A Modeling Framework for Synchronizing Global and Local Situation Awareness

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Abstract - *A Common Operational Picture (COP) is intended to provide timely and accurate information, enabling shared situational awareness across multiple commands [1]. Building and sustaining a COP is at the center of command and control for today's complex endeavors. Whether in military defense, homeland security, or industrial facility maintenance, the problem of maintaining such a representation of the current state of the endeavor is greatly hindered by several common factors, such as the distributed nature of the enterprise, the heterogeneity of its distributed components, and the lack of interoperability of its communication systems. In this paper, we propose a conceptual framework based on modeling and simulation that intends to capture the core elements involved in maintaining a COP across the components of a complex distributed and heterogeneous enterprise.*

Keywords: DEVS, probabilistic reasoning, situational awareness, discrete event simulation, Multi-Entity Bayesian networks, probabilistic ontologies, Common Operating Picture, system entity structure.

1 Introduction

Networked systems are becoming ubiquitous across a wide array of human activities, growing ever more complex with each passing year. Complexity increases not as an end in itself, but as a side effect of success. New capabilities are implemented, new technologies are added, scope is broadened, specialization increases, larger problems are tackled -- and complexity grows. Because of complexity creep, success can be a mixed blessing. An intricate but capable system is a blessing in its ability to support complex user operations, but it can become a curse when the need arises to interoperate with other equally complex systems

IT Complexity explosion is driven by faster, cheaper computers, networking, web middleware, and others. Wherever choices are possible in choosing platform, language, line of code, etc, different developers will make different choices. The underlying structure/behavior dependencies force local decisions to have global impact breaking neat design patterns. Further, environments impose a plethora of special situations and an exponentially growing number of parameter combinations. The obvious consequences are increasingly evident signs of complexity explosion, such as proliferation of incompatible variations on same themes, ubiquitous heterogeneity, and vertical integration (Stove piping).

The response from software developers to these phenomena is the increasing adoption of Model-Driven Development Methodology, in which a model is an abstract representation of software code, that is technology independent, can survive technology changes, can be implemented in multiple code instantiations, and enables reuse and automation. One example is the wide adoption of UML [2], a framework to support model driven development promoted by the Object Management Group as a standard within its Model Driven Architecture (MDA). UML is supported by increasingly powerful commercial tools, and has already spawned enhancements such as SysML [3], which provides a requirements front end and is incorporated in architectural frameworks such as the DoDAF and MoDAF.

However, complex IT development often does not start from scratch, it is usually conditioned by idiosyncratic requirements, it is powered but not constrained by applicable standards, requires legacy system integration and rigorous testing to cope with complexity. Also, the methodology must scale with growth and evolution of system. UML/MDA can only partially address the issues of developing complex IT systems.

Our conceptual framework addresses these caveats by adopting a System-of-Systems (SoS) approach, in which collections of disparate systems are federated to satisfy new requirements. Evolution of IT systems is often toward SoS and each participating system may itself be large and complex. In this paradigm, participant systems usually have become efficient at achieving their own specialized requirements, and often adhere to idiosyncratic formalisms and development approaches. In order to deal with this, one must first understand the spectrum of interoperation and integration to set appropriate objectives.

More specifically, as pointed out by Pollock and Hodgson [4], the term interoperation is usually linked to situations in which participant systems remain autonomous and independent, are loosely coupled, their interaction rules are soft coded and encapsulated, local data vocabularies and ontologies for interpretation persist, share information via mediation, and provide asynchronous data transfer. Keywords are usually reusability, composability, and flexibility. Conversely, the term integration often implies in participants being assimilated into whole, losing autonomy and independence, tightly coupled, deal with interaction rules that are hard coded and co-dependent, have to adopt a global data vocabulary and ontology for interpretation, must share information conforming to strict standards, and include synchronous data transfer. Keywords in this case being fit-to-purpose and responsiveness. In our work we adopt the view in [4] that integration and interoperability are not polar opposites, Instead, there is a spectrum of interaction modes that must be acknowledged for any successful SoS framework.

A clear example of such spectrum is provided by the "Kill Chain" as depicted in Figure 1 below.

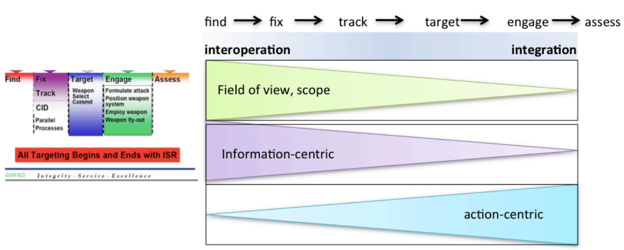

Figure 1 – The Kill Chain

As can be seen in the picture, it illustrates the co-existence of interoperation and integration modes of component interaction. Early activities in the chain are characterized by larger field of view and have more information-centric functions than do later activities. They need the loose coupling and flexibility of interoperation. Later activities are more action-centric requiring the tight coupling and responsiveness of integrated components.

Another major aspect of the framework being proposed is its coverage of all linguistic levels of information exchange: *syntax*, *semantics*, and *pragmatics*. The first is concerned with common rules governing composition and transmitting of messages, so a SoS is syntactically consistent when its participants can mutually parse their messages. The second level is related to the shared understanding of the meaning of the messages, so in an semantically consistent SoS all receiving participants assign the same meaning as the sender did to the message. Finally, pragmatics concern is on how information in messages is used and embodies a distinct dimension of knowledge that is crucial in ensuring interoperable systems. In this case, a SoS entity interoperates at this level when any given receiver participant re-acts to the message in a manner that the sender intends (assuming non-hostility in the collaboration).

The shift from the syntactic to the semantic to the pragmatic level of interoperability brings a shift from "Which format?" to "What is going on?" to "How can/should I respond?" Each level presupposes and requires the levels below it. At the syntactic level, the systems are able to interchange data; at the semantic level, they attach the same meaning to the data being interchanged; the pragmatic level, additional context or information is exchanged to enable appropriate action to be taken.

The SoS framework being presented in this work encompasses the notion of a spectrum of integration/interoperability modes, as well as all the linguistic levels of component interaction, and pragmatic frames.

This paper is structured as follows. Section 2 presents the main technologies behind our framework, while Section 3 explains our approach to merge them in a consistent fashion. In Section 4 we illustrate the SoS framework usage via a sample use case from the maritime domain. We present our conclusions in Section 4.

2 Background

There is no established scientific theory of, and no general-purpose, theory-based methodology for high-level information fusion. Therefore, our vision on how to enable high-level fusion to support the establishment of a COP relies on a multi-disciplinary approach. The component technologies underlying our approach are described below

2.1 DEVS

Discrete Event Systems Specification (DEVS) is the basis for our formal framework for modeling and simulation. It is a mathematical formalism for specifying and composing components into systems.that started from the work by Zeigler in 1976 [5]. DEVS is used to describe components across a spectrum that ranges from mathematical expressions and mathematical approximations to discrete approximations and discrete interpolation, with the discrete aspects of the DEVS spectrum executable on a digital computer. The descriptive range allows DEVS to cope with the specification of components across several levels. It exploits the separation between model, experimental frame and simulator and thus offers a standard for distributed simulation to support interoperability, composability, and reuse. DEVS also supports automated, integrated complex systems development and testing, providing an infrastructure for rigorous simulation-based Net-Centric test agent capability.

A major concept in modeling with the DEVS formalism is that of a system entity structure (SES, [6]). It is a structural knowledge representation scheme that systematically organizes a family of possible structures of a system. Such a family characterizes decomposition, coupling, and taxonomic relationships among entities [5, page 482]. As we explain later in Sections 3 and 4, in our SoS framework the interrelationship model family is comprised of a set of SES (*i.e.*, a SES base) and a library of models (*i.e.*, a model base) that capture the many possible structural relationships among the entities considered in the system. This separation between model and structure not only reduces the complexity of the system, as mentioned in [5], but also facilitates composeability and modularity in our SoS framework.

2.2 Multi-Entity Bayesian Networks

Multi-entity Bayesian Networks (MEBN) [7] is a probabilistic logic with first-order expressive power. MEBN was developed to meet the representational and computational challenges inherent in higher-level multi-source fusion and situation awareness. Specifically, MEBN can represent degrees of plausibility for any hypothesis that can be expressed in first-order logic. Its basis in directed graphical models gives it a natural representation for cause and effect relationships. Its built-in capability for context-specific independence provides a natural way to represent contextual factors important for hypothesis management, such as conditions under which a hypothesis can be pruned because it has little or no impact on conclusions of interest. MEBN also supports a natural representation for essential categories of uncertainty for general situation awareness, such as uncertainty about entity existence (*i.e.*, is a report a false alarm); uncertainty about the type of entity; and uncertainty about functional relationships (*e.g.*, which entity gave rise to a report). Its basis in Bayesian theory provides a natural theoretical framework for learning with experience. Its graphical representation supports an intuitive interface for specifying probabilistic ontologies. Finally, its modular representation formalism supports adaptability, by allowing changes to be made to parts of an ontology without affecting other parts or other ontologies, and composability, by allowing problem-specific models to be constructed "on the fly," drawing only from those resources needed for the specific problem.

MEBN represents the world as made up of entities that have attributes and are related to other entities. Knowledge about the attributes of entities and their relationships to each other is represented as a collection of MEBN fragments (MFrags) organized into MEBN Theories (MTheories). An MFrag represents a conditional probability distribution of the instances of its resident random variables (RVs) given the values of instances of their parents in the fragment graphs and given the context constraints. RVs are graphically represented in an MFrag either as resident nodes, which have distributions defined in their home fragment, or as input nodes, which have distributions defined elsewhere. Context nodes are the third type of MFrag nodes, and represent conditions assumed for definition of the local distributions. Figure 2 depicts the generic structure of an MFrag.

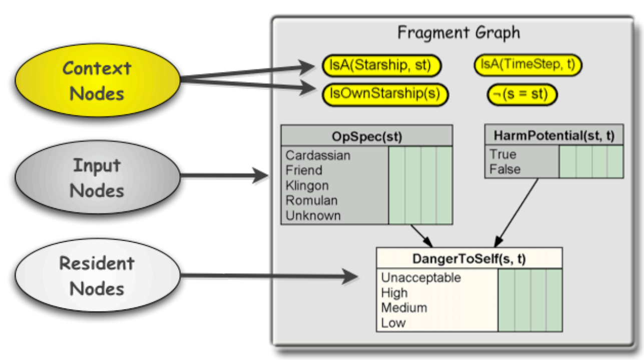

Figure 2 – The basic components of an MFrag

Typically, MFrags are small, because their main purpose is to model "small pieces" of domain knowledge that can be reused in any context that matches the context nodes. This is a very important feature of the logic for modeling complex situations — the knowledge representation version of the "divide and conquer" paradigm for decision-making. Decomposition is accomplished by modeling a complex situation as a collection of small MFrags, each representing some specific element of a more complex situation. The additional advantage of MEBN modeling is the ability to reuse these "small pieces" of knowledge, combining them in many different ways in different scenarios. A coherent collection of MFrags is called an MTheory. An MTheory represents a joint probability distribution for an unbounded, possibly infinite number of instances of its random variables. This joint distribution is specified implicitly through the local and default distributions within each MFrag, together with the conditional independence relationships implied by the fragment graphs.

2.3 Probabilistic Ontologies

Ontologies provide the "semantic glue" to enable knowledge sharing among distinct systems cooperating in data rich domains such as Predictive Analysis. An ontology specifies a controlled vocabulary for representing entities and relationships characterizing a domain. Ontologies facilitate interoperability by standardizing terminology, allow automated tools to use the stored data in a context-aware fashion, enable intelligent software agents to perform better knowledge management, and provide other benefits of formalized semantics. However, effective higher-level knowledge fusion requires reasoning under uncertainty, and traditional ontology formalisms provide no principled, standardized means to represent uncertainty. Interest is growing in combining semantic technology with probabilistic reasoning (e.g., [8-11]). Probabilistic ontologies provide a principled, structured, sharable formalism for describing knowledge about a domain and the associated uncertainty and could serve as a formal basis for representing and propagating fusion results in a distributed system.

The PR-OWL probabilistic ontology language [12-13] is founded in MEBN logic and has the expressive power to represent any first-order Bayesian theory. PR-OWL provides the representation power required for information fusion and prediction services in net-centric environments. PR-OWL ontologies interoperate with the non-probabilistic part of ontologies written in the World Wide Web Consortium's standard ontology language OWL, thus facilitating interoperability with other semantically aware systems. In this proposed research, PR-OWL is used to design a distributed high-level fusion framework that performs approximate coherent Bayesian reasoning on problems of greater complexity than previously possible. UnBBayes-MEBN [14, 15] is an open source, java-based graphical editor for PR-OWL ontologies being developed in conjunction with the University of Brasilia. Figure 3 shows the current UnBBayes-MEBN graphical interface for developing MTheories displaying an MFrag of a Maritime Operations MTheory built for the PROGNOS project [16].

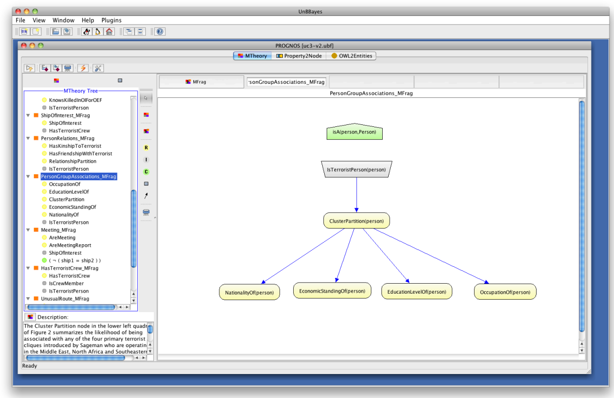

Figure 3. Snapshot of a graphical PR-OWL plugin.

2.4 Pragmatic Frames

Zeigler and Hammond define the idea behind pragmatics is that the consumer's use of the information should determine the description mechanism, or ontology, used by the producer. Then, the developer of the ontology, also called data engineer, has the task of tuning the ontology to the pragmatic frame [6].

Pragmatics is defined as the use of metadata in relation to metadata structure and context of application. In other words, pragmatics uses metadata to convey context and its relation to meaning, and pragmatic frames uses such context information to disambiguate meaning. The idea was based on Speech-Act theory [17-18] and focuses on elucidating the intent of the semantics constrained by a given context. For example, suppose that I say: "I see the plane." There is no context here to determine whether the word "plane" refers to a flat space defined by at least 3 points, an airplane, or a wood working tool, which are all valid semantic values for the word "plane." It does not make sense to examine, in detail, the low level semantics of attributes of the word "plane" when an examination of the use of the plane will obviate further examination of the details.

Pragmatic frames are a means to convey Pragmatics through an ontological framework.

Basically, they are used to delineate a data engineer's domain of interest and relate the ontology as being adequate or not to this domain. That is, an ontology supports (or is applicable to) a pragmatic frame if the world states (or state changes) that it can describe include those that are needed by the frame. Further, an ontology is minimal for a frame if it supports only that frame, not a larger one, and two ontologies are pragmatically equivalent in a pragmatic frame if there is a one-to-one correspondence of their world state descriptions such that corresponding descriptions are used in the same manner within the pragmatic frame of interest.

Pragmatic equivalence is an important concept. Even though world state descriptions generated by the ontologies may differ, the manner in which they are processed downstream leads to the same results. For example, messages sent within one ontology might not differ from those of a second except in numerical precision. Consider corresponding number strings that are the same only up to a given number of significant digits. Pragmatic equivalence holds if both strings are treated equally by downstream processors. We say that this difference is absorbed within, or modulo, the pragmatic frame. Of course, another frame may treat these strings differently, leading to pragmatic inequivalence in this frame.

Finally, pragmatic frames can address both static and dynamic situations. Static pragmatic frames focus on the comparisons to determine the degree of similarity of two frames, subtrees, or trees. Dynamic pragmatics refers to the change in state of the pragmatic frame due to a continuously occurring change of context, a discrete-time context change, or a discrete event.

3 The COP Framework

3.1 Basic Structure

The framework recognizes the following:

- There is a centralized capability, which we call the *global concentrator*, for gathering information from distributed components to create a COP, although it does not necessarily support a strict top down control hierarchy.
- The global concentrator maintains the COP as a state of a model of the enterprise, where this model is necessarily an abstraction that facilitates responding to questions of interest to its current endeavor.
- The global concentrator's model is capable of projecting its state into the future in support of evaluation of plans, interventions, actions, depending on the nature of the endeavor proposed to be undertaken.
- The distributed components have direct sensor-based awareness of their local situations and, similar to the global center, maintain this picture as the state of a model
- *Local models* are characterized by more detailed representations of their (limited) environments then the those *global model*, with its greater scope, can; such models are also more oriented to addressing questions of local interest

This framework sets up a foundation for considering problems such as the following:

1. How can global and local models be synchronized to maintain consistent states despite their differences in scope and purpose?
2. How can global and local models be projected forward from their current states in a manner that does the best prediction possible while qualifying such predictions with meaningful uncertainty caveats?

These problems are addressed in this paper as a basis for consideration of many others that arise in the framework. To address the first question, we call upon modeling and simulation concepts for family of model approximations and pragmatic frame concepts for consumer-based information targeting. For the second question, we propose multi-entity Bayesian nets (MEBN) and probabilistic ontologies (PR-OWL) as an effective means for providing state prediction within the confines of the model and pragmatic frame structures set up in answer to question 1. This approach is depicted in Figure 4

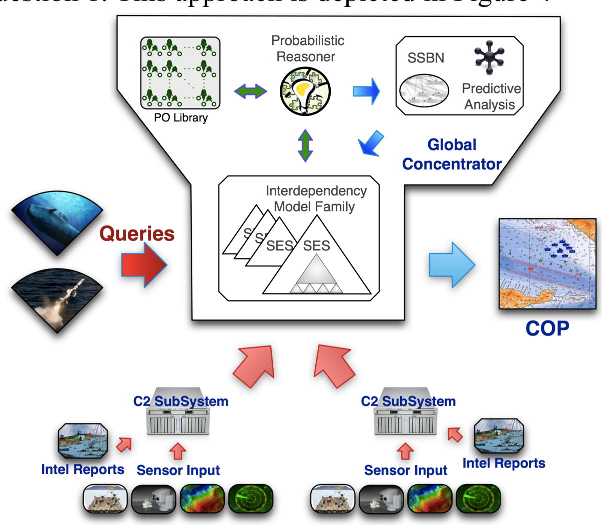

Figure 4 Overview of the COP framework.

As shown in the picture, the architecture is built around the core integrated family of approximation models and the Bayesian inference on the model future states (i.e. predictive analysis). Data from diverse sensors, intelligence reports and other information sources is continuously collected to inform (cross-calibrate) the models. In the global concentrator, the interdependency model family is based on domain specific SESs that convey the parameter interrelationships. As implied by the front SES, these structures can be decomposed to uncover deeper levels of detail, thus capturing both global-level models as the more detailed local models. This architecture ensures that both the global and the local models are synchronized to maintain consistent states despite their differences in scope and purpose. The DEVS' SES/pragmatic frame architecture expresses model and state prediction, which is provided by the Probabilistic reasoned. This is obtained via the tight semantic integration between the knowledge stored in the probabilistic ontologies and the contextual information provided by the pragmatic frames. In response to query, the probabilistic reasoned consults its POs, gathers the most updated knowledge from the Interdependency Model Family (i.e. level of detail for the knowledge gathering is defined via pragmatic frames), and performs the SSBN construction algorithm to respond the query. The result of this process is an updated COP.

Since the architecture in the figure is domain agnostic (i.e. any domain can be represented via the POs, pragmatic frames, and SES), this model is general enough to accommodate diverse types of situations in which an updated COP is required.

3.2 Integrating the Framework Technologies

Our approach to integrating the technologies involves developing support for pragmatic frames in the PO editor and devising the necessary adaptations to the System Entity Structure (SES) framework [19], and the reasoning aspects of MEBN / PR-OWL.

A key aspect of our current work is the fact that DEVS supports Systems Entity Structure/Pragmatic Frame ontology. This support is depicted in figure 5.

DEVS Protocol specifies the abstract simulation engine that correctly simulates DEVS atomic and coupled models. This gives rise to a general protocol that has specific mechanisms for:

- declaring who takes part in the simulation
- declaring how federates exchange information
- executing an iterative cycle that:
  - ✓controls how time advances
  - ✓determines when federates exchange messages
  - ✓determines when federates do internal state updating

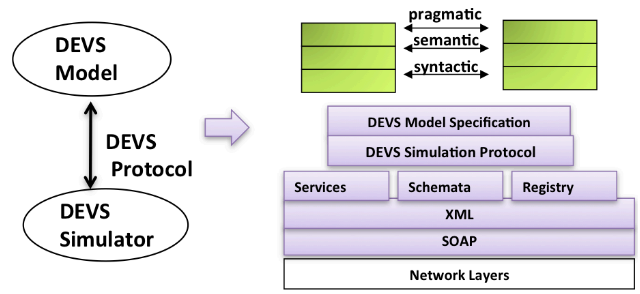

Figure 5 DEVS support for the COP framework.

Moreover, If the federates are DEVS compliant then the simulation is provably correct in the sense that the DEVS closure under coupling theorem guarantees a well-defined resulting structure and behavior.

The current formulation of a pragmatic frame relies on the SES as an implementable semantic and pragmatic ontology. The axiomatic formulation of the SES allows expressions to be represented in a formal mathematical/logical language. Zeigler and Hammonds [6] show that formal representations allow translations that claim to be equivalent to be examined rigorously. In our research, we aim to extend this formulation to include support for probabilistic ontologies as a way of keeping the advantages of the current SES framework while incorporating the benefits of principled representation of uncertainty and plausible reasoning.

4 Sample Use Case

To provide a less abstract overview of how the framework explained in the previous section operates; we now describe a possible C2 application within the maritime domain. Please, refer to figure 4 for a better visualization of the framework components. In this sample use case, the global concentrator receives information from various C2 subsystems geographically distributed at a large area. Some of these systems employ moving sensors (e.g. radars, sonars, lidars, etc, aboard the fleet of a Navy Group), while others might be either fixed (e.g. submarine sensor networks) or temporarily available (e.g. deployable sonar buoys). Parameters characterizing the output of these sensors, as well as the interrelationships among them are captured via the *model base* and the *system entity structure base*, which together form the interdependency model family represented as decomposable triangles in figure 4. As an example, an SES capturing the geo-referencing of the submarine sensor networks would also include structural information on the level of detail of these networks. That is, at a global level the models would be mostly interested in the output of each sensor network as a whole, while at a local level the models would be driven down in detail to capture output of specific sensors or subgroups of sensors within a given network. In this case, each sensor within a submarine sensor network might be modeled as a sub-entity, whereas the sensor network itself would be the complex entity formed by its associated individual sensors. The SES/MB framework captures not only the hierarchical aspects but also the details on how the sub-entities are coupled.

The interdependency model family includes the various SES/MB that collectively capture all the relevant aspects needed to answer queries posed to the global concentrator. Further, the DEVS formalism ensures that data continuously coming from the various information sources attached to the global concentrator are used to keep the model states updated. We now describe how the pragmatic frames, POs, and probabilistic reasoner work together to provide consistent, timely, and reliable answers to the queries posted against the system.

Pragmatic frames convey contextual information that is used to define the level of detail required by the system to answer a specific query. As an example, lets suppose that the system received query **G**, which requires among other things the system to know the number of vessels known to be within sector **Tango**. The reasoning process triggered by query **G** would then require feedback from sensors within area **Tango** at a level of detail that is global in nature. In this case, the SES containing the hierarchical structure of submarine sensor network **CoralX** would return parameters (e.g. number of know targets within range) that are at a level in which **CoralX** is depicted as an atomic entity, since this is enough to ensure a proper answer to query **G**. Conversely, a more specific query **L** requiring the system to infer acoustic patterns of potential targets resembling class **Kilo** submarines within sector **Tango** would cause the very same SES to be decomposed at a level of detail in which each sensor output is considered separately.

Each of the queries in the above example will trigger the SSBN construction algorithm, which will verify the PO library for MFrags related to each query. As explained earlier, MEBN "sees" the world as composed by entities that have their respective properties represented as nodes (random variables) in an MFrag and their relationships as the arcs connecting these nodes. A PO library supporting our sample maritime use case would be composed by many POs addressing various aspects of the maritime domain. Some of these POs would be more general in nature (e.g. POs on ship types, temporal aspects, sensor types, etc) while others would be much more specific (e.g. POs on submarine tactical warfare, sensor coupling characteristics, etc). In the above example, query **G** would likely trigger MFrags in the first group, while query **L** would resort to task specific POs (e.g. POs with MFrags depicting sensor deceiving tactics employed by enemy **Kilo** submarines).

The combination of POs and Pragmatic frames enable the global concentrator to focus on the right knowledge to be retrieved at the level of detail that is just enough to properly answer each query. In both queries, the pragmatic frames would select the proper SES configuration to address each query. The entity resolution of the SES would then define what specific subset of the PO library should be made available to the probabilistic reasoner. In query **G**, these would be mostly aggregated, high-level entities that would then drive the SSBN construction. The more detailed query **L** would likely result in an SES/MB output with a much a higher resolution, but also resulting in a greater pruning of these structures since more specific questions require a smaller subset of the higher-granularity entities of interest to the query. This in turn would drive the probabilistic reasoner to look after a more specific subset of POs conveying probabilistic relationships among entities at a much higher granularity level.

5 Conclusions

The combination of pragmatic frames to convey context and define the entity granularity of the models and structures captured in the interdependency model family, of POs to convey the semantics and probabilistic relationships within distinct domains at different levels of specificity enables our framework to address many of the issues that plague complex SoS architectures. For instance, the modularity of the scheme its flexibility to adapt to the many possible queries posed against SoS architectures ensure that the whole Integration-Interoperation spectrum is addressed. That is, there is no need for establishing a hard coded trade-off between reusability, composability, and flexibility (i.e. for interoperable, loosely connected systems) and the fit-to-purpose and responsiveness required for integrated systems, since the SoS framework can respond to requests at various levels of granularity without compromising consistency (e.g. by lack of detailed enough parameters) and performance (e.g. by querying over a large knowledge base to support high-granularity inferences). This adaptability to the many possible levels of granularity required at different "positions" in the interoperability-integration spectrum is made possible by two major aspects of our work. The first is that our SoS framework addresses all linguistic levels of component interaction, ensuring not only syntax and semantics (i.e. as current state-of-art is headed) but also the pragmatics embedded in each query. The second is its use of a consistent first-order probabilistic logic for both uncertainty representation and reasoning, which enables situation update with incomplete, dissonant, and ambiguous data that can arrive not only from the application domain (e.g maritime, disaster relief, etc) but also from the legacy systems connected to the framework.

Our major challenge remains to consistently integrate the DEVS representation of multi-entity to the one employed in MEBN/PR-OWL, as well as to integrate the implementations of both technologies.

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