Towards a Formal Pedigree Ontology for Level-One Sensor Fusion

Christopher J. Matheus
Versatile Information Systems, Inc.
5 Mountainview Drive
Framingham MA 01701 USA
cmatheus@vistology.com

David Tribble
Referentia Systems, Inc.
550 Paiea Street, Suite 236
Honolulu, Hawaii 96819 USA
dtribble@referentia.com

Mieczyslaw M. Kokar
Northeastern University
360 Huntington Avenue
Boston, MA, 02115 USA
kokar@coe.neu.edu

Marion G. Ceruti
Space and Naval Warfare Systems Center
SSC-SD Code 2725, 53560 Hull Street
San Diego, CA 92152 USA
marion.ceruti@navy.mil

Scott C. McGirr
Space and Naval Warfare Systems Center
SSC-SD Code 2725, 53560 Hull Street
San Diego, CA 92152 USA
scott.mcgirr@navy.mil

Abstract

This paper describes the authors' efforts to develop a pedigree ontology for level-one sensor fusion. This work was performed in the context of naval operations but the concepts employed are applicable to any domain involving sensor fusion. The ontology that has been developed is formally represented using OWL, the Web Ontology Language used in defining ontologies for the Semantic Web; one advantage of using OWL is that it has a formal semantics and there is a growing number of formal systems for processing and reasoning about OWL-based documents. The paper will describe the pedigree ontology in detail along with the motivation for various design decisions. An example will be given of the ontology's use in conjunction with OTH-T GOLD track data; in a simulated scenario pedigree information permits the informed selection of preferred vessel tracks. The paper concludes with a discussion of open issues and future directions.

1. Introduction

Level-one sensor fusion attempts to combine data collected from multiple sensory sources into a single cohesive description of the sensed characteristics of objects in an evolving situation. A classic example of this sort of sensor fusion is the generation of track reports including data regarding location, classification, threat identification, etc. Sensors come in a variety of types that collect passive and/or active energy in the form of acoustic, electro-optical or magnetic radiation. Each sensor type comes with certain capabilities as well as inherent limitations. Even within a given type there can be a wide range of capabilities across sensor sub-types; within the class of sonic sensors, for example, the capabilities and limitations of sonobuoys vary widely from those of towed-array sensors or hull-mounted sonar. Furthermore, a specific sensor can be configured in various ways (e.g., depth, frequency, direction), it may be of a specific model type or version having certain features and it will be operating under specific environmental conditions that may affect its performance. All of this "meta-data" describes how the raw data was collected and contributes to what is usually referred to as the data's *pedigree* or *provenance*. While it is extremely important to take data pedigree into consideration when performing level-one fusion there has been surprisingly little done to date to formalize the capture and representation of pedigree information in this domain (for related work on the representation and use of data pedigrees in the sciences see [1, 2, 3]).

In this paper we describe our efforts to develop a formal pedigree ontology for level-one sensor fusion. This work was performed in the context of naval operations but the general concepts employed are applicable to any domain involving sensor fusion. The ontology that has been developed is formally represented using OWL[4], the Web Ontology Language developed for the Semantic Web[5]. One advantage of using OWL is that it has a formal semantics that permits sound and complete automated reasoning.

Another advantage is that there are a growing number of practical systems for processing and reasoning about OWL-based documents. In the rest of this paper we describe our proposed pedigree ontology in detail along with the motivation for various design decisions. An example is given of the ontology's use in conjunction with OTH-T GOLD[6] track data with the intent of being able to make a more informed selection of preferred vessel tracks. The paper concludes with a discussion of open issues and future directions. First, however, we introduce the concept of ontologies and their use in formal reasoning systems.

2.   The Semantic Web and Ontologies

This is an opportune time to be considering the potential of exploiting pedigree information. Meta-data has gained renewed emphasis and clout in various domains, both commercial and military. It has also become a hot topic in the computer science research community, particularly from those involved with the development of the Semantic Web. The goals of the Semantic Web are to make the World Wide Web as accessible to software systems and intelligent agents as it is today to humans. The current contents of Web pages are very difficult for computers to automatically process because of their high reliance on natural language and graphic images, which computers are still relatively poor at interpreting. The W3C's proposed solution is to annotate Web pages with meta-data markup that describes the contents of a page in terms that a computer can readily process and "understand".

For the Semantic Web to achieve its objectives requires a formal set of languages and tools for representing and reasoning about information. The first step in this process is the development of a language for defining *ontologies*. An ontology is an explicit, formal, machine-readable semantic model that defines the classes (or concepts) and their possible inter-relationships pertinent to some specific domain. To construct an ontology one must have an ontology specification language. As part of its Semantic Web effort, the W3C has developed the OWL Web Ontology Language, which is XML-based and was derived from the language originally developed in the DARPA Agent Markup Language (DAML) Project[7]. OWL is rooted in the fields of artificial intelligence, knowledge representation and description logics[8]. It is a mathematically formal language for logical representation and reasoning with a well-established formal semantics[9]. As such, it represents the most advanced state of the art in languages for developing formal ontologies intended for the use in defining and describing a large class of meta-information.

OWL has matured to the level where it can serve as an ideal language for the definition and description of pedigree data. The description of pedigree information alone, however, does not represent a completely satisfactory solution since the information also needs to be interpreted and operationalized; this requires the development of intelligent systems that can automatically process the OWL ontologies and annotations and make logical deductions based on their content. While OWL is great for representing concepts and their properties, it is limited to the capabilities of description logics and thus does not have the full power of implication one would expect for general-purpose reasoning. The

developers of OWL were well aware of the language's limitations and sought ways to extend its power without sacrificing its inherent benefits. Their effort resulted in the development of SWRL, Semantic Web Rule Language[10], first released in the fall of 2003. SWRL permits the specification of implication rules over concepts, properties and instances specified using OWL. This advancement has opened the door to much more powerful knowledge representations and automated inferencing from within a single formal framework. From the perspective of working with pedigrees it makes it possible to define pedigree meta-data for specific types of information objects, describe instances of the pedigree for particular instances of these objects (i.e. annotations) and then logically reason about what implications can be drawn from the pedigree information.

There are a number of challenges to effectively implementing information pedigrees using OWL and SWRL. First, there is the knowledge engineering task of designing an appropriate pedigree ontology to describe the concepts and properties important to the definition of pedigrees. This requires in-depth experience in ontology development, working knowledge of the strengths and limitations of OWL and a thorough understanding of how information objects are processed and assembled. Second, one must have a good idea for how the information captured in a pedigree ontology might be used to provide some advantage during the use of the information objects. There is no sense in constructing a pedigree ontology if it is not clear that the meta-data it can capture will lead to measurable benefits. Third, there needs to be a way to represent and execute the reasoning processes that must be carried out to make effective use of the pedigree information and realize the anticipated benefits.   This requires the ability to capture domain knowledge in the form of SWRL rules and then systematically apply them to OWL-based pedigree information. Fourth, there must be an effective way of capturing and distributing pedigree information. This will require the development of pedigree annotation tools as well as pedigree servers. In this paper we focus on the first challenge – that of developing a formal pedigree ontology in OWL – while our ongoing work continues to address the remaining challenges.

3. An Initial Pedigree Ontology

The motivation for developing a pedigree ontology came from a need to process and reason about OTH-T GOLD[6] contact messages.   These messages contain track information pertaining to naval vessels derived from sensors and data fusion systems. While the messages contain useful information about the location, bearing, vessel type and likely threat they contain very little pedigree information about how the contact message was created other than the source organization and sensor type. Realizing that there was a lot more meta-data that could be communicated about how contact messages are assembled, we set out to develop a pedigree ontology that could capture this information. Our initial attempt to develop such an ontology is shown in
Figure 1. The intention of this *initial* version was to capture meta-data about how a *single sensor* was being used when it recorded the data that was reported in an OTH-T GOLD message.

In the ontology the highest-level concept is that of an "information object" represented by the InfoObject class.   InfoObjects may take on various forms, some of which are represented here as subclasses (i.e. Signal, Track, Report). Associated with this InfoObject is its pedigree represented by a class called InfoObjectMetaData.   The InfoObjectMetaData contains information about when the InfoObject was created and what its source was, i.e., what Sensor reported the data.   This class also contains a property, *infoObjectConfidence,* to record a measure of the confidence that should be placed on this InfoObject; the value of this property is something that would usually be filled in by a program that analyzes the pedigree information to determine the level of confidence that should be attributed to the data.
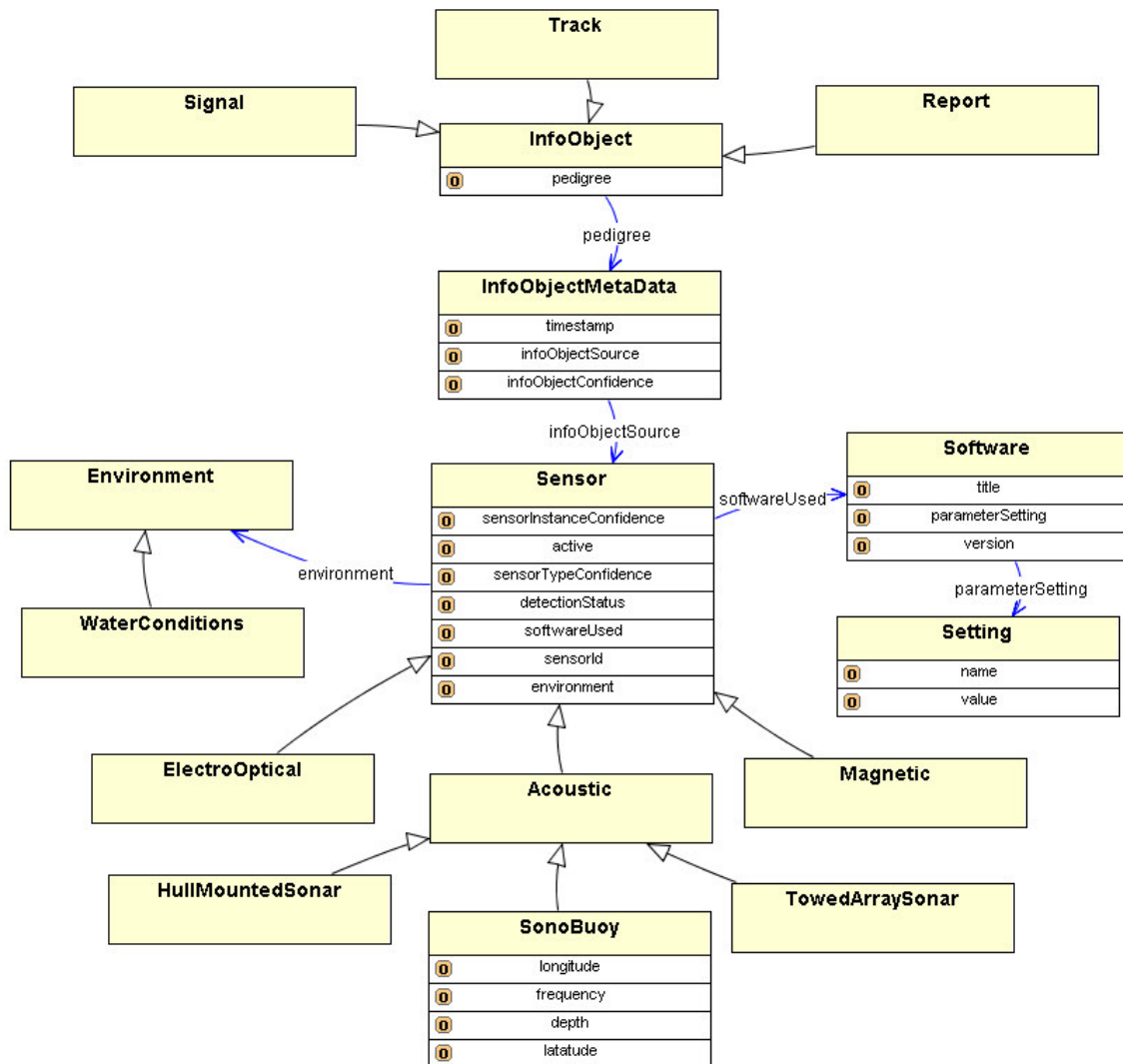

Figure 1: Initial Pedigree Ontology for Single Sensors.   Rectangles represent classes, large headed arrows depict the subclass relation, labeled arrows represent properties between objects and the labels within class rectangles indicate data properties.

The Sensor class captures relevant meta-data about the Sensor, specifically how it was configured and under what conditions it was operating when it made its recording. The type of sensor that was used is determined by the subclass used to instantiate it, e.g., SonoBouy, TowedArraySonar. The Sensor class has been subclassed into ElectorOptical, Acoustic and Magnetic and each of these subclasses is expected to be further subclassed into specific sensor subtypes, as we have patially done for the Acoustic class. In the incomplete ontology shown in the figure we have focused on Acoustic SonoBouy class as an example of how each of these classes would be further fleshed out in a more complete ontology. For the type of Sonobouy we had in mind, important properties to be recorded include its location (*lat*, *long*, and *depth*) as well as the *frequency* it was operating at.

There are two additional properties on the Sensor class: *sensorTypeConfidence* and *sensorInstanceConfidence*. As was the case for *objectSourceConfidence* the values of these properties are intended to be filled in after the pedigree information has been analyzed either by a program or humans and relative confidence levels are defined; as such they may represent highly subjective values. The *sensorTypeConfidence* property is meant to capture the relative confidence one has in the entire class of sensors of the given type. The *sensorInstanceConfidence* captures the confidence that is attributed to a specific instance of the sensor type. This use of two properties may be valuable in the case that a class of sensors is viewed as highly reliable but a given instance of the sensor has recently proven to be much less reliable.

4. Refined Pedigree Ontology

After further consideration of how the Pedigree Ontology might be used, the ontology was refined in a couple of ways; these enhancements are depicted in Figure 2. First of all we had decided to work with the C2 Information Exchange Data Model (C2IEDM)[11] developed and maintained by the Multilateral Interoperability Programme (MIP). C2IEDM (also referred to as the "Generic Hub" and soon to become the JC3IEDM -- Joint C3 Information Exchange Data Model) is a NATO standard for exchanging military information among multi-national allied forces. Since we had developed an OWL-based C2IEDM ontology (see [12]) for this same R&D effort we needed to integrate the pedigree ontology with the C2IEDM ontology. In the C2IEDM ontology the small amount of pedigree information that it permits is captured in the Reporting-Data class. To incorporate our pedigree ontology we have added *informationObjectConfidence* and *infoOjectSource* properties to this Reporting-Data class, which takes the place of our former InfoObjectMetaDataClass. Since we are not changing the Reporting-Data class but merely extending it this is consistent within the intended extensible use of the C2IEDM data model.

Second, in considering more complex situations, it became evident that we would need to be able to talk about information that was derived from multiple sensors, for example when the track from one sensor is correlated with that from another sensor. Since this form of data fusion must be done by either a System or a Human, we added these two

classes to the ontology. If the fusion is done by a System then it will have its associated Software with its possible parameter Settings. Note that the System class is now the parent of the Sensor class, which remains otherwise unchanged. The ontology could readily be extended to deal with more involved details about Human and Human-System produced information sources, but for our current effort it seemed prudent to focus on the systems side alone.
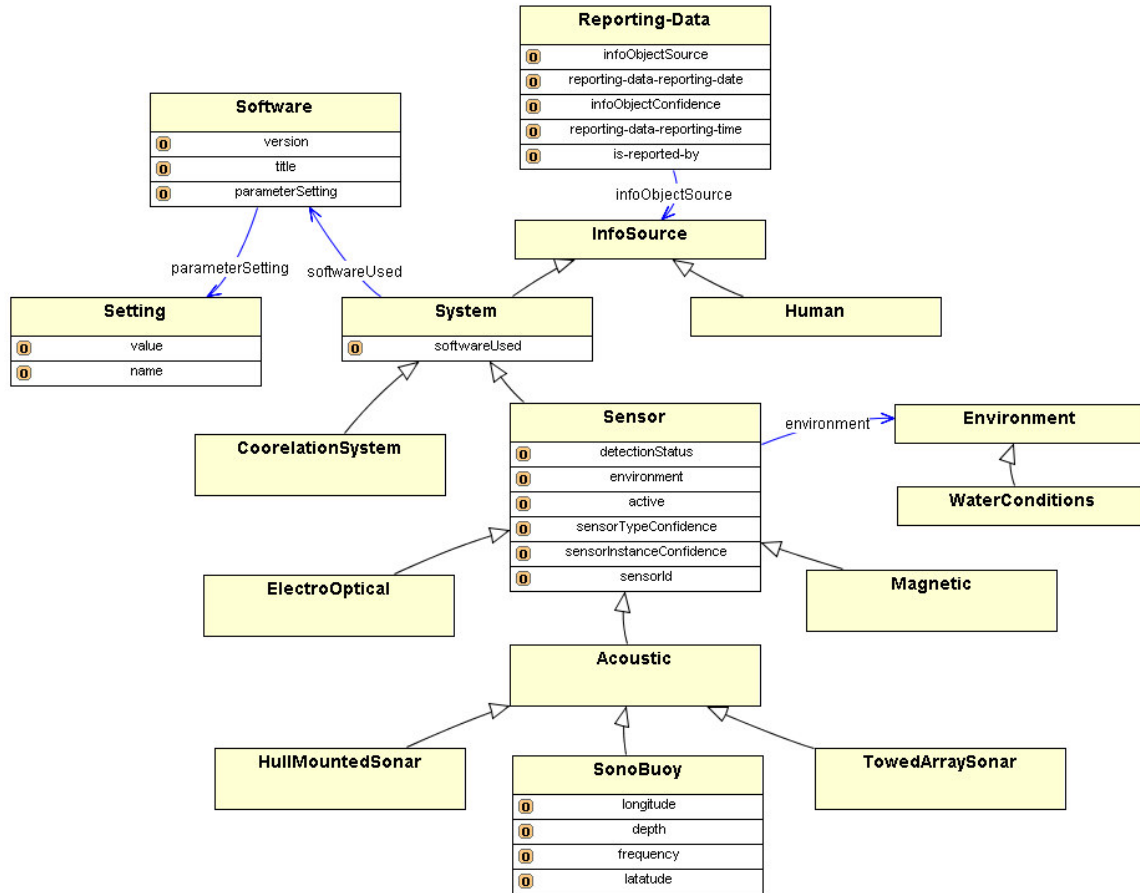

Figure 2: Refined Pedigree Ontology with Link to C2IEDM Reporting-Data Class. Rectangles represent classes, large headed arrows depict the subclass relation, labeled arrows represent properties between objects and the labels within class rectangles indicate data properties.

5. Pedigree Sources

Having a pedigree ontology is not very useful unless you have sources for the pedigree information and ways of attaching the information they provide to the corresponding information objects. Other than the limited amount of pedigree data that currently comes in OTH-T GOLD messages (e.g., sensor id) there is no standard for how to add additional meta-data to the messages. It is possible however to add *remarks* to OTH-T GOLD messages using the RMKS line. Using this line we could hypothesize that a new sensor has become available that is designed to send pedigree information encapsulated in structured fields with one or more RMKS lines following a CTC (i.e., contact) or POS

(i.e., position) line of an OTH-T GOLD message. One such structured format approach based on our pedigree ontology is as follows:

RMKS/PDGRE/*reportedBy/date/time/sourceType*
RMKS/PDGRE/SNSR/*id/sensorType/active?/status/depth/lat/long/freq*
RMKS/PDGRE/SFT/*title/version/param1/param2/parm3*
RMKS/PDGRE/ENV/*temp/salinity/current/grad1Depth/grad2Depth*

This message structure depicts a subset of a more complete format definition that could be developed. In this subset we show how in the first line a pedigree (PDGRE) remark could convey the critical information about who reported the CTC, when it was reported and the source of the reported information (some of this is redundant, obviously, with what is in the CTC line). The second line provides specific information about the sensor (SNSR) that was used. The third line describes the software (SFT) operating on the sensor and the final line describes the environmental (ENV) conditions at the time of the recording.

An alternative approach to providing pedigree information to information systems is to assume that all pedigree information is collected, maintained and distributed by either a centralized or distributed Pedigree Service. In such a case the pedigree information for an information object could be queried from this service by providing it with the time and id of the sensor/system that provided the data. In this way a system analyzing data from information objects could obtain the most up-to-date pedigree data available. This has some advantage in that within this approach the OTH-T GOLD track data does not have to be altered in any way. On the down side, it assumes the establishment of a broad based service having access to current operational characteristics of all sensors and systems in operation. This approach is seems rather infeasible, as it calls for a massive development effort and huge changes in the current infrastructure to permit the detailed monitoring of all sensors and systems.

An alternative to the two identified approaches is a hybrid solution. One feature the first approach lacks is the ability to record the track record of systems, sensors and humans (i.e., how well they have performed over time). This type of meta-data may well prove to be some of the most valuable types of pedigree information – knowing for example that a given track was produced under the direction of the Navy's top sonar operator may make it more valuable than a track produced by a couple of sonobouys that have proven in the past to have wide error margins under the environmental conditions they are currently experiencing. One could augment OTH-T GOLD data with some pedigree information as described above and in addition provide access to a centralize Pedigree Service that could distribute meta-data about the historical performance and compiled confidence levels established for the information sources. Such a service could in fact permit individual users to form their own confidence measures for various systems and humans, and they could even base these on the profiles created by others in the system (e.g., more experienced commanders).

6. A Naval Scenario

In developing the various aspects of the pedigree ontology it was valuable to have a scenario to help ground the concepts. The general idea behind our working scenario is to attempt to track a small pack of submarines using a collection of sonobouys and towed array sonar. Each sensor will be uniquely located, may be configured with different settings/orientations and may be operating under different environmental conditions. This set of meta-data about where and how a sensor is functioning will contribute to the sensor's pedigree. Each sensor will provide track information for one or more of the submarines resulting in multiple tracks for each submarine. The goal is to use pedigree information to help in determining which track or which set of fused tracks should be taken to be the most reliable. For the sake of this scenario we assume that the identity of the submarine described by each track from each of the sensor is unique and correct.
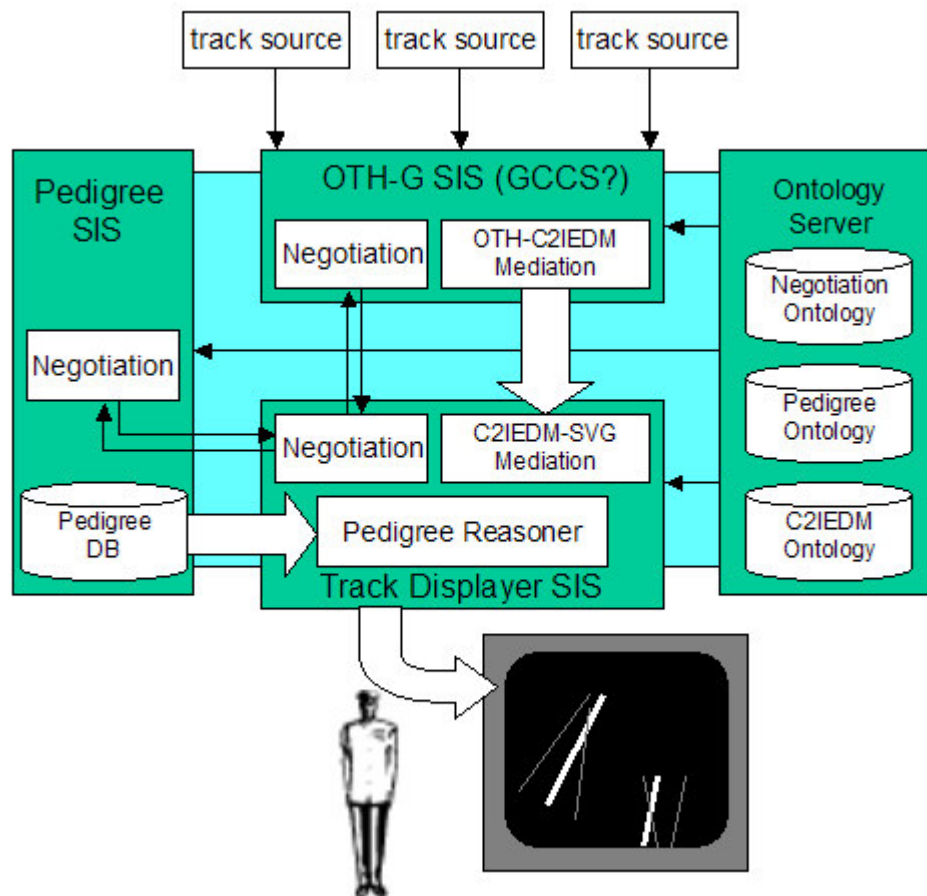

Figure 3: Concept for Enhancing Track Selection through Pedigree Reasoning using an Architecture based on the SIXA Methodology.

The general concept for the scenario, along with its high level architecture based on the SIXA Methodology[13], is depicted in Figure 3. The architecture includes three Semantic Information Services (SIS): two information producers – the Pedigree SIS and the OTH-T GOLD SIS – and one consumer – the Track Displayer SIS. The OTH-T GOLD SIS

provides track information annotated according to the C2IEDM Track Ontology. The Track Displayer SIS negotiates with the OTH-T GOLD SIS to request specific track information, for example tracks for a given region or tracks for a certain type of platforms. After a successful negotiation the OTH-T GOLD SIS would begin sending the Track Display SIS a continuous stream of relevant track data. This track data would be enhanced over normal OTH-T GOLD data in that it would have some additional pedigree information embedded within each contact. The Track Displayer SIS would also negotiate with the Pedigree Server SIS for historical and credibility information regarding the sensors that it is receiving track data from. Requests made to the Pedigree SIS would be simple one-time queries and would not require a data stream connection as is employed with the OTH-T GOLD SIS.

The Track Displayer SIS would be capable of displaying all of the track data that it receives from the OTH-T GOLD SIS, but it would also be able to provide an enhanced view on the track information that would assign relative confidence ratings to the various tracks based on reasoning about the pedigrees. In the diagram the monitoring screen shown at the bottom suggests that tracks for the same vessel but coming from different sources could be displayed differently according to the level of confidence the reasoner was able to derive from their pedigrees; this display would also be interactive permitting the operator to turn off or adjust the pedigree-based display as well as query it for explanations about the reasoning behind the assigned confidence ratings. This reasoning would take place using a combination of ontological reasoning and rules-based reasoning which would capture domain knowledge about how sensors operate and could incorporate generic and learned confidence ratings for various types of sensors and sensor configurations.

7. Conclusions

In this paper we described our efforts to develop a pedigree ontology using the OWL Web Ontology Language. The ontology is designed to capture meta-data concerning the conditions and circumstances under which level-1 sensor data is collected and processed. Our focus for this ontology was on Naval operations, specifically concerning the use of OTH-T GOLD contact messages for describing track of Naval vessels. Our interest in developing this ontology is to improve the ability to interpret and evaluate track data, particularly in the case where information about a vessel is obtained from multiple sources and choices need to be made about the validity of conflicting data[14]. We described a scenario in which pedigree information encoded using the proposed ontology could assist an automated reasoning system in selecting the most reliable track data. We are in the process of designing and prototyping such a system as part of our current work with the Office of Naval Research.

One challenge to the use of pedigree information is the relative lack of support for gathering and distributing such information. Both OTH-T GOLD and C2IEDM have very limited built-in capabilities for representing pedigree information. Fortunately, both formats provide means for extending their representational capabilities, with C2IEDM being explicitly designed to be extended and OTH-T GOLD providing some rudimentary

capacity for extension through the use of structured remark lines. It is anticipated that as these formats evolve or are replaced with more modern representations that support for pedigree information will improve and become commonplace. Ideally, these representations will leverage some of the advantages afforded by the use of XML and ontology-based languages such as OWL and SWRL. Adoption of these modern languages will greatly facilitate the design and development of advanced automated systems with human-like reasoning capabilities that can be formally verified and trusted to provide sound results.

8. Acknowledgements

Appendix A: Pedigree Ontology in OWL

```
<?xml version="1.0"?>
<rdf:RDF
  xmlns="http://a.com/ontology#"
  xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
  xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
  xmlns:owl="http://www.w3.org/2002/07/owl#"
 xml:base="http://a.com/ontology">
 <owl:Ontology rdf:about=""/>
 <owl:Class rdf:ID="ElectroOptical">
  <rdfs:subClassOf>
    <owl:Class rdf:about="#Sensor"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Reporting-Data"/>
 <owl:Class rdf:ID="InfoSource"/>
 <owl:Class rdf:ID="SonoBuoy">
  <rdfs:subClassOf>
    <owl:Class rdf:about="#Acoustic"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Acoustic">
  <rdfs:subClassOf>
    <owl:Class rdf:about="#Sensor"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Software"/>
 <owl:Class rdf:ID="System">
  <rdfs:subClassOf rdf:resource="#InfoSource"/>
 </owl:Class>
 <owl:Class rdf:ID="Human">
  <rdfs:subClassOf rdf:resource="#InfoSource"/>
 </owl:Class>
 <owl:Class rdf:ID="TowedArraySonar">
  <rdfs:subClassOf rdf:resource="#Acoustic"/>
 </owl:Class>
 <owl:Class rdf:ID="Setting"/>
 <owl:Class rdf:ID="CoorelationSystem">
  <rdfs:subClassOf rdf:resource="#System"/>
 </owl:Class>
 <owl:Class rdf:ID="Sensor">
  <rdfs:subClassOf rdf:resource="#System"/>
 </owl:Class>
 <owl:Class rdf:ID="Magnetic">
  <rdfs:subClassOf rdf:resource="#Sensor"/>
```

```
</owl:Class>
<owl:Class rdf:ID="Environment"/>
<owl:Class rdf:ID="HullMountedSonar">
 <rdfs:subClassOf rdf:resource="#Acoustic"/>
</owl:Class>
<owl:Class rdf:ID="WaterConditions">
 <rdfs:subClassOf rdf:resource="#Environment"/>
</owl:Class>
<owl:ObjectProperty rdf:ID="environment">
 <rdfs:range rdf:resource="#Environment"/>
 <rdfs:domain rdf:resource="#Sensor"/>
</owl:ObjectProperty>
<owl:ObjectProperty rdf:ID="infoObjectSource">
 <rdfs:domain rdf:resource="#Reporting-Data"/>
 <rdfs:range rdf:resource="#InfoSource"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
</owl:ObjectProperty>
<owl:ObjectProperty rdf:ID="softwareUsed">
 <rdfs:range rdf:resource="#Software"/>
 <rdfs:domain rdf:resource="#System"/>
</owl:ObjectProperty>
<owl:ObjectProperty rdf:ID="parameterSetting">
 <rdfs:range rdf:resource="#Setting"/>
 <rdfs:domain rdf:resource="#Software"/>
</owl:ObjectProperty>
<owl:ObjectProperty rdf:ID="pedigree">
 <rdfs:range rdf:resource="#Reporting-Data"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
</owl:ObjectProperty>
<owl:DatatypeProperty rdf:ID="version">
 <rdfs:domain rdf:resource="#Software"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="depth">
 <rdfs:domain rdf:resource="#SonoBuoy"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#float"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="sensorTypeConfidence">
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
 <rdfs:domain rdf:resource="#Sensor"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="value">
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
 <rdfs:domain rdf:resource="#Setting"/>
```

```
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="reporting-data-reporting-date">
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#date"/>
 <rdfs:domain rdf:resource="#Reporting-Data"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="name">
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
 <rdfs:domain rdf:resource="#Setting"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="latatude">
 <rdfs:domain rdf:resource="#SonoBuoy"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#float"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="detectionStatus">
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
 <rdfs:domain rdf:resource="#Sensor"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="title">
 <rdfs:domain rdf:resource="#Software"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="sensorInstanceConfidence">
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
 <rdfs:domain rdf:resource="#Sensor"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
</owl:DatatypeProperty>
<owl:FunctionalProperty rdf:ID="is-reported-by">
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#anyURI"/>
 <rdfs:domain rdf:resource="#Reporting-Data"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="active">
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#boolean"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
 <rdfs:domain rdf:resource="#Sensor"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="longitude">
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#float"/>
 <rdfs:domain rdf:resource="#SonoBuoy"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="sensorId">
 <rdfs:domain rdf:resource="#Sensor"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
```

```
    <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
   </owl:FunctionalProperty>
   <owl:FunctionalProperty rdf:ID="reporting-data-reporting-time">
    <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#time"/>
    <rdfs:domain rdf:resource="#Reporting-Data"/>
    <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
   </owl:FunctionalProperty>
   <owl:FunctionalProperty rdf:ID="infoObjectConfidence">
    <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
    <rdfs:domain rdf:resource="#Reporting-Data"/>
    <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
   </owl:FunctionalProperty>
   <owl:FunctionalProperty rdf:ID="frequency">
    <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#float"/>
    <rdfs:domain rdf:resource="#SonoBuoy"/>
    <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
   </owl:FunctionalProperty>
</rdf:RDF>
```

References

1   Data Provenance/Derivation Workshop Position Papers and Talks. Workshop on Data Derivation and Provenance, Chicago, Oct. 17-18, 2002. http://people.cs.uchicago.edu/~yongzh/position_papers.html.

2   L. Pouchard, L. Cinquini, B. Drach, D. Middleton, D. Bernholdt, K. Chanchio, I. Foster, V. Nefedova, D. Brown, P. Fox, J. Garcia, G. Strand, D. Williams, A. Chervenak, C. Kesselman, A. Shoshani and A. Sim, An Ontology for Scientific Information in a Grid Environment: the Earth System Grid. Semantic Web Technologies for Searching and Retrieving Scientific Data. ISWCII, Sanibel Island, FL, October 20, 2003.

3   Collaboratory for Multi-scale Chemical Science. Project Lead: L. Rahn, Sandia National Laboratories. http://cmcs.ca.sandia.gov/technical.php.

4   D. McGuinness and F. van Harmelen. OWL Web Ontology Language Overview. http://www.w3.org/TR/2003/PR-owl-features-20031215/.

5   T. Berners-Lee, J. Hendler and O. Lassila. The Semantic Web. Scientific American, May 2001.

6   U.S. Navy Center for Tactical Systems Interoperability. Operation Specification for Over-The-Horizon Targeting GOLD (OS-OTH-T GOLD), March 2004.

7   The DARPA Agent Markup Language Homepage. http://www.daml.org/.

8   F. Baader, D. Calvanese, D. L. McGuinness, D. Nardi, and P. F. Patel-Schneider, editors. The Description Logic Handbook: Theory, implementation, and applications. Cambridge University Press, 2003.

9   P. F. Patel-Schneider, P. Hayes, and I. Horrocks. OWL web ontology language semantics and abstract syntax. W3C Recommendation, 2004. Available at http://www.w3.org/TR/owl-semantics/.

10 I. Horrocks, P. F. Patel-Schneider, H. Boley, S. Tabet, B. Grosof and M. Dean, SWRL: A Semantic Web Rule Language Combining OWL and RuleML, April 2004 http://www.daml.org/rules/proposal/.

11 Multilateral Interoperability Programme, The C2 Information Exchange Data Model, Edition 6.15a. Greding, Germany, January 2005.

12 E. Dorion, C. Matheus and M. Kokar. Towards a formal ontology for military coalitions operations. 10th International Command and Control Research and Technology Symposium, McClain, Virginia, June 2005.

13 C. Matheus, M. Kokar and D. Tribble. SIXA Phase I Project Final Report, ONR STTR Report, February, 2005.

14 M. G. Ceruti, Ontology for Level-One Sensor Fusion and Knowledge Discovery. Knowledge Discovery and Ontologies Workshop at ECML/PKDD, Pisa, Italy, September 2004.