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Comparing Information Structures Used in the Maritime Defence and Security Domain

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Abstract. As assets are engaged to collect data and intelligence on the entities or parties of interest to a defence or security operation, much of the collected data are represented in electronic form and subsequently stored in an assortment of files or databases. It is also typical that these data or information need to be shared with others involved in the investigation, task group, coalition, or security force. The effectiveness of this sharing is ultimately judged by how well the receiving party understands the information it has received. In this paper we examine the commonality of concepts between information systems in the Canadian defence and security regime. Specifically, we consider components of the National Information Exchange Model (NIEM), the Canadian Naval Positioning Repository (NPR), a port clearance structure, and a messaging structure that evolved out of a Canadian defence research and development effort. We then investigate the performance of graph-based approaches for automatic schema matching over these schemas. The information structures, or schemas, are examined using the open-source software for combining match algorithms (COMA). Results of the investigation show how the diverse terminology in maritime defence and security introduces unnecessary differences in the vocabularies (e.g., using vessel, ship, or identity as the descriptor for an object). Results also show how discrepancies are introduced through data typing, the structure itself, and semantics. Overall, the investigation indicates that the graph-based methods do not appear to offer a way of automating structure matching while maintaining confidence in the output for schema used across the different systems underlying the Canadian MDA.

Keywords. Information model, schema matching, structure comparison, maritime domain awareness

Introduction

In Canada, Maritime Domain Awareness (MDA) is described as "having true and timely information about everything on, under, related to, adjacent to, or bordering a sea, ocean or other navigable waterway. This includes all related activities, infrastructure, people, cargo, vessels, or other means of transport. For marine security, it means being aware of anything in the marine domain that could threaten Canada's national security." [1].

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MDA in Canada is a multi-departmental activity that relies on the assembly and aggregation of large quantities of information. However, often the information to be assembled originates in application-specific sources, such as databases or websites. Such structured sources do offer an advantage in that quality and relationship rules can be explicitly placed on the data held within the structure, thus helping reduce errors in the data. However, these structured sources also contain varied naming conventions and data relationship differences as compared to other sources. Such differences introduce barriers to the automated sharing and incorporation of these data into other systems.

There are many information structures used to provide data of relevance to MDA. For example, the International Organization for Standardization (ISO) has defined the Electronic Port Clearance (EPC) standard [2] (i.e., ISO 28005) for describing important vessel arrival information to port authorities. The EPC notifications contain vessel owner information, cargo manifest, specifics on dangerous items that are onboard, etc. This type of information is important to the port authorities, but is also useful for gaining an understanding of the vessel traffic in national approaches.

The information structures used to contain and transfer the MDA-relevant information are varied. For example, the information structure may be built based on extensible markup language (XML) schemas, relational database schemas, or entity-relationship models. Each such structure allows the definition of allowed content, typically through the labelling of the content (e.g., <VesselName></VesselName> as represented in XML), and definitions of permitted data types (e.g., string, integer, decimal).

The following work is motivated by a desire to explore automated matching of information structures pertinent to Canadian MDA [3]. The investigation makes use of graph-based methods to represent the information structure as a collection of objects (i.e., nodes) and relationships (i.e., edges) in a graph. Multiple structures are then characterized in multiple graphs, allowing for comparison between the graphs. The goal of such a comparison is the identification of similarities, differences, strengths, and weaknesses of the information structures.

Graph similarity has been used in a wide variety of fields. For example, it has been used for measuring similarity between pieces of music to then generate user specific playlists [4, 5]. Graph theory has long been used to represent network and data structures, but is also used in applications involving pattern recognition and computer vision [6]. It is used in social network analysis to characterize relationships between individuals involved in social networking sites [7, 8]. Finally, graphs can be used to represent biological networks, thereby providing a mathematical basis for the analysis of relationships found in fields such as ecology and evolutionary biology [9]. A final example is in the field of chemistry, where graphing can be used to represent different types of atoms (nodes) and interatomic bonds (edges) [10, 11].

In broad terms the objective of this work is to determine if graph-based methods offer a way of automating the structure matching while maintaining confidence in the output. If successful, automated matching would provide a step towards schema integration, which is the merging of a set of schemas into a single all-encompassing schema. Schema integration would represent significant progress in Canadian MDA.

In order to reach these objectives, multiple matching strategies were automatically run and evaluated using measures of performance described in the literature. The comparisons that have been performed highlighted many difficulties for automatic schema matching and similarity measurements.

The remainder of this paper is structured as follows: Section 1 describes several technologies that offer graph-based matching of information structures. A brief overview of the information structures considered in this investigation is also provided. Section 2 describes the results of the matching exercise. A conclusion section then summarizes the important findings.

1. Methodology

1.1. Matching Tools

It is useful to describe the matching tools based on some of the differences in the approach of the matching algorithm and the access to the tool. Four differences are described here.

Schema vs. instance: Matching tools can be either schema-based or instance-based [12]. A schema-based matcher utilizes only the information structure (i.e., no content) in the match process, while an instance matcher uses the structure and the content of a message (i.e., structure and content).

Single vs. hybrid vs. composite: Matching tools produce an output either from the use of a single match process (i.e., single) or some combination of match processes (i.e., hybrid or composite) [13]. A hybrid matching process considers criteria A and B within a single algorithm, while a composite matching process would merge the output of criteria A applied with one algorithm and the output of criteria B applied with a second algorithm. A composite matcher provides more flexibility to apply individual matching algorithms for each criterion.

Generic vs. specialized: Some schema matching software is designed to address specific matching problems, for example, matching related to protein structures or social network analysis. These specialized tools are tuned to the specific characteristics of the input graph topologies. The more generic matching tools [14] consider a larger group of graph topologies and usually contain a larger set of matching algorithms. In both cases, the ultimate performance is directly correlated with the ability of the user to relate the strengths of the matching algorithm to the characteristics of the input schemas.

Open-source vs. commercial: Much of the schema matching software originated in academia around the early 2000's. Some of these tools have since evolved to become commercial products while others remain within academia, typically available as open-source software. We note that many software tools described in the literature are of the open-source variety.

A variety of matching tools were considered in this investigation. Table 1 provides a summary of the tools given cursory examination for this work.

Selection of the tool to be used in this study was based on the following criteria:

- Support for schemas – the inputs used in this investigation did not include message content, thus schema matching is required,
- Support for hybrid or composite – the ability to apply multiple match processes is required. This allows flexibility in the combining of existing matchers,
- Support for generic topologies – generic matching applications are not tuned to specific topologies and thus should be useful for the varied set of schemas in this investigation,
- extensibility – the ability to add new matchers or learners and new methods for combining the results,
- support for multiple schema types – the ability to utilize varied schema formats (e.g., W3C XML schema definition (XSD), W3C Ontology Web Language (OWL), Relational model expressed in SQL),
- open source – this is based on a desire to minimize licensing fees and a desire to have flexibility in code modifications.

Based on the above criteria and the summaries provided in Table 1, the COMA 3.0 [15, 16] and Harmony (OpenII) software applications are appropriate for the investigation. However, Harmony specializes in problems involving very large topologies such as those existing in social network graphs (i.e., thousands of nodes). As well, preliminary examination of COMA 3.0 showed a very manageable and modifiable code base that was easy to install and use. For these reasons, COMA 3.0 software application was selected.

COMA 3.0 implements the composite approach to combine independently executed matchers. This is particularly important as the extensibility of the composite matchers allows the adding of new matcher algorithms and new methods for combining their output. COMA 3.0 supports a flexible infrastructure for constructing new matchers and the ability to construct new match strategies from existing matchers.

1.2. Schemas

Five schemas were selected for this investigation, based on their use in Canadian defence research, current use internationally or in Canada, or anticipated future use in Canada. The schemas are represented in the form of XML-schema and SQL database table definitions. The selected schemas are described below.

National Information Exchange Model (NIEM) – Maritime (NIEM-M): The NIEM-M schema represents one domain within the broader NIEM [17], with this domain specifically addressing the needs of the maritime community. NIEM has been used extensively within numerous defence and security related communities, and has been adopted by US DoD [18] "as the best suited option for standards-based data exchanges". NIEM is currently being discussed within Canada as a possible exchange model for defence and security related information.

NIEM components may be combined in different ways, to construct community-specific exchange message structures [19]. Two of the exchange message structures were used in this investigation, namely Position [20] and Notice of Arrival (NOA) [2].

Table 1. The matcher tools given cursory examination during this work.

Matcher Software Name	License	Approach	Year Created
Cupid, Biztalk	Commercial	Instance Hybrid Generic	2001
Similarity Flooding/Rondo	Academic	Schema Single	2001
COMA, COMA++, COMA 3.0	Open-source and Commercial	Schema Composite Generic	2002
Onto-Builder (OntoM module)	Open-source	Hybrid	2004
Altova Mapforce	Commercial	Instance Specialized	2008
Clio, InfoSphere Data Architect	Commercial	Schema Hybrid	2009
YAM	Academic	Schema Generic	2009
JitterBit	Open-source and Commercial	Schema Generic	2009
Harmony (OpenII)	Open-source	Schema Composite Generic	2010
NetWeaver Process Integration	Commercial	Schema Composite Generic	2010
AMC	Commercial	Schema Composite Generic	2011

NIEM-M Position includes structure elements that describe a vessel's geospatial position, course, heading, speed, and status at a specific time. Vessel identifying information is also included in the message definition. The NOA message structure utilizes a number of NIEM-M components including the definition of vessel, person, arrival, departure, and cargo information.

Naval Positional Repository (NPR): The NPR is a Canadian maritime database currently being used for the storage of large quantities of vessel-related data for both real-time and delayed processing. In this investigation, the NPR is represented as an SQL database structure. The structure consists of multiple database tables that receive vessel position data and other vessel-specific data from numerous national sources, and some international data sources such as the Maritime Safety and Security Information System [21].

Electronic Port Clearance (EPC): The EPC schema [2] is a message specification that defines the information to be sent from a vessel to a port authority, when the vessel is planning to enter that port. The message represents a pre-arrival notification and includes cargo manifest, company information, vessel information, estimated time of arrival, passenger information, name of the captain, voyage description, etc. The EPC message is described by ISO 28005 which contains the definition of the data elements.

MUSIC Track Structure: A previous defence research effort named the Multi-Sensor Integration within a Common Operating Environment (MUSIC) project defined a track message structure which was used to exchange vessel track information among applications developed within the project. The MUSIC track information structure, referred to as MtbTrack, includes a vessel's attributes and positional history with a naming convention that matched the global system requirements within the MUSIC project. The structure was heavily influenced by software developers, as the resulting structure followed a typical Java package and naming convention. The terminology used was typical of a military Command & Control (C2) environment as compared to the broader MDA community.

A summary of the schemas is provided in Table 2. The Table indicates the representation of the schema (i.e., see Table heading Type), the number of nodes and edges, an indicator as to the length and thus complexity of the element naming used in the schema, and the data typing (e.g., common data types such as integer or string as compared to user defined types that may encapsulate other elements).

Each of these schemas has characteristics that make them applicable to specific communities-of-interest (COI). As a result, we narrow the match comparison to examine three cases that have similar COIs. Specifically, the comparisons consider matches between:

- NIEM NOA – EPC
- NIEM Position – NPR
- NIEM Position – MtbTrack

Table 2. Schemas used in this investigation. The input type and the number of resulting nodes and edges are given.

Schema Name	Type	Nodes/Edges	Naming Convention	Data Types
NIEM NOA	XSD	287 / 287	Long names	User Defined
NIEM Position	XSD	100 / 100	Long names	User Defined
EPC	XSD	687 / 694	Long names	User Defined
NPR	SQL	143 / 143	Short names	Base (float, string)
MtbTrack	XSD	33 / 33	Short names	Base (float, string)

2. Results

Considerable research has been conducted in the area of match evaluation quality measures. For this investigation we will use measures previously proposed, referred to as F-Measure [22], Compactness [23], and Accuracy [12].

Each of these measures use some type of comparison of the correspondences, where correspondences are defined as the resulting matches determined by either a subject matter expert (SME) or a matching algorithm. In the following nomenclature, the real correspondences between the two schemas are denoted set A, and are determined by a SME. The correspondences suggested by the automated mapping are denoted set C. The intersection of the two sets represents true positives identified by the automated matcher and is denoted set B. Figure 1 illustrates the domain of the correspondences.

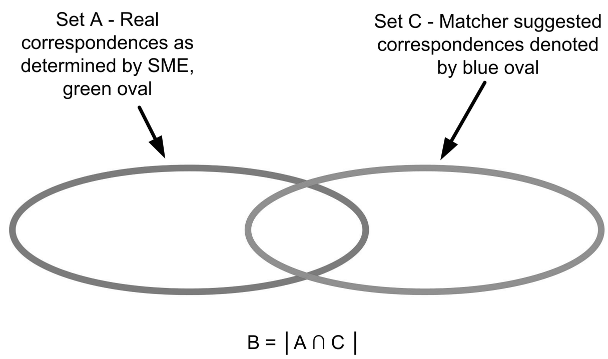

Figure 1. Sets A and C denote real and matcher suggested correspondences. Set B represents the set of true correspondences that were determined by the matcher.

The match evaluation quality measures are determined based on the precision and recall of the automated matches. The precision represents the ratio of matcher suggested true correspondences (i.e., true positives) as compared to all suggested correspondences. Recall represents the ratio of matcher suggested true correspondences as compared to all real correspondences. These values can be expressed as:

$$\text{Precision} = \frac{|A| \cap |C|}{|\mathrm{C}|} = \frac{|B|}{|C|} \tag{1}$$

$$\text{Recall} = \frac{|A| \cap |C|}{|\mathrm{A}|} = \frac{|B|}{|A|} \tag{2}$$

where we define $|B| = |A \cap C|$.

Since either recall or precision can be maximized at the expense of the other, precision and recall are often combined to define the F-Measure. The F-Measure [22] represents the harmonic mean of the precision and recall. Its value has a range from zero to one, with one being the preferred value. F-Measure is expressed as:

$$\text{F - Measure} = \frac{2 * precision * recall}{(precision + recall)} \quad (3)$$

Compactness was introduced as a ratio of the real correspondences and the suggested correspondences [23]. It was noted that compactness is not semantically grounded, in that the ratio does not require any intersection set. Note that the compactness value can be greater than one, however one is the preferred value. Compactness is defined as:

$$\text{Compactness} = \frac{|A|}{|C|} \quad (4)$$

Accuracy (sometimes called overall) was developed specifically in the schema matching context [12]. Accuracy embodies the idea of quantifying the post-match effort needed for adding false negatives (i.e., adding those actual correspondences that were not automatically identified, |A|-|B| in the nomenclature of Figure 1) and removing false positives (i.e., removing those automatically generated correspondences that are not true, |C|-|B|).

$$\text{Accuracy} = 1 - \frac{(|C| - |B|) + (|A| - |B|)}{|\text{A}|} = \frac{|B|}{|A|}(2 - \frac{|C|}{|B|}) = recall(2 - \frac{1}{precision}) \quad (5)$$

Table 3 presents some of the results from the matching investigation. The table of values is constructed from the application of many match algorithms and shows only partial results from the investigation.

The complex matchers reported in Table 3 (see column Matchers Combined) are defined [24] as:

- Name: A matcher that considers node names and applies multiple string matchers to derive a similarity value for the node names. The matchers break the node name into individual words or phrases (i.e., string tokenization), and expand abbreviations and acronyms.
- NameType: A matcher that combines both the Name matcher as described above, with a data type similarity match algorithm.
- NameStat: A matcher that combines node names and structural information to derive a similarity value. It aims at differentiating inner elements, which lack data type but provide rich structural information.

- Children: A structural matcher used in combination with a leaf-level matcher (i.e., leaf-level indicating the last node in the branch of nodes). It follows a bottom-up approach to propagate element similarity.
- Parent: A structural matcher that propagates element similarity in a top-down manner and derives the similarity between elements from the similarities between their parents.
- Siblings: A matcher that complements the bottom-up and top-down approaches of Children and Parent, by allowing the similarity to be propagated from the neighbour elements at the same level.

It is worth noting that the results shown in Table 3 utilize the COMA 3.0 synonym feature. This feature allows a user to manually declare synonyms that exist in the terminology between sets |A| and |C|, synonyms that could not be expected to be matched by the automated algorithm (e.g., VesselNameText and ShipName). As an enhancement to the existing synonym feature, COMA 3.0 was modified during this work to permit the declaration of partial node name synonyms (e.g., Vessel as a partial node name in VesselNameText and Ship as a partial node name in ShipName). This allowed the application of the partial node name synonyms throughout the input sets.

Overall, Table 3 reflects the generally poor results of the matching. The F-measure, which quantifies the non-correspondences that remain after the match exercise, generally has values < 0.5, indicating the large symmetric difference that remains after the correspondences have been determined. Ideally the F-measure would be close to one, indicating a symmetric difference (i.e., $|A| \cup |C| - 2|B|$) that tends toward zero.

Regarding accuracy, Table 3 indicates negative values for Cases 1 to 4. A negative accuracy occurs when precision is less than 0.5. Precision below 0.5 indicates that the intersection |B| is less than half the total number of matcher suggested correspondences. Effectively, the negative accuracy is indicating that there is more manual effort to remove the false positives (i.e., |C|-|B|) and add all the missing correspondences (i.e., |A|-|B|) as compared to completing all the matches manually. The remaining positive accuracy values (Case 5 and 6) indicate that the matcher is reducing the required manual effort. In the case of the accuracy = 0.63, the manual effort to correct the correspondences requires the addition of three correspondences; while the case of accuracy = 0.25 requires adding three correspondences and removing three correspondences.

The compactness values as compared to the match results (denoted by |A|, |B| and |C|), indicate a disconnect between the intersection set |B| and the compactness measure. Case 2 correspondences illustrate this disconnect, where the compactness value is one while the intersection set |B| is nevertheless small. As noted previously, compactness is not semantically grounded; meaning the compactness value can be optimal (i.e., one) with an intersection set of zero.

As noted previously, Table 3 results utilize the COMA 3.0 synonym feature with the added enhancement of partial node name synonyms. However, the use of the synonym features did not produce the expected increase in match correspondence. As shown in Table 4, this is due to the large variation in concept representation, termed semantic heterogeneity.

Table 3. Partial results from the schema matching process.

Schemas	A	B	C	F-Measure	Accuracy	Compactness	Matchers combined
Case 1 NIEM:NOA – EPC	41	11	66	0.21	-1.07	0.62	Name Siblings NameStat
Case 2 NIEM:NOA – EPC	41	8	41	0.20	-0.61	1.00	Name NameType Siblings Parent
Case 3 NIEM:Position– NPR	8	6	24	0.38	-1.50	0.33	Siblings Parent NameType
Case 4 NIEM:Position– NPR	8	1	9	0.12	-0.88	0.89	NameStat Parent
Case 5 NIEM:Position – MtbTrack	8	5	5	0.77	0.63	1.60	NameStat Siblings Name
Case 6 NIEM:Position – MtbTrack	8	5	8	0.63	0.25	1.00	Name Children Siblings

Semantic heterogeneity may occur when:

- The same real world entity has different representations. In this case, the manner in which the information is arranged and described can vary greatly between independently developed structures (e.g., Name in MtbTrack is under Attributes and Name in NIEM is represented as VesselName which is under VesselAugmentation).
- The attribute names and data values from different information structures do not have lexical similarities (i.e., the words used are not similar; e.g., vessel, ship, identity) or are not described using the same description language [25].

Table 4 illustrates the difficulty. Some MDA schemas (i.e., NIEM-M and EPC) are considered highly expressive and contain many user-defined types and classes. Such classes provide component reuse capabilities and support for distributed schemas and namespaces, which improve schema flexibility and application. However, this also introduces levels of abstraction, for example the definition of objects based on other abstract objects. These levels of abstraction present a challenge to matching tools.

Table 4. Vessel Name representation under the retained schemas.

Schema Name	Vessel Name Representation	Data Type
NIEM NOA	Notice.Vessel.VesselAugmentation.VesselNameText	nc:ProperNameTextType
EPC	EPCMesseage.EPCRequestBody.ShipID.ShipName	epc:string
NPR	dbo.Identities.IdentityName	varchar
MtbTrack	MtbTrack.Attributes.Name	string

3. Concluding Remarks

This work has revealed many complexities related to the use of schema matchers and the matching process. For example, a schema that includes data abstraction layers, common in XML schemas, is a challenge for the COMA 3.0 matcher algorithms. Although the abstraction layers provide a benefit related to ease of reuse of the XML schema-defined objects, the abstraction does introduce a layering of terminology that matchers find problematic to decipher.

If we consider the COMA 3.0 as indicative of the available tools, then we can conclude that the graph-based methods do not appear to offer a way of automating structure matching while maintaining confidence in the output. The indication that the tools do not appear to be ready for mass application at the schema level is further supported by the high research activity level that is ongoing in the field. As well, the continued use of manual mapping [26] indicates that many vocabulary sets are internally too complex for automated approaches to be used with total confidence.

The problem in reconciling the different MDA schemas is in part due to the large variation in design choices used in the schemas. For example:

a) Large differences in type choices mean that in some cases there is too little typing (i.e., most objects are defined as strings) while in other cases, the object typing is unique to each object;
b) Large differences in name convention mean that in some cases, schema object naming can be vague (e.g., ship) while in other cases naming can be specific (e.g., VesselNameText). Abbreviations used in place of specific names also present a challenge;
c) Large differences in the structure, relationships between the objects, and reusability. Variations in these three characteristics are often related to variations in abstraction layers which result in differences in path length and topology. Often the variations in these characteristics are linked to human design choices and resulting descriptions of concepts in the particular domain.

All of these design choices contributed to the relatively poor performance of the matching tool. This is in contrast with more mature fields such as protein matching where chemical elements and structures have driven the schema design to globally agreed upon terminology and structures. Canadian MDA could certainly benefit from an agreed upon and defined terminology that is adopted by stakeholders. Such a terminology could be used as the authoritative schema, with all other schemas existing in individual systems then mapped to the authoritative schema.

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