Message Format) Type K02.33 message. The purpose of this message is to provide all essential information for conducting a CAS mission.

B. Task-oriented Interoperability Analysis

Within the K02.33 message, there are 26 individual fields (or field-groups), and the syntax for each field/field-group is well defined. The precise semantics for these fields/field-groups is less well defined, but in most cases it probably does not matter – any semantic gap that might exist between the FAC's information-originating equipment and the aircraft's information-consuming equipment would not likely cause a serious problem.

However, with the increasing use of small precision guided munitions (PGMs) to conduct "surgical" CAS in urban environments (where there is a very small margin for error), the exact meaning of the field that conveys the target location becomes crucially important.

Although the K02.33 message allocates a sufficient number of bits allocated to Latitude, Longitude, and Elevation data elements to permit precise targeting [1] (if the actual measurement accuracies provided by the equipment being used was commensurate with the information) the semantics are ambiguous. The VMF Data Element Dictionary simply states that latitude/longitude (LAT/LON) coordinates shall be "in accordance with the WGS-84 datum." The elevation is defined as "the vertical distance of a point or level, on, or affixed to, the surface of the earth measured from mean sea level, in feet." These definitions may appear to be sufficiently precise, but in actuality they are not – they allow the developers of the targeting equipment used by the FAC and the PGM guidance equipment used by the CAS aircraft to adopt *slightly* different interpretations of what the information in those fields really means (yet both being compliant with the specification) – thereby creating a semantic gap between the data originator and the data consumer. Those different interpretations could then result in catastrophic consequences when executing an urban CAS task that expects the PGM to be delivered within a few tens of centimetres from the target location.

C. Mediation Resources Related to DCAS – Preparation Phase

To exploit this insight into the exchanged information properties required for successful task execution, the following items are needed:

(a) A formal representation of the exchanged information objects – expressed in a way that is machine-understandable.

For this example, the VMF messages that are used in DCAS for information exchange have been expressed using the Web Ontology Language (OWL). The definition of track report messages includes time-space-position-information (TSPI).

(b) A formal representation of the native semantic understanding of those exchanged information objects for both the producer and consumer (also expressed in a way that is machine-understandable).

One of the properties of TSPI is its "spatial reference frame" (SRF), which specifies how the position information is related to the surface of the earth. The SRF ontology that was

[1] The least significant bit (LSB) for the latitude and longitude fields represents an increment of 9 mm, and the LSB of the elevation field represents an increment of 1 foot.

used in the example defines properties of 3D SRFs such as "vertical offset surface" (VOS). SRF information is seldom included explicitly in messages, but may be identified in metadata about the messages. Since SRF information is sometimes absent, incomplete, or ambiguous in standard documentation, an important objective of any TSPI-related SILF ontology is to ensure that all necessary metadata such as VOS is provided.

(c) A formal representation of the native pragmatic capabilities of the producer (in creating the exchanged information objects) and the consumer (in using the exchanged information objects).

An important attribute of TSPI data is its accuracy. The example ontology captures the target location measurement equipment uncertainty value (U_{TL}) for each equipment grade category employed by FACs (e.g., 2.1 m for primary grade, 5 m for secondary grade, and 10 m for Tertiary grade).

The success of a DCAS mission is also affected by the uncertainty in the ability of the PGM's guidance equipment to manoeuvre the ordnance to the specified target location coordinates (U_{MG}). The example uses hypothetical (but representative) uncertainty values for three levels of munition guidance equipment (i.e., 1.7 m for primary grade, 3.1 m for secondary grade, and 4.7 m for tertiary grade).

If message source and recipient use different VOS geoids, semantic mediation is required, which may leave residual TSPI uncertainty, or introduce additional uncertainty. The semantic mediation uncertainty (U_{SM}) depends on the particular geoid pair and the geographic location. In the example, mediation from a WGS 1984/EGM84 Geoid to a WGS 1984/EGM2008 resulted in 0.9 m in Kandahar and 6.4 m in Peshawar.

(d) A collection of rules (also expressed in a machine-understandable form) that provide constraints to quantify how large a semantic gap may be tolerated by the task (and/or rules for computing such constraints from knowledge artefacts captured using the representation tools from above).

The desired operational effect of the DCAS task is the elimination of the threat forces – subject to the constraint that friendly forces and neutral persons and property not be damaged. If the operation being planned entails a possibility of requiring DCAS in an urban setting using PGMs, that fact would be associated with a need for a high degree of accuracy in the end-state: delivery of the ordnance to the precise location of the target. The example defined a hypothetical maximum uncertainty that can be tolerated for CAS in urban, suburban, and rural regions. We call this a Combined Uncertainty (U_C) because it is composed of multiple contributing sources of uncertainty.

The potential sources of error that would result in failure to reach that end-state can be decomposed into the three main components described above (U_{TL}, U_{SM}, and U_{MG}) [2]. Since these three sources of uncertainty are clearly uncorrelated, it is valid[3] to combine them into an overall combined uncertainty (U_C) using the *law of propagation of uncertainty* (in common parlance the "root-sum-of-squares" [square root of the sum-of-the-squares] or "RSS" method of combining uncertainty components estimated as standard deviations):

$$(U_C)^2 = (U_{TL})^2 + (U_{SM})^2 + (U_{MG})^2$$

This RSS relation is one of the rules that is captured in a machine-understandable representation as in the example. The actual values for the parameters U_{TL}, U_{SM}, and U_{MG} are made available to the reasoning analysis engine from the knowledge Bases (KBs) that use the formal representation schemes mentioned in (c) above. A constraint compares total uncertainty with the specified maximum allowed uncertainty for the task.

In the SILF proof of concept implementation, rules were developed using Sunflower Studio [13]. Sunflower Studio is an IDE designed for rapid creation and validation of complex systems of rules and ontologies. Sunflower uses the Flora logic language, which is more expressive than OWL or SWRL. It can import OWL ontologies and SWRL rules and translate them to OWL. It can import data from spreadsheets, SQL databases, and X ML. It can export ontologies to OWL and reasoning result data to XML. Tools include text and graphical editors, semantically enabled search of knowledge bases (including rules, ontologies, and instance data), reasoning over rules and knowledge bases, and explanation of reasoning results in English, Flora, and graphical representations.

(e) A formal representation of the task as depicted in Figure 4, including communication need lines, interactions between NATO forces and the target, and implied support infrastructure such as networks,

The example DCAS task definition includes subtasks for measuring target location (task event 7a), sending TSPI information (task event 7b) and for use of TSPI by the guided munition flyout (task event 11).

D. *Mediation Resources Related to DCAS – Force Configuration Phase*

This subsection describes examples of KBs and rules related to DCAS that may be used primarily in the Configuration Phase to support the ontology subsetting, mapping, and rule generation functions.

(f) A formal representation of the task configuration of a particular operational deployment, including actual or

[2] There is an important observation that should be noted here: the operational constraint that is derived from the task objective is not solely related to the magnitude of the semantic gap (this is the typical situation). Instead, the error component due to the semantic gap is confounded with other factors that may not be known until the time of task execution. This complicates the SILF job, but not beyond the realm of reasonable implementation.

[3] Per the procedures identified in Appendix E of the document ***Evaluation of measurement data — Guide to the expression of uncertainty in measurement***, JCGM 100:2008, Joint Committee for Guides in Metrology, September 2008 (a 1993 version of this document was published as an ISO standard)

potential assignment of particular forces to task roles and other information such as geographical location and available networks.

The selected area of operation was in the vicinity of Peshawar, Pakistan, which has relatively challenging conditions for VOS differences (e.g., ellipsoid to EGM 96 geoid. The Peshawar lat/lon location was assigned as a task parameter.

(g) *Software that implements a reasoning analysis engine function and determines if the properties associated with the information objects being exchanged by the candidate role players can satisfy the constraints, given the native semantic understandings of the producer and the consumer.*

For the proof of concept demonstration, KBs for three FAC target designation kits, three CAS aircraft/guided munitions, and two semantic mediator candidates were created The capabilities of their DCAS-related systems covered the range of uncertainty values for each of the parameters described above in (d).

The SILF analysis engine uses the task definition (as illustrated in item (e) above) to identify the subsets of the ontologies and KBs that are relevant for each communication exchange. Omission of required information in any of the KBs will be reflected in analysis engine results, for example, by issuing a warning or disqualifying a system for a particular role in a mission task.

Another parameter defines task constraints for the maximum total uncertainties allowable for urban, suburban, and open country DCAS operations.

The analysis engine determined that the total TSPI uncertainty of one of the FAC and CAS Aircraft pairings is 2.7 m, which in this example is sufficiently accurate to perform DCAS in any setting without need for SILF mediation to guard against collateral damage.

(h) *Software that implements a reasoning synthesis engine function and determines if gaps identified in (f) above can be bridged by use of a mediation engine function interposed between the information producer and the information consumer, and then creates the necessary translation rules to effect that bridging.*

The 46.9 m uncertainty of the TSPI exchanged between a second pair of FAC and CAS Aircraft in is inadequate for DCAS in any setting without SILF mediation. The combined uncertainty is mostly due to the difference between the EGM 96 geoid applied by the FAC and the WGS 84 ellipsoid assumed by the CAS Aircraft.

However, when a particular SILF mediator service interposed between the same FAC and CAS Aircraft pair reduced the geoid mismatch is by the mediator to 0.5 m. Because the combined uncertainty of 5.9 m is greater than 5.0 m but less than 7.0, collateral damage is still possible in urban and suburban settings, but rural DCAS cannot be supported.

Table I shows the constituent input and output values for the three cases described above. Table II shows results for all 27 possible combinations of FAC kit, CAS aircraft/PGM, and SILF geoid mediator roles, including qualification of the combination of resources for DCAS in urban, suburban, and rural settings.

TABLE I. SUMMARY OF UNCERTAINTY COMPUTATION FOR REPRESENTATIVE SYSTEM AND RESOURCE COMBINATIONS

FAC Num	**FAC TL & Geoid Values**	**CAS Air Num**	**CAS Air TG & Geoid Values**	**Geoid Mediator**	**U_{TL} (m)**	**U_{Vert} (m)**	**U_{MG} (m)**	**U_C (m)**
1	TL-Primary EGM 96	1	TG-Primary EGM 96	-	2.1	0.0	1.7	2.7
2	TL-Secondary EGM 96	2	TG-Secondary WGS 84 Ellipsoid	none	5	46.6	3.1	47.0
2	TL-Secondary EGM 96	2	TG-Secondary WGS 84 Ellipsoid	GeoidEval Mediator-1	5	0.5	3.1	6.0

(i) *Software that implements the mediation execution engine function mentioned above, capable of being tailored to a specific job by the translation rules produced by the reasoning synthesis engine.*

The proof of concept implementation includes some of the mediation rules needed to reduce the semantic gaps in messages sent between sample pairs of DCAS systems. For example, two of the candidate entities assigned to DCAS roles use different TSPI message types and VOSs. The ontologies, originally created using OWL, were translated to Flora and enhanced in the Sunflower Studio environment. Similarly, some of the interoperability analysis and mediation rules were originally created using SWRL, then translated to Flora and expanded.

A runtime mediation engine was written in Flora and implemented in the Sunflower Studio environment. The mediation includes the following steps:

- Receive and decode position location messages exchanged using heterogeneous message types, namely NATO Friendly Force Information (NFFI) and Distributed Interactive Simulation (DIS) messages in XML format.
- Translate message contents to a standard semantic representation. The messages are mapped to SILF ontologies for position, velocity, time, and entity identification. The message translation is performed by Flora rules. The rules that convert between geodetic and geocentric spatial reference frames include a procedural attachment that calls Synthetic Environment Data Representation and Interchange Specification (SEDRIS) software to perform part of the calculation.
- Output messages with correct semantic and syntactic translation to DIS and NFFI XML format.

IV. Discussion and Lessons Learned

When we connect two large systems, the mapping task becomes a significant problem. We may have hundreds of translation rules. In the legacy approach, mapping rules reside either in various parts of system code or, what is more problematic, in programmers' heads. Very often assumptions are not explicated neither in documentation nor in system code. In the legacy approach, quality may be negatively affected by the large number and complexity of hand-crafted mappings and translation rules. The consistency of the mappings is typically validated by conducting a limited number of test cases, which do not cover a larger spectrum of situations. Even if in the legacy approach mappings reside in system-to-system brokers, they are based on low formalized languages e.g. XML, and do not support automation sufficiently. In the SILF approach, on the other hand, consistency checking is automated by formalizing mappings rules and running consistency checking mechanisms. This is especially useful when re-validation of integration is needed after updates happen to schemas of one of the systems or there are changes in task parameters. SILF facilitates reuse of components in various tasks/scenarios.

Maintaining the translation rules in the absence of explicit semantics is hard and expensive, since it requires an extensive amount of experts work. When expert changes and updates are required, revisiting mapping rules is problematic and validation error prone. With introduction of new systems or tasks, existing rules cannot be easily reused since they were written for a particular ad-hoc interaction. Via using ontologies, SILF facilitates building layered interoperability, by defining some rules on the general level and specializing them for particular tasks. Such an approach facilitates reuse and allows for setting up communities of interest, which extend domain models with additional attributes for specific purposes. Nowadays, in the era of NNEC, systems face faster evolution (task and schema changes) and process large volumes of data. SILF proposes a framework for managing mapping rules in a dynamic environment.

For military operations, information superiority is paramount and within a coalition, semantic interoperability in a timely fashion plays a major role. Automatic means to transfer knowledge have been explored over a number of years with varying degrees of success. The main issue is to derive inference from raw or processed data, which is highly context sensitive.

SILF is a sophisticated framework for guiding future coalition operations to accomplish their intended objectives by avoiding semantic interoperability problems. To achieve this, an integrated approach was developed (and critical aspects were prototyped) for representing: (a) operational knowledge characterizing the precise semantics employed within various national instantiations of combat systems (C3, ISR, weapons, etc.), and (b) the individual performance thresholds necessary to achieve the intended operational effects in the execution of a military task by a networked system-of-systems (SoS). The knowledge artefacts created for (a) and (b) have been demonstrated to be capable of supporting discovery (by a software reasoning engine) of semantic gaps among the SoS component systems that could defeat the intended objectives.

The semantic interoperability problem is mathematically hard, but if ontologies are invoked, the mapping effort is linear in the number of communicating systems compared to the quadratic complexity with bilateral ad hoc mediation. The introduction of the innovative SILF-element – mediation resources (“common ground”) – provides reusable algorithms, nested ontologies, references, mappings and possibly already implemented mediation solutions and thus promises decreasing effort for each further appearing mediation. Multiple developments are avoided and the stability of existing and maintained components will increase. The framework allows the transfer of solutions but also the flexibility to deviate if necessary.

SILF does not reinvent the wheel. The core of the advancement is the result of the innovative orchestration and adaption of existing technologies, concepts and approaches in a well-considered framework. By means of semantic technologies, possible semantic mismatches in heterogeneous

IT-systems can be discovered and solutions for the bridging of sematic gaps can be established. SILF increases the degree of interoperability above the syntactical and technical level and thus improves the validity of decisions basing on data exchanged in a coalition.

In times of shrinking defence budgets and in the light of Smart Defence and the Connected Forces Initiative, intensive collaboration between nations and the systems they provide is an essential aspect of all future Alliance operations. Connecting diverse C4IS systems comes with many interoperability challenges, and although some of these can be addressed through technical standardization, semantic interoperability – understanding concepts in the same way – remains a difficult issue. With the focus on coalition operations and the involvement of partner nations, semantic interoperability will become an even greater challenge.

Smart Defence and modern Cloud Computing technologies will increase the number of smaller systems with specific properties that have to be integrated. Lengthy development phases for interoperability solutions are unacceptable in that context. SILF aims at a use in a context of quickly changing system architecture, where partners change and shorter innovation cycles bring up new IT-components (e.g. APPs). Furthermore, SILF can provide the assurance of a successful operational result without requiring expensive changes in the existing systems. Hence, it is also applicable to legacy systems.

By means of SILF, the probability of semantic mismatches decreases and thus the quality of decisions increases. SILF's concept for 'mediation resources' helps to shorten the preparation phase before engagements due to the utilization of already existing interoperability concepts. Modifying the software in all national systems (that could potentially be used in a coalition SoS event) to use representations having precisely the same semantics for all parameters that might cause interoperability problems is a hopelessly expensive, unscalable, and unachievable notion. SILF provides a pragmatic alternative, where only those parameters that are crucial to the success of a specific task in a specific context are dealt with – and then only to the extent necessary to achieve a "good enough" match.

It is recognised that it is difficult for the automatic process to hold sufficient information to be aware of the environment and hence apply the appropriate logic. Not all mediation is possible and the users must be informed of the caveats associated with the output together with a measure of confidence. SILF also helps to clarify the limitations of interoperability.

V. Conclusions

NATO operations are, by their very nature, coalition operations including various coalition partners with their respective C2 systems. As NATO moves towards using the smart defence paradigm in order to attain decision superiority, there is a need for extensive information exchange between the coalition partners. Experience tells us that information sharing involving various C2 systems will lead to semantic interoperability challenges, thus a solution to this problem is important for future coalition operations.

SILF is a framework that addresses these challenges. By applying knowledge-based techniques, SILF provides support to (a) determine possible semantic gaps in the planned information exchange between C2 systems, (b) determine if in-line mediation can adequately close the gaps, (c) configure an automatic mediator to perform the necessary mediation, thus avoiding the need for changing the C2 systems, and (d) operate the mediator during the execution of military operations.

SILF can be integrated with MIP / MIM (MIP Information Model) / NIEM (National Information Exchange Model) by enhancing MIP / MIM / NIEM with the SILF approach. Alternatively, MIP, MIM, and NIEM can be used as information sources for SILF (e.g., semantic descriptions of communicating systems for the Common Ground). It is known that these models are large, and may cause problems with ontology-based mediation. The computational complexity issues, which may arise during the SILF online phase in these cases, will need to be identified and handled, case by case, in preparation and configuration phases.

The use of SILF is expected to provide an easier path for achieving semantic interoperability between C2 systems, and thus a more reliable, fast, and scalable support of a coalition mission.

References

[1] E. Morris, L. Levine, C. Meyers, P. Place and D. Plakosh, "System of Systems Interoperability (SOSI): final report (No. CMU/SEI-2004-TR-004)," Carnegie Mellon University, Software Engineering Institute, Pittsburg, PA, USA, 2004.

[2] IEEE, "IEEE standard for modeling and simulation (M&S) high level architecture (HLA)-object model template (OMT) specification," IEEE, 2000.

[3] H. Zhu and L. Fu, "Quality of data standards: Empirical findings from XBRL," in Proceedings of the International Conference on Information Systems (ICIS), Phoenix, AZ, USA, 2009.

[4] Wikipedia, "Operation Bramble Bush," [Online]. Available: http://en.wikipedia.org/wiki/Operation_Bramble_Bush. [Accessed 07 12 2014].

[5] R. Bergman, "Ynet," [Online]. Available: http://www.ynet.co.il/articles/0,7340,L-2842713,00.html. [Accessed 07 12 2014].

[6] IST-094, "Position Paper on Framework for Semantic Interoperability," Oslo, Norway, 2011.

[7] M. Wunder, "Framework for Semantic Interoperability," STO Technical Report AC/323(IST-094)TP/525, 2013.

[8] F. Bacchelli, A. Boury-Brisset, A. Isenor, S. Kuehne, B. Martinez Reif, J. Miles, V. Mojtahed, R. Poell, R. Rasmussen, A. Uzunali and M. Wunder, "Semantic Interoperability, RTO Scientific Report AC/323(IST-075) TP/315," 2009.

[9] D. Nogalski and A. Najgebauer, “Semantic mediation of NATO C2 systems based on JC3IEDM and NFFI ontologies,” in proceedings: NATO RTO symposium on Semantic and Domain based Interoperability, RTO-MP-IST-101, paper 17, Oslo, 2011.

[10] Mojtahed, M. Eklöf and J. Zdravkovic, “Towards Semantic Interoperability between C2 Systems Following the Principles of Distributed Simulation,” in 16th ICCRTS Conference on Collective C2 in Multinational Civil-Military Operations, 2011.

[11] R. Ford, D. Martin, D. Elenius and M. Johnson, “Ontologies and Tools for Analyzing and Composing Simulation Confederations for the Training and Testing Domains,” in Enhancing Simulation Composability and Interoperability using Conceptual/Semantic/Ontological Models, A. T. a. J. A. Miller, Ed.

[12] D. Elenius, D. Martin, R. Ford and G. Denker, “Reasoning about Resources and Hierarchical Tasks Using OWL and SWRL,” in 8th International Semantic Web Conference, 2009.

[13] G. Denker, R. Ford and S. Riehemann, “Semantics in Finance: Addressing Looming Train Wreck in Risk Management, Regulatory Compliance and Reporting,” in 10th Annual Semantic Technology and Business Conference, San Jose, California, 2014.

TABLE II. SUMMARY OF RESULTS FOR ALL SYSTEM AND RESOURCE COMBINATIONS

Num	Total Uncert	FAC	CAS Aircraft	Meas Pos Err	Guidance Uncert	Vert Off	Rural Max	Suburban Max	Urban Max	Mediator
1	2.7	FAC-1	CAS_Air-1	2.1	1.7	0	true	true	true	GeoidEvalMediator-1
2	2.7	FAC-1	CAS_Air-1	2.1	1.7	0	true	true	true	SEDRIS_Mediator-1
3	2.7	FAC-1	CAS_Air-1	2.1	1.7	0	true	true	true	
4	3.78	FAC-1	CAS_Air-2	2.1	3.1	0.5	true	true	false	GeoidEvalMediator-1
5	5.15	FAC-1	CAS_Air-3	2.1	4.7	0	true	false	false	GeoidEvalMediator-1
6	5.15	FAC-1	CAS_Air-3	2.1	4.7	0	true	false	false	SEDRIS_Mediator-1
7	5.15	FAC-1	CAS_Air-3	2.1	4.7	0	true	false	false	
8	6.86	FAC-2	CAS_Air-3	5.0	4.7	0	true	false	false	GeoidEvalMediator-1
9	6.86	FAC-2	CAS_Air-3	5.0	4.7	0	true	false	false	SEDRIS_Mediator-1
10	6.86	FAC-2	CAS_Air-3	5.0	4.7	0	true	false	false	
11	5.9	FAC-2	CAS_Air-2	5.0	3.1	0.5	true	false	false	GeoidEvalMediator-1
12	5.28	FAC-2	CAS_Air-1	5.0	1.7	0	true	false	false	GeoidEvalMediator-1
13	5.28	FAC-2	CAS_Air-1	5.0	1.7	0	true	false	false	SEDRIS_Mediator-1
14	5.28	FAC-2	CAS_Air-1	5.0	1.7	0	true	false	false	
15	45.16	FAC-1	CAS_Air-2	2.1	3.1	45	false	false	false	SEDRIS_Mediator-1
16	46.75	FAC-1	CAS_Air-2	2.1	3.1	-46.6	false	false	false	
17	45.38	FAC-2	CAS_Air-2	5.0	3.1	45	false	false	false	SEDRIS_Mediator-1
18	46.97	FAC-2	CAS_Air-2	5.0	3.1	-46.6	false	false	false	
19	11.06	FAC-3	CAS_Air-3	10.0	4.7	0.5	false	false	false	GeoidEvalMediator-1
20	46.34	FAC-3	CAS_Air-3	10.0	4.7	45	false	false	false	SEDRIS_Mediator-1
21	47.89	FAC-3	CAS_Air-3	10.0	4.7	-46.6	false	false	false	
22	10.47	FAC-3	CAS_Air-2	10.0	3.1	0	false	false	false	GeoidEvalMediator-1
23	10.47	FAC-3	CAS_Air-2	10.0	3.1	0	false	false	false	SEDRIS_Mediator-1
24	10.47	FAC-3	CAS_Air-2	10.0	3.1	0	false	false	false	
25	10.16	FAC-3	CAS_Air-1	10.0	1.7	0.5	false	false	false	GeoidEvalMediator-1
26	46.13	FAC-3	CAS_Air-1	10.0	1.7	45	false	false	false	SEDRIS_Mediator-1
27	47.69	FAC-3	CAS_Air-1	10.0	1.7	-46.6	false	false	false	