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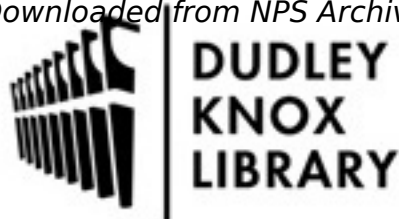Blais, Curtis L.; Gates, Buhrman Q.; Nagle, Joyce A.; Burk, Robin K.; Goerger, Niki C.; Richmond, Paul W.

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ABSTRACT: *Achieving semantic interoperability between simulation systems and Command and Control (C2) systems continues to be a challenging area of research and development. One area of considerable study is development of a common representation of the maneuver network to obtain consistency in the results computed by simulations and C2 systems when determining how a ground force will move through some portion of the battle space. The Common Maneuver Network (CMN) program has implemented and demonstrated the ability to obtain consistent results from the One Semi-Automated Force (OneSAF) and an Army C2 system (Army Battle Command System). Moreover, the Army's Assured Mobility concept calls for establishing the mobility common operational picture (M-COP) facilitating command decision-making regarding how best to deploy, move, and maneuver, by ground or vertical means, where and when desired, without interruption or delay, to achieve the intent. The Department of Defense Global Information Grid (GIG) will play a central role in composing the M-COP as a focus area of interest to land warfare decision makers. Network centric operations require the integration of complex communications networks, data from disparate sources, and service-oriented software applications. In the GIG, data and information necessary for the M-COP will be made available through discoverable and callable web-based services to the spectrum of users, software agents, and software systems. The use of ontologies to formally represent data semantics and knowledge combined with service based software architectures provides new opportunities for the integration of command and control systems, simulations, models, and dynamically changing data. This paper describes concepts and architecture for an experiment to further investigate and demonstrate the use of knowledge-based technologies to support tactical maneuver. Automated route planning, route monitoring and intelligent software-initiated route changes are provided in response to unexpected external events such as reports of improvised explosive device (IED) incidents. We discuss the utility of the M-COP ontology for real-time software-based sense-making in response to battlespace data streams fed by a variety of sensor systems. We also discuss lessons learned and planned follow-on experiments that will investigate higher scale capabilities and other characteristics of GIG services based on an expanded version of this initial demonstration prototype, including integration with emerging Simulation Interoperability Standards Organization (SISO) standards such as the Coalition Battle Management Language (C-BML).*

1. Introduction

Achieving semantic interoperability between simulation systems and Command and Control systems continues to be a challenging area of research and development. One area of considerable study is development of a common representation of the maneuver network to obtain consistency in the results computed by simulations and C2 systems when determining how a ground force will move through some portion of the battle space. Recently, the ability to obtain consistent results from the One Semi-Automated Force (OneSAF) Testbed Baseline (OTB) and a Command and Control (C2) system using Battlefield Terrain Reasoning and Awareness (BTRA), a geospatial information system application [1, 2] was demonstrated. Moreover, the Army's Assured Mobility concept [3] calls for establishing the mobility common operational picture (M-COP) to enable command decision-making regarding how best to deploy, move, and maneuver, by ground or vertical means, where and when desired, without interruption or delay, to achieve the intent. The emerging Department of Defense (DOD) Global Information Grid (GIG) will play a central role in composing the M-COP as a focus area of interest to land warfare decision-makers. Network centric operations require the integration of complex communications networks, data from disparate sources, and service-oriented software applications. In the GIG, data and information necessary for the M-COP will be made available through discoverable and callable web-based services to the spectrum of users, software agents, and software systems. The use of ontologies to formally represent data semantics and knowledge, combined with service based software architectures, provides new opportunities for the integration of command and control systems, simulations, models, and dynamically changing data.

In 2005-2006, the Army Simulation to Command, Control, Communications, Computers, and Intelligence (C4I) Interoperability (SIMCI) program sponsored work to define the semantics of the M-COP supporting ground maneuver planning and execution [4]. This work resulted in definition of a data model and preliminary ontology (formalized semantics) relating to information critical to ground vehicle mobility. The data model describes content on the order of a glossary or thesaurus [5] and can serve as a point of reference for design and implementation of new databases and applications, as well as a basis for enhancements to existing data models. Formal ontology work resulted in a standardized vocabulary and relationships that allow representation and transfer of ground vehicle maneuver data, planned routes, trafficability assessments, and other information associated with the assured mobility concept between Modeling and Simulation (M&S) systems and Battle

Command (BC) systems. This in turn facilitates automated planning, analysis, and embedded training. The team implemented and demonstrated prototype software as a proof of principle.

To achieve the net-centric data strategy, a means of interpreting ground vehicle mobility-related data and information to obtain a level of understanding and interoperability for exchanging and processing such data and information is required. This necessitates that the elements of the M-COP be well-defined to promote common understanding and consistent application.

This paper describes concepts and architecture for an experiment to further investigate and demonstrate the use of knowledge-based technologies to support tactical maneuver. Automated route planning, route monitoring and intelligent software-initiated route changes are provided in response to unexpected external events such as reports of improvised explosive device (IED) incidents. Discussed is the utility of the M-COP ontology for real-time software-based sense-making in response to battlespace data streams fed by a variety of sensor systems. Additionally lessons learned and planned follow-on experiments that will investigate higher scale capabilities and other characteristics of GIG services based on an expanded version of this initial demonstration prototype, including integration with emerging Simulation Interoperability Standards Organization's (SISO) standards such as the Coalition Battle Management Language (C-BML), are presented.

2. Background

Several tasks performed over the past three years established the foundation for continuing and expanded work that can lead to a deployed operational capability. The following subparagraphs provide brief background information on these key efforts:

- Common Maneuver Network (CMN) – discusses enabling a simulation and an operational C2 system to perform maneuver planning on a common representation of the maneuver network.
- M-COP – reviews defining a data model and preliminary formalized semantics for the collection and processing of information critical to assuring ground vehicle mobility.
- CMN/M-COP – describes a demonstration, providing an implementation and proof of principle of the concepts discussed.

2.1 Common Maneuver Network

The BTRA research program in the U.S. Army Engineer Research and Development Center (ERDC) provides tools

to the Commercial Joint Mapping Tool Kit (C/JMTK) to support BC systems [6]. One of the BTRA base products is a ground vehicle maneuver network, which can be developed by a terrain analyst using C/JMTK, automation tools, subject matter expert knowledge, and the Standard Mobility Application Programmer's Interface (API) [7] for estimating ground vehicle speeds. Richmond *et al.* [1] described the implementation into OTB of route planning algorithms based on this network. Comparisons are made between a standard OTB route and a BTRA-based route, along with the additional environmental influences that can be considered. Figure 1 shows a BTRA-generated network (white lines) and a BTRA platoon route (thick blue lines) in OTB; the platoon moves from a line formation into a column formation to follow a road.
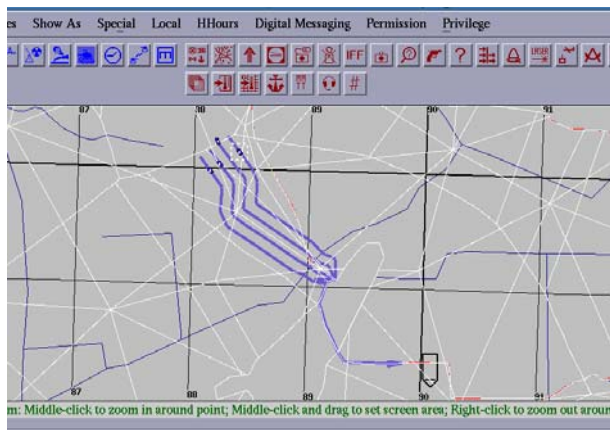

Figure 1. A maneuver network in OTB, with a route plan.

2.2 Mobility Common Operational Picture

The Army's Assured Mobility concept calls for establishing the M-COP to enable command decision-making regarding how best to deploy, move, and maneuver, by ground or vertical means, where and when desired, without interruption or delay, to achieve the intent. A common operational picture (COP) provides "a single identical display of relevant information shared by more than one command" [3]. It is intended to be tailorable to a specific decision-maker's needs and able to facilitate collaborative planning involving multiple decision-makers and staff.

The M-COP is defined as "a subset of the COP consisting of relevant tactical movement and maneuver data and information shared by more than one command" [4]. The M-COP can be tailored for various users and will include data and information for mobility of individual combatants, ground vehicles, and autonomous/robotic vehicles.

Previous Simulation Interoperability Workshop (SIW) papers [8-11] described earlier work on this project and are identified, along with the overall project approach, in Figure 2. These papers discuss the operational basis of the M-COP and identify components and attributes of an M-COP data representation.

The M-COP will be obtained through the creation of virtual links between information requirements on the user side and information sources on the network side. The information requirements – i.e., the data and computational products needed to populate the user's view of the battlespace situation relating to mobility – are derived from the metadata description of the M-COP. In addition to basic data, the M-COP data representation must also support GIG services related to ground vehicle mobility and maneuver.
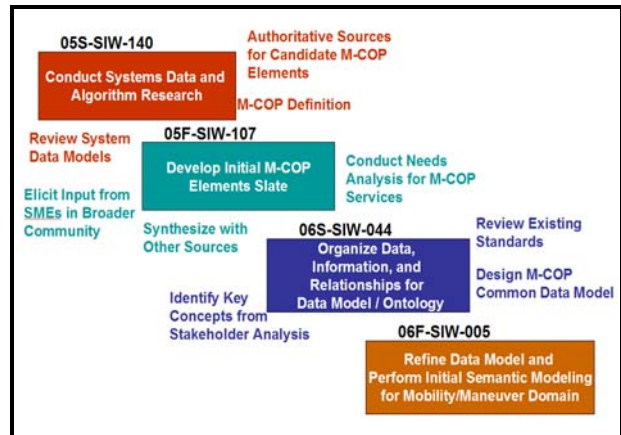

Figure 2. Earlier papers describing M-COP approach, products, and documentation.

The principal categories of information requirements of the M-COP are identified in Table 1. It is important to recognize that there is not a single definitive "answer" regarding the categorization of the M-COP elements. The goal was not to provide a "perfect" data model but to identify a set of categories that can be used to guide further specification, and to identify interactions between the categories and underlying data classes.

Clearly, the amount of information needed to represent ground vehicle mobility and maneuver at a high level of fidelity is voluminous, particularly in the area of terrain attribution. The linkages and analysis required between terrain information and maneuver performance can be complex; however, identifying the information requirements is a first step to achieving an M-COP from and between BC and M&S perspectives. For the first time, a body of knowledge is specified for this domain that indicates both the raw data necessary for movement planning as well as the logic products needed to support

movement planning through software services or as decision support tools.

The M-COP data model defined to date can neither be called a definitive work nor a completed work. It is, however, an example of an "80% solution" that is so important to today's advances in military information technology. Taking the lead from the long-standing, practical, multinational, multiservice Joint Consultation Command and Control Information Exchange Data Model (JC3IEDM) development, the M-COP data model provides a core set of information requirements for ground vehicle mobility that can be extended and refined as the concepts are employed in emerging M&S and BC systems. Based on the primary information specified in the data model, a portion of the data model was formalized using the Web Ontology Language (OWL) to serve as a basis for software implementation and demonstration. It is worth noting that the M-COP project was just one of several recent initiatives in the DOD striving to introduce stronger semantics into data representations to improve interoperability across M&S and BC systems [12].

Table 1. M-COP top-level categories.

Categories	Definitions
Terrain	Natural and manmade features and attributes that influence mobility or maneuver of ground vehicles.
Obstacles	Terrain features or other objects or conditions that disrupt or impede movement of ground vehicles.
Weather	Observed and forecasted weather conditions that affect mobility and maneuver.
Maneuver Analysis	Results of analysis of ground vehicle movement relative to mission, C2, local culture, and other considerations.
Route Finding	Results and related information of finding a minimum-cost route in a maneuver search space.
Threat Analysis	Locations, capabilities, potential actions and other information relating to threat maneuver that can include, in addition to enemy forces, local population, and cultural effects.
Forces	Information relating to maneuver and transportation units, individual platform locations, and capabilities as related to mobility and maneuver.
Utilities	Metadata (e.g., spatial and temporal concepts) that may be applicable to all elements of the M-COP.

2.3 Limited Extent Demonstration and Network Science Application

An application which demonstrated the use of knowledge-based technologies to support tactical maneuver was developed by the authors [13] using open source and in-house software linked together to conduct a simple simulation of a realistic mission (move from A to B along a "safe" route). Events which may affect the route are initiated, reported, and stored in the knowledge base. Through the use of an automated reasoner, events which affect the route were identified and passed to the decision-maker along with a proposed alternate route. Figure 3 shows the scenario. A maneuver network is used to plan a route avoiding IED threats. During the mission, a bridge is destroyed and reported to the knowledge base. Since the knowledge base is also aware of the unit's current route and location, the software determines that the unit should be notified. The unit then requests a revised route.
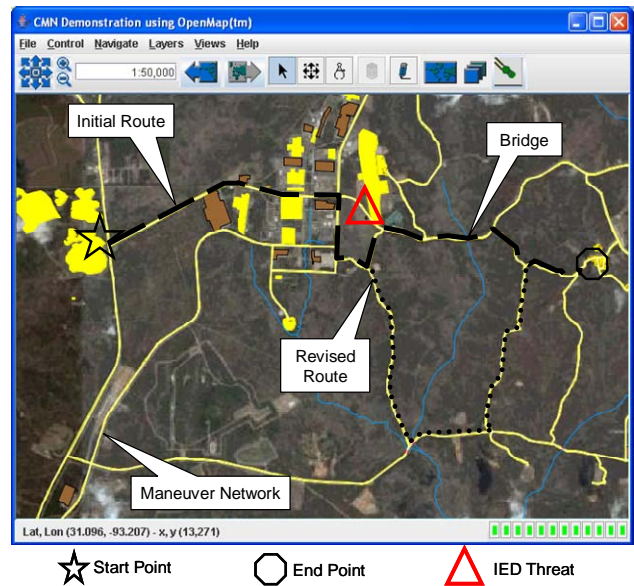
Figure 3. Demonstration scenario and maneuver network.

While the rules and methodology could easily have been programmed in any computer language, use of an ontology in OWL together with the Semantic Web Rule Language (SWRL) to form the knowledge base condensed the complexity of developing this software and encoded the rules in human-accessible and computer-accessible form. Moreover, by extracting knowledge regarding the mobility implications of threats and obstacles into stand-alone rules, this architecture offers ease of modification, extension, and reuse in response to changing conditions in a theater of operations.

3. Network Science

Network Science involves the study of networks - how to characterize them, how they form, how they behave, and how they can be influenced [14]. The study of networked phenomena of all kinds (including social, cognitive, communications and information, and biological networks) has gained importance in recent years as we have witnessed the unprecedented growth of the Internet and World Wide Web, including web-based social phenomena such as MySpace and Facebook. In response to new IED threats in places like Iraq and Afghanistan, network science is entering into expanded research and development efforts that are concerned with "defeating the network." These efforts endeavor to detect and counter the network of materials, funds, skills, and human operators that precede an actual detonation event and subsequent losses to equipment and personnel.

In light of the importance of emerging network science methods and insights, the authors presented the CMN/M-COP demonstration at the Network Science Workshop held at the United States Military Academy, West Point, in October 2007. In the context of CMN/M-COP, the concern is with network dynamics affecting ground vehicle mobility. In other words, how are maneuver networks formed in light of mission objectives, terrain features, vehicle and soldier capabilities, and other considerations identified in the M-COP data modeling and ontology work? How can maneuver networks be characterized based on flow capacities and security issues? How do they evolve over time due to civilian activities, enemy threats, weather, and other factors? Understanding these dynamics will enable systems and decision-makers to make better use of the networks for mission success and safety, and even for more effective neutralization or destruction of the enemy.

The CMN/M-COP route planning, data modeling, and ontology efforts have set the foundation for exploration of the dynamics of maneuver networks. The ontology characterizes relationships of battlespace information to the ability of forces to maneuver. As information becomes available from the battlespace concerning the various factors of interest, conditions needed for assured mobility are satisfied or violated, causing reassessment of the viability of various arcs and nodes along the maneuver network. New movement arcs can be "activated" as prior arcs are "deactivated" due to weather, enemy activity, or other factors. Patterns of activation and deactivation[1] may emerge that indicate particular portions of the network that have greater volatility. Weights on the arcs can be adjusted to cause new routing to be computed for ongoing

and planned movements. Network science may hold the key to interpreting the dynamics of the maneuver network to provide insights for improved decision-making.

Perhaps of equal importance is a more subtle area for application of Network Science in this domain. The M-COP knowledge base consists of assertions and axioms relating to the knowledge structure (classes) and knowledge content (individuals). Expressed in Resource Description Language (RDF), RDF Schema (RDFS), and OWL, the knowledge base is literally an arc-node graph constructed from subject-predicate-object triplets. As new information is asserted, software processes in the M-COP application perform queries, description logic reasoning, and rule-based reasoning to determine if conditions of interest are satisfied and to infer new knowledge. One can imagine numerous pathways in the knowledge base graph being "activated" as the query and reasoning processes are performed. Over time, "activation" patterns may reveal additional insights about the battlespace as represented in the knowledge base. Perhaps the patterns occurring in this logical representation of the battlespace can reveal insights into characteristics and behaviors of the battlespace itself or the operations being conducted in the battlespace. The key is the ability to represent and evaluate the rich dynamics inherent in these military operations. It will be exciting to see what may be revealed through this line of inquiry.

4. M-COP Pragmatics

The power of modern information technology is producing an information glut [15] for today's military decision-makers. Command and control systems possess more information than human decision-makers are able to process efficiently. Numerous initiatives have tried to address this issue, attempting to provide only the most critical information to the decision-maker in a timely manner and in a form he/she can readily interpret. This has led to such efforts as the User-Defined Operational Picture and the Common Relevant Operational Picture, and has indeed been a primary driver in defining the M-COP. In decision-making, the value of information is measured in its ability to reduce uncertainty. This is a pragmatic concern – that is, will a certain bit of information serve to reduce uncertainty? Commanders must make sense of a flurry of facts and make potentially life and death decisions in the face of rapidly changing situations and, often, in the face of significant uncertainty as well. As a result, a mobility-oriented ontology must go beyond capturing information relating to vehicles, terrain, and weather conditions. To be valuable, a mobility-oriented ontology needs to capture the logical relationships which, when applied to specific conditions, allow accurate judgments regarding the operational implications of those conditions. This is the sense-making

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[1] Evocative of the passage of chemical discharges along neural pathways.

task, expertise in which is developed in commanders over an extended period of professional development and training.

Ontology development can be a difficult and cumbersome process. Industry efforts such as the Institute of Electrical and Electronics Engineers' (IEEE) Standard Upper Ontology and Standard Upper Merged Ontology [16] focus on top level, abstract concepts in the expectation that working groups can flesh them out with domain-specific detail. While top-down ontology definition has some value for broad problems such as Semantic Web interoperability, it entails several difficulties when applied to complex operational domains such as ground-based maneuver and mobility for military operations. One reason for this difficulty lies in the need for military command and control decisions to take into account and respond to a very wide range of potential "facts on the ground" as discussed above.

The broad range of possible judgments to be made and the need to earn user confidence in automated judgments of this sort argue against a top-down ontology development effort. Instead, progress may best be made toward useful and trusted mobility software services if a 'bottom up' approach is taken. Formalizing the ability to make small, discrete judgments such as the trafficability of a given route in response to conditions on a given day, combined with services such as automatically identifying alternative routes, meets operational needs of our forces today while also providing a system capable of incremental improvement and extension without disruption to existing software code.

4.1 Valued Information at the Right Time

To best serve decision-makers, information systems need to be able to determine what information is valued by the decision-makers. Current mechanisms in prominence today largely continue to place the onus of discovery and filtering on the user side of the "information highway." Unfortunately, this part of the network (denoted the "edge" in [17]) has far less bandwidth and fewer processing resources (human cognition and machine intelligence) than exists across the full distributed enterprise. For example, using "smart pull," the edge user/system has to query (often repeatedly) the distributed information enterprise (i.e., the emerging GIG in the military context) for data of interest and to obtain the results of that search. The same is true of subscription mechanisms where the user/system has to find the source of potentially useful information and subscribe to receive the information when it is available. The user/system generally has limited ability to place explicit conditions to filter the information flow. The knowledge of what information is important (has value) is held locally (in the

user or user's decision support system) and has to be formulated for transmission to the information enterprise. Information from the enterprise has to be assessed for relevance at the user end. Any extraneous or irrelevant information has at that point consumed valuable network resources (bandwidth) and processing resources (human and mechanical).

How can we turn this around so that the information enterprise can more effectively and efficiently serve the needs of the decision-maker? One approach currently being researched is called Valued Information at the Right Time (VIRT) [18]. The basic precept is that efficient communications requires a shared context (mental model). This means information providers need to understand the information requirements of their "customers," much as suppliers in modern manufacturing supply chains have detailed knowledge of customer needs to reduce intermediate costs by providing the correct materials at precisely the right time in the production process. Information that matters to the decision-maker is identified as *conditions of interest* (COIs). This is information that indicates deviations from the expected state of the world within the context of the planned action or operation. This includes conditions that need to be true when the plan is formulated, conditions that need to be true prior to plan execution, and conditions that need to be true during plan execution. Of course, the earlier that valued information can be provided to the decision-maker to enable possible replanning or changes to the operation, the better.

For practical application, a way to generate information requirements from the semantics of plans and orders is required. Thinking of the knowledge base as a large network of information elements as introduced earlier, of interest is the derivation of COIs from the elements expressed explicitly and implicitly in the plan or order. In earlier VIRT research, the COIs are generally created by the user decision support system and presented to the information enterprise as standing queries or logical axioms to be proven or disproven. In the M-COP concept, the knowledge base is actually a part of the information enterprise rather than part of the local system. The plan or order is passed to the knowledge base (e.g., via web services). Conditions explicit or inferred in the plan or order are checked against the knowledge base. Information available at the time of receipt of the plan or order can be used to evaluate viability of the mission, including initial computation of a movement route to accomplish the conditions set in the plan or order. Alerts can immediately be sent to the decision-maker if current information is available that indicates there are potential problems in accomplishing the plan or order. If initially viable, the plan or order is reevaluated as new information is obtained (new assertions in the knowledge base) so that

the decision-maker can be alerted if subsequent information indicates a potential problem in achieving the mission. If new routing can be computed, the route is provided to the decision-maker for possible use. Or, of course, the decision-maker can abort the mission if he/she considers conditions to be unsuitable for that operation.

4.2 Coalition Battle Management Language

The Coalition Battle Management Language (C-BML) is an emerging international standard currently in Product Development status in the Simulation Interoperability Standards Organization (SISO) [19]. C-BML is a standard language for expressing plans, orders, and reports that can be exchanged and understood by C4I systems, M&S systems, and (eventually) robotic systems. The basic concepts of C-BML are the 5Ws – *Who*, *What*, *When*, *Where*, and *Why*. The draft Phase 1 C-BML Specification defines these as follows:

Who: C-BML information component identifying the battlespace object directed to perform an action (plan or order), that has been observed or has performed an action (report), or on which an action is to be performed (e.g., target).

What: C-BML information component identifying an action to be performed (plan or order) or that has been performed (report).

When: C-BML information component describing the time frame in which an action is to occur (plan or order) or when an action or event has occurred (report).

Where: C-BML information component providing the location of an object in the battlespace (C-BML Who), the location where an action is to occur (plan or order), or the location where an action or event has occurred (report).

Why: C-BML information component describing the rationale or purpose of an action to be performed (plan or order), or the desired end state of a planned action.

When finalized, C-BML will provide a well-defined vocabulary, syntax, and semantics for expressing plans, orders, and reports.

The content of the plan or order implicitly identifies information of consequence - COIs. Consider a plan or order to move forces from one location to another. Information of consequence to this operation is precisely what has been identified in the M-COP data model and ontology, relating specifically to the route that is computed or assigned to the movement and the region through which that route passes. Given a C-BML

expression of the plan or order to move a force, the following "activations" of the knowledge base occur:

Who: Identifies the force conducting the movement. Critical information relates to the capabilities, readiness, and supply conditions of the force (including its equipment). Spatial and temporal constraints may exist based on current position of the force and location of the movement. Activates common COIs in the *Forces* category in the M-COP data model/ontology.

What: Describes the movement action to be performed. Critical information relates to the ability of the force to perform the mission given its operational status. Activates common COIs in the *Maneuver Analysis* and *Forces* categories in the M-COP data model/ontology.

When: Identifies any temporal requirements on the movement task (e.g., start time, end time, duration of movement). Activates common COIs in the *Forces* and *Maneuver Analysis* categories in the M-COP data model/ontology.

Where: Identifies location of the movement (e.g., explicit or implied start point, end point, assigned route). Together with *When* requirements, activates common COIs across the *Terrain*, *Obstacles*, *Weather*, *Maneuver Analysis*, *Threat Analysis*, and *Forces* categories in the M-COP data model/ontology (that is, aspects of these categories that relate to the space-time window of the operation).

Why: Indicates the desired end state of a planned action. Together with *When* and *Where* information, *Why* can establish criteria for assessing the success of the operation. In so doing, it activates common COIs across all categories of the M-COP model/ontology.

C*ommon* COIs in the above implies a standard set of COIs that can be predefined based on operational experience. These COIs create a pragmatic precedence in movement of information - what is most valued to the decision-maker is given precedence over other information. Established tactics, techniques, and practices enable immediate creation of the "80% solution," an initial capability that can meet the majority of situations normally encountered. Of course, the system must provide a means for adaptation to changing conditions. The use of the ontology representation helps support adaptability through modification of data rather than modification of software logic. While the M-COP data model/ontology has been engineered to represent information of value to the decision-maker, more work is needed in generating the COIs from the information

elements in the plan/order, where the COIs will take the form of semantic queries, rules, and axioms in the knowledge base.

5. Summary and Recommendations

Work to date has shown the potential benefits of application of formalized semantics to describe important considerations in the context of assuring ground vehicle mobility in today's complex warfare environment. The employment of well-defined semantic models across multiple systems is essential to achieve high levels of interoperability [20]. With the introduction of appropriate semantic models it becomes possible not only to exchange data among C2 systems and simulations, but also to incorporate simple elements of the battlefield sense-making task into simulation-based studies and, eventually, into GIG software service agents and autonomous unmanned equipment. By freeing commanders from the need to identify the mobility implications of threats and events, semantic reasoning systems enable warfighters to focus on other critical information and decisions while also ensuring they benefit from the GIG's access to increasing amounts of real time data from the battlespace.

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