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Operationalizing C2 Agility

Cornerstone: Foundational Models and Services for Integrated Battle Planning

Topic 4: Collaboration, Shared Awareness, and Decision-Making

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1 Abstract

The Air Force has three mission elements, air, space and cyber that it must command and control as a Joint and Coalition partner. Today's Air Operations Centers (AOCs) want to improve multi-domain collaboration. To address these challenges, Air Force Research Laboratory Information Directorate (AFRL/RI) is sponsoring exploration and development of an Integrated Battle Planning Capability (IBPC) to coordinate and synchronize planning across the three domains. As a first step toward this goal, BAE Systems is developing Cornerstone, a suite of web services for mission request brokering, dynamic model management, plan management, and a Unified Plan Representation (UPR). The UPR is based on already established community standards and a common ontology of shared and domain-specific concepts. This paper describes Cornerstone's research and development accomplishments to date, including an overview of the ontology, system design, and elaboration of the web services. Results from an initial Limited Technology Experiment (LTE) are reviewed. In the LTE, Cornerstone services correctly used the Jena semantic reasoning engine to broker air, cyber, and space mission option data among simulated and human domain-planners.

2 Introduction

To improve unity of effort, the US Air Force has called for improving coordination and synchronization among its mission domains, air, space and cyber, to keep up with an increasingly dynamic adversary decision cycle, and to be more efficient at synergizing available resources. Current computerized planning systems lack both a common basis for representing and maintaining cross-domain mission needs and a coherent structure to guide workflow and communication.

To address these challenges, AFRL is sponsoring development of Cornerstone, a foundational data representation and suite of services for brokering and managing missions that span air, cyber, and space operations; across both mission domains and security domains. During the first phase of Cornerstone (Mar-Nov 2010), AFRL, BAE Systems, and supporting contractor Metatech Corp, conducted knowledge acquisition workshops, collected many existing schemas and Community of Interest (COI) documents, and synthesized salient schemas and standards into a shared ontology supporting the three targeted domains. During Phase 2 (Aug 2010- Sep 2011), the team focused on prototyping components and web services for request brokering, plan management, and model management.

To get things working together, we also designed and built additional infrastructural services for interfacing with existing, external planners and translating between them. At the end of Phase 2, the end-to-end workflow, run-time performance and extensibility of the prototype system were tested in various configurations during a Limited Technology Experiment (LTE) held on-site at AFRL Rome Research Site. This experiment demonstrated Cornerstone's ability to broker requests, and store and retrieve mission data across all three domains. It demonstrated how Cornerstone services could extend models rapidly on-the-fly at run-time to process evolving mission needs and planner capabilities. The experiment also exposed specific areas for performance improvement that were addressed early in the subsequent phase.

This paper describes Cornerstone research activities and findings, beginning with Section 3 describing our multi-domain ontology and model representation approach and design. Section 4 provides an overview of our system design. Section 5 discusses the five Cornerstone web services, and Section 6 covers integration of the end-to-end system. In Section 7 we provide a more detailed account of the procedures and results observed in the Phase 2 LTE. We close with a summary of future planned research.

3 Cross-Domain Knowledge Representation

One of the primary reasons behind the interoperability struggles we have been facing with current C2 systems is their use of what used to be state-of-the-art: monolithic relational databases and stove-piped applications necessarily specialized for each function. Because early applications were designed and built in the ancient days of manual, paper-based techniques, it was deemed acceptable, and even necessary, that communication between functions used human-readable text messaging. These systems have since proven very expensive to extend and modify to get them interoperating with each other. A consequence of this state of affairs and the "new" need for interoperability is the proliferation of custom translators, adaptors and interface wrappers.

The evolution away from monolithic databases to more semantically aware and agile methods using standards such as eXtensible Markup Language (XML), Resource Description Framework (RDF), and Web Ontology Language (OWL) hold high potential to increase extensibility and reduce long-term integration and maintenance costs [OWL]. For this reason, we are experimenting with OWL as the representation language for Cornerstone's multi-domain ontology.

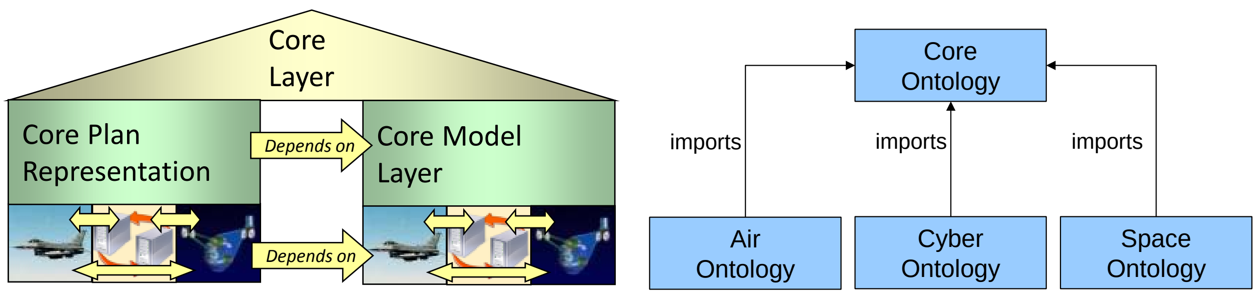

Figure 1: Cornerstone uses the OWL semantic web standard and object-oriented design principles to model shared vs. domain-specific concepts for plans and models.

As shown in Figure 1, our ontology is designed with three layers (left) and four OWL file segments: Core, Air, Cyber, and Space (right). The core layer is an upper ontology containing the most general concepts such as AbstractObject, Entity, EntityState, SpatialThing, and Situation. The middle layer encodes concepts specific to C2 models (e.g., resources, organizations, planners) and plans (e.g., requests, tasks, missions, intent) but still generalizable across specific domains. The third layer includes domain-specific model and plan concepts unique to a specific mission domain. In this way, a mission domain does not have to change to comply with an evolving standard, thereby giving us an affordable way of interoperating.

The main concepts in the Cornerstone Core Ontology are depicted in Figure 2 below. A *Mission* is a high level task related to accomplishing a military objective. A *Task Request* (recently simplified to *Request*), represents a request by one planning agent for another agent to accomplish a certain task. Requests in the Cornerstone ontology specify "what" a task should accomplish but not "how." A *Request* must include the desired effect, time window, and a location or target, but typically does not specify a particular domain; often an effect may be fulfilled by any multiple of domain planners. A *Mission Task* (simplified to *Task*) is a military action that can be assigned to a military organization with resources in order to achieve an objective. A *Task* can be performed using one or more *Resources* (e.g., a fighter aircraft or a cyber capability), each under the control of an *Organization.* An *Organization* may also issue requests for original or supporting missions and tasks. The self-referential link on *Task* allows for an arbitrarily deep nests of such supporting tasks. The self-referential link on *Organization* can be used to represent a hierarchy of subordinate military units.

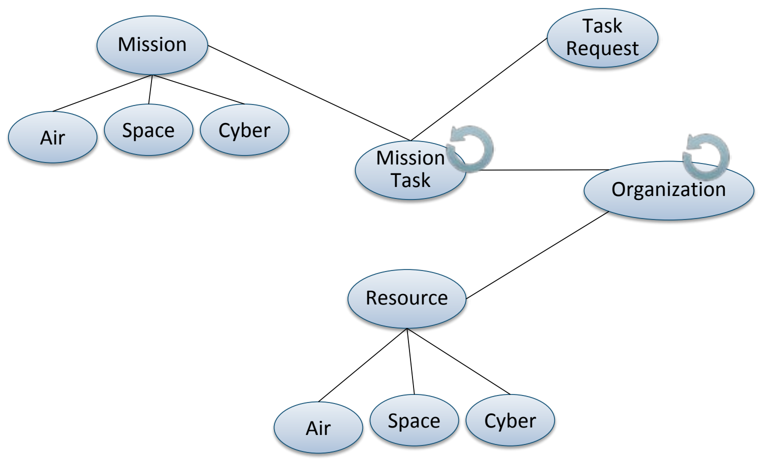

Figure 2: The Core Ontology captures concepts common to all planning domains, including Mission, Request, Task, Organization, and Resource.

The domain-specific ontology layer extends the core concepts to encode concepts and relationships specific to air, cyber, or space. Figure 3 shows a selected subset of concepts from all three domains and all four ontology segments. It also depicts, via colored, lettered boxes, the original sources that informed the design of the concepts in that box. Much of the Core ontology was derived from the Universal Core (UCore), an XML-based schema for U.S government interoperability. It describes general concepts for Who, What, When, and Where [UCore]. The air-domain ontology is mainly based on recent data standards published by the Air Operations Community of Interest (AO COI). The AO COI defines the Mission Task Request (MTR) for basic mission requests, and the Common Mission Definition (CMD) for representing more specific air mission requests, tasks and related concepts such as *RoutePoint* (a Route Point is a description of a location at which a sub-task of a Mission occurs).

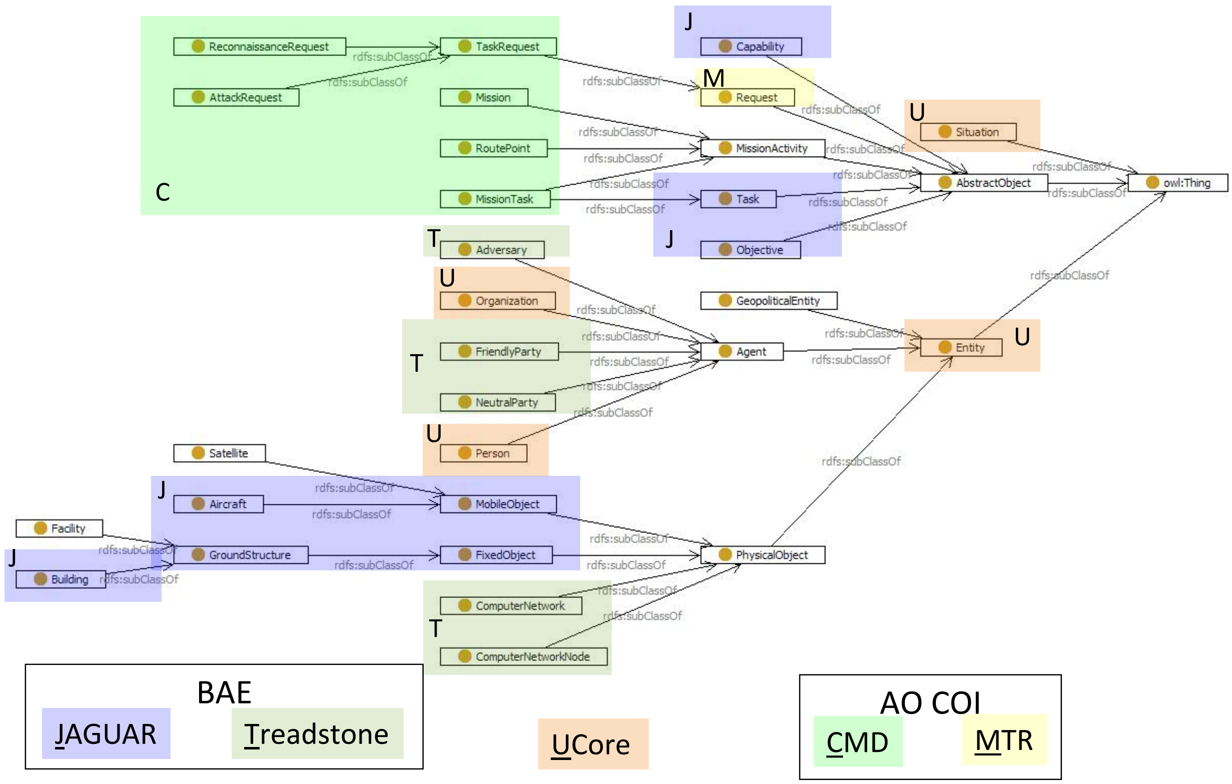

Figure 3: Cornerstone's ontology synthesizes concepts and relationships from emerging and established air, cyber, and space data standards from prominent/authoritative communities of interest.

Cornerstone adapted additional air concepts such as *Capability*, *Objective*, *Aircraft*, and *FixedObjects* vs. *MobileObjects*, and others from BAE's previous research in automated plan generation under the Defense Advanced Research Projects Agency (DARPA) Joint Air Ground Unified Adaptive Re-planner (JAGUAR) program [JAGUAR]. For the cyber domain, Cornerstone imported and expanded on concepts from AFRL's recent Treadstone Computer Network Attack characterization research, also performed by BAE [Treadstone]. Cyber-specific concepts include *ComputerNetwork*, *ComputerNetworkNode*, and Friendly vs. *NeutralParty* affiliation. Space-domain ontology concepts and missions such as Satellite, Space ISR, and Overhead Persistent Infrared ISR (OPIR), were defined by partners in Metatech Corp. They based designs on their extensive experience developing space warfare scenarios and datasets for space operations wargames and recent space situational awareness research for AF Space Command.

4 System Design

In parallel with the multi-domain ontology development described above, the Cornerstone team designed and prototyped the software design shown in Figure 4. The architecture is service oriented and includes Java 2 Enterprise web service standards, utilizing the Service Oriented Architecture (SOA) stack embodied in the Navy's Afloat Core Services (ACS), which has standardized on RedHat CentOS 6.2 (Linux 2.6) and JBOSS 5.1 [ACS]. The thin blue and yellow cylinders represent http-based communication capabilities among services and various external planning tools (of which our current focus is on air, cyber, space, and joint strategy planning). These external planners may be either manual or automated as long as they conform to the Cornerstone UPR and request workflow encoded in its exposed Web Service Definition Language (WSDL) specification.

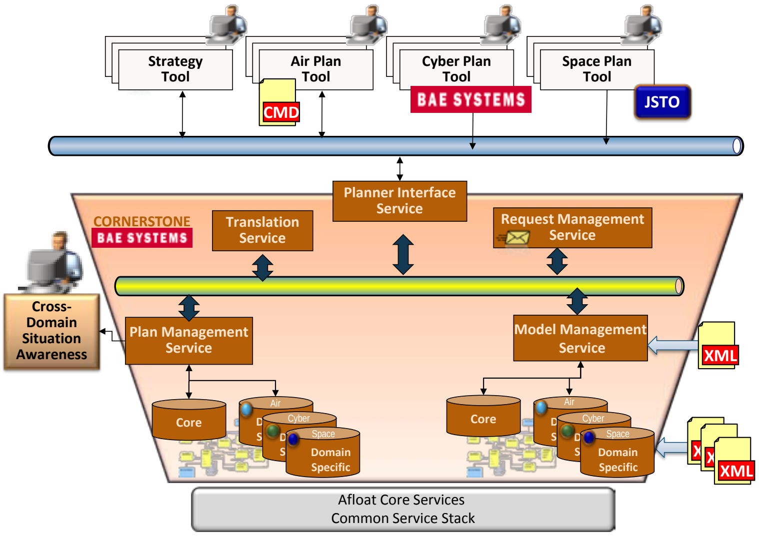

Figure 4: Cornerstone consists of web services for plan, model, and request management, and planner interface and data translation services to provide interoperability with domain-specific planners.

On initialization, Cornerstone's Model Management Service ingests the four OWL files encoding its Core, Air, Cyber, and Space ontology concept definitions, as well as RDF planner capability models describing active organizations, planners, and the types of effects their capabilities can achieve. Cornerstone's Plan Management Service also initializes the Plan Repository, a PostgreSQL knowledge base storing all past, current, and potential future missions, tasks, requests, supporting objects and their interrelationships in RDF triple format. The operator to the left of Cornerstone represents a notional Situation display in a Program Of Record (POR) that would offer on-demand queries and visualization of multi-domain missions stored in the Plan Repository.

We now describe briefly the five web services comprising the Cornerstone system:

- **Request Management Service (RMS)** – Enables collaboration among air, space and cyber domains by performing brokering business logic for mission requests from one domain planner to others, and processing options. RMS also tracks and maintains the request workflow.

- **Plan Management Service (PM)** – Provides access to plans, requests, tasks, and other mission objects stored in the Plan Repository. It includes the full suite of semantic Create, Read, Update, Delete, and Find (CRUDF) operations for ManagedObjects.

- **Model Management Service (MMS)** – Initializes the Cornerstone ontology and manages dynamic updates to models, including new effects, planner capabilities, and world state.

- **Planner Interface Service (PI)** – Provides a common external interface to Cornerstone services. Also mediates between Cornerstone derived processing and external planners' planning process(es).

- **Data Translation Service (DTS)** – Translates documents from external planners' representations into Cornerstone's OWL representation (and back).

The next section describes these web services in more detail.

5 Cornerstone Services

The Cornerstone team employed a spiral implementation in which the first spiral focused on developing and unit testing the five services as stand-alone Java components, the second spiral focused on integration and system testing of the end-to-end workflow across components, and the third spiral focused on exposing each component's functionality as a web service, utilizing the Apache CXF framework [CXF]. This last stage began with the Planner Interface Service, since it is the main external point of contact for domain planners, and proceeded with Request Management, Plan Management, Data Translation, and Model Management Services.

5.1 Request Management Service

RMS enables collaboration among air, space and cyber domains by accepting, coordinating and processing requests for mission tasks. RMS matches requests to appropriate planners based on the Model Management Service's models of domain capabilities and sends the request to appropriate planners (e.g., their planning domain, organization, area of responsibility, and the set of effect types they support). It continues to track the request workflow until the request is denied or accepted.

As shown in Figure 5 below (left bottom), RMS acts as a task broker among all participating planners of varying domain specialties and echelons. Typically, one external planner is the requestor, and one or more external planners serve as responders, each providing one or more mission options that could fulfill the request. Current experiments have RMS convey the list of candidate planners to the request originator, who selects none, any, or all of the suggested planners. Based on the selection, RMS routes the request to the chosen planners. Each planner processes the request and sends an asynchronous response message to RMS with one or more mission options. RMS again routes these options to the request originator who selects one or more of the candidate options. Finally, RMS sends an approval/acceptance notification to the external planners whose options were selected. It is then assumed (for now) that the POR planners will include the mission in their next Tasking Order.

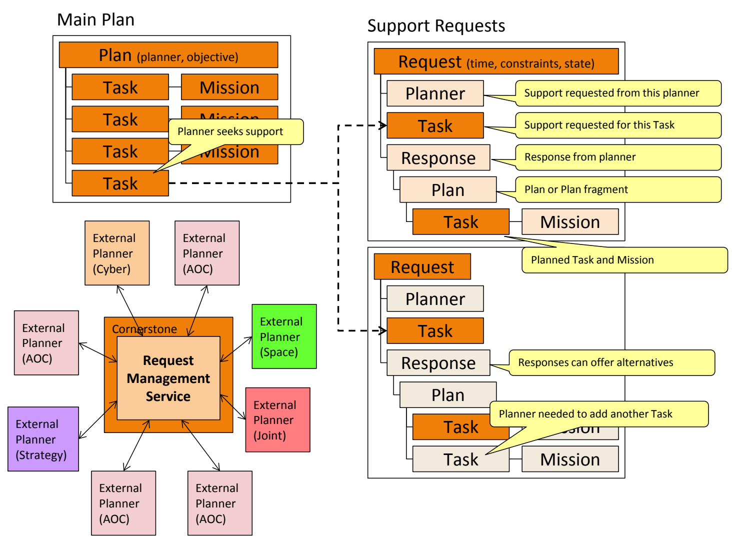

Figure 5: The Request Management Service brokers both original task requests for the main plan and support requests (e.g. air refueling, space ISR) among external domain planners

RMS also performs a check for each incoming request to determine if there is an existing mission in the Plan Repository that can fulfill the needs of the request. If a match is found, it is presented by RMS to the user as a mission option and the user may request reuse of the existing option or ask for new options from matching domain planners.

RMS also supports multiple stages of mission requests as support requests, (Figure 5, right). Examples of support requests include within-mission support such as mid-air refueling or follow-up requests for space ISR to perform Battle Damage Assessment (BDA) to confirm successful effects. In a support request, an external planner determines that it cannot fulfill the original request on its own, possibly due to limitations in resource availability, so it issues a secondary request to RMS describing the supporting task requirements (time window, effect type, etc.). RMS manages these requests using the same workflow as above, but after processing is complete, the resulting task support relationships and selected planners and mission options are stored hierarchically in the Plan Repository via the Plan Management Service.

In an operational environment, RMS offers a scalable, flexible approach to collaborative planning by decoupling direct dependencies among external planners. By leveraging extensible models of domain-specific planner capabilities, it continuously provides human and automated planners with a wide range of options for fulfilling incoming mission requests, all resulting in more efficient, robust plans.

5.2 Plan Management Service

The Plan Management (PM) Service is responsible for storing and updating the evolving multi-domain plan as planner clients issue new requests and users approve resulting options via RMS process.

The PM Service exposes the full array of relational database operations: Create, Read, Update, Delete, and Find (CRUDF). However, the Plan Repository's underlying RDF triple representation is more flexible than traditional relational tables in that it allows a wider range of changes to the schema on-the-fly at run-time without affecting existing data. Cornerstone uses SQL Database (SDB), a component of Apache Jena, to support RDF query and storage [JENA]. SDB supports a range of underlying SQL database instances for storage; we have demonstrated compatibility with both PostgreSQL and MySQL. The use of RDF also enables the PM Service to expose a SPARQL query interface, which offers more expressive semantic queries than SQL alone.

Another important design feature of the PM Service is support for multiple stored representations. Because Cornerstone's ontology is not intended to be exhaustive for all domains, we are experimenting with an option to store a *payload* containing the original native representation of a message or object alongside the Cornerstone OWL representation (a *digest*). The PM Service maintains this digest-payload association in the repository and makes it available to any clients who may require the additional detail for replanning, plan assessment, or visualization.

In addition to SPARQL or SQL queries, the PM Service provides an object-level notification mechanism in which clients may subscribe to events relating to the lifecycle of Cornerstone ManagedObjects. ManagedObjects represent a kind of "first class" object, particularly those types referenced directly in the top-level API, such as Mission, Task, Request, Organization, Resource, etc.

5.3 Model Management Service

The MMS performs a similar function to the PM Service but as the name suggests, it mediates access to Cornerstone models rather than plan data. There are three main types of models, each with increasing dynamicity:

• *Domain Ontologies* – The air, cyber, and space segments of the ontology may require periodic extensions, for example, to incorporate concepts for new cyber capabilities or mission types, given the rapidly evolving nature of cyber supporting warfare. These changes may occur at run-time or load-time, and are expected to occur relatively infrequently.

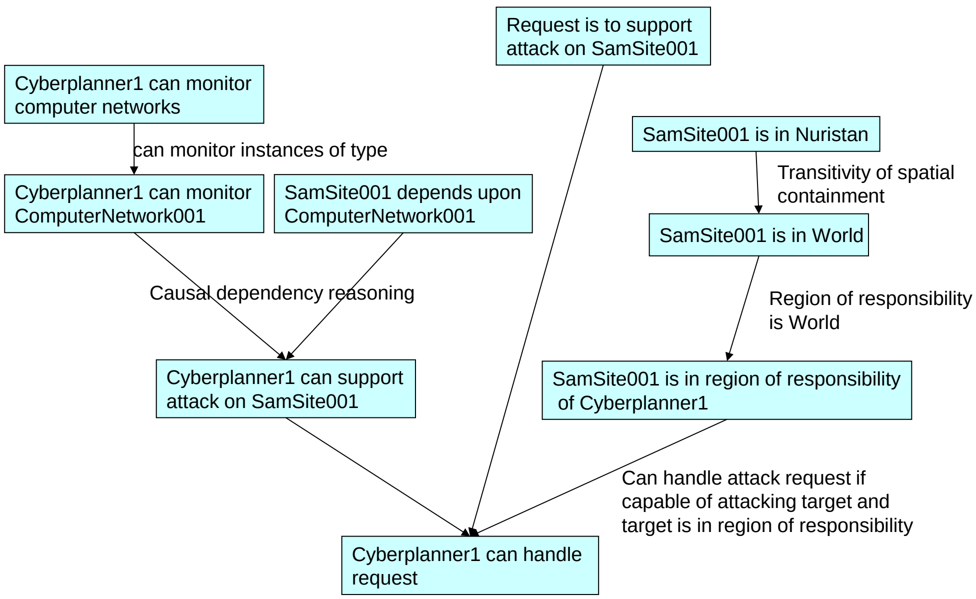

Figure 6: The Model Management Service maintains the OWL ontology and dynamic capability models, and the rules for complex reasoning to match domain planners against requests.

• *Planner Capabilities* – The MMS contains capability models of each domain planner and the effect types and mission types that it supports so that RMS can effectively broker requests to the best-suited domain planners. These capability models may be readily extended as improved versions of existing domain planners or newly deployed planners come on-line. To facilitate rapid extensions to the broker's reasoning, we use a Jena OWL encoding scheme of the business rules for selecting eligible planners, as illustrated by the example in Figure 6. In this example, a request for cyber support for an attack on SamSite001 is matched to Cyberplanner1 by RMS because: a) it has the ability to deploy resources against nodes of type ComputerNetwork; b) SamSite001 depends on the computer network in question; and c) SamSite001 is in the area of responsibility for CyberPlanner1.

• *World State* – The MMS loads an initial description of the state of the world in terms of regions, targets, networks, and their dependencies. With significantly more development, these models would be connected to live operational feeds to ensure an up-to-date picture is maintained for RMS reasoning and command staff decision-making.

Later, in Section 6, we discuss an experiment thread in which an MMS planner-capability model was dynamically extended to support a new type of effect (i.e., during run-time).

5.4 Planner Interface and Data Translation Services

For external planners that are "Cornerstone-aware" (i.e., those that already produce and/or ingest data that is compliant with Cornerstone's OWL format), the above services are sufficient to enable interoperability with Cornerstone's end-to-end workflow. Since no such planners exist yet at this early stage of development, we developed two additional services to bootstrap the integration of several candidate planners:

- The *Planner Interface (PI) Service* acts as a central interface point for non-Cornerstone-aware planners, exposing a facade interface to both RMS workflow and PM Service data access functionality. The PI Service determines which translations are necessary based on the client data.

- The *Data Translation Service (DTS)* exposes bi-directional mediation functionality for translation of request and mission-related ManagedObjects. Early Cornerstone efforts currently support translation from MTR and Space Support Request (SSR) XML formats to its internal format, and two-way translation of CMD, Air Tasking Order (ATO), Joint Space Tasking Orders (JSTO), and the BAE Systems cyber-planner XML format (see next section). Figure 7 illustrates the DTS translation workflow. An external planner issues a request or mission option in a native format, typically XML-based, which is translated within the DTS to create a new ManagedObject in OWL. The native XML is retained as the payload alongside the OWL object in the Plan Repository, as described in Section 5.2 above. When clients request this object in the future, the DTS translates the current OWL instance to the native format but also attaches the original native payload, which typically offers a level of detail beyond what is stored in the ManagedObject.

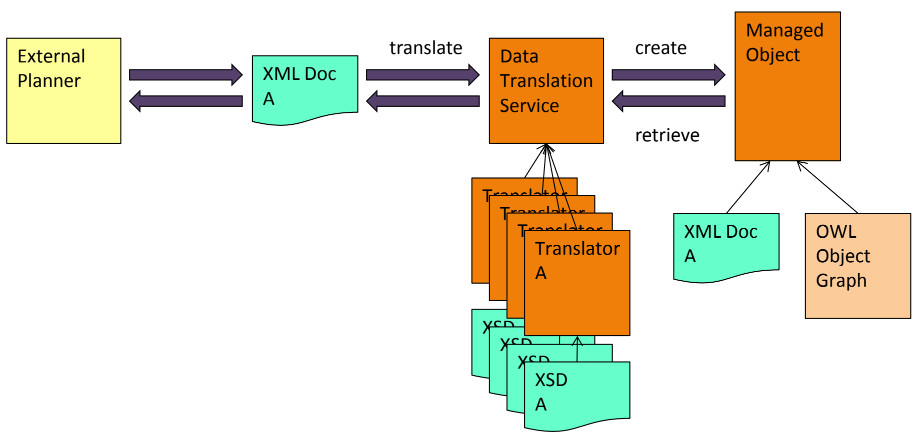

Figure 7: The Data Translation Service mediates between external native request and mission formats and Cornerstone's OWL-based representation.

6 External Planner Integration

As a first test of the services and Cornerstone system workflow, during Phase 2, we surveyed candidate planners for an initial integration effort and settled on a BAE Systems cyber-planner. This planner was chosen in part because the cyber-planner was still under active development and the planner team shared personnel with the Cornerstone team, offering maximum flexibility and shared expertise. The cyber-planner is based on the Generic Modeling Environment (GME), a "meta-modeling" toolkit originally developed by Vanderbilt Univ. [GME1, GME2]. Using a similar approach to that of Cornerstone, the Arlington, VA team first used GME to define a graphical domain model for the cyber domain and then compiled that model into a specialized planning tool. The tool enables graphical authoring of cyber-plans whose elements and relationships conform to the domain model. Unlike Cornerstone, the cyber-planner uses an XML-based schema rather than OWL and RDF to represent plans (but this will change as we progress in both developments).

Thus, to integrate the cyber-planner with Cornerstone, we performed the following tasks:

- Developed bi-directional translators from the cyber-planner XML format to Cornerstone's format, and incorporated the translators within the Cornerstone DTS.
- Added a capability-model of the cyber-planner to the MMS.
- Incorporated code into RMS to notify the cyber-planner when it is selected from the list of candidate planners to provide mission options.

We have yet to get to the task of translating support requests from the cyber-planner because our experiment threads have not yet called for initiation of such requests from the cyber domain. However, we have successfully developed request translators for the MTR and SSR requests for the air and space domains respectively and therefore demonstrated that we can do it for any domain. We discuss the results of end-to-end experiments with the cyber planner and mission data from other domains in the next section.

7 Limited Technology Experiment

At the end of Phase 2, AFRL organized a Limited Technology Experiment (LTE) in order to test the functionality developed to date and establish a run-time performance baseline. AFRL has successfully applied this experimental methodology in recent years to SOA, C2 and Situational Awareness research to establish metrics, verify milestones, and provide formative feedback for ongoing programs.

Figure 8 illustrates the cross-domain vignette that was designed for the Cornerstone LTE. The vignette is triggered by detection of indicators of a direct ascent Anti-Satellite (ASAT) launch by a notional adversary. This leads to requests for missions in multiple domains: 1) a cyber capability activation against the adversary's C2 network to delay the ASAT launch (so that we have time to get other options engaged), 2) a space Overhead Persistent Infrared (OPIR) mission to surveil potential targets, 3) a subsequent air-attack on the launch facility, and 4) other space ISR missions to perform Battle Damage Assessment (BDA) on the strike targets, and to monitor for potentially downed aircraft requiring search-and-rescue contingency missions. The vignette also includes a ground-based Special Forces insertion mission, but was not exercised in the first LTE because of funding scope and lower priority relative to the air, cyber, and space domains; however, we are planning to include other domain capabilities in future LTEs in order to demonstrate that we can incorporate any military capability.

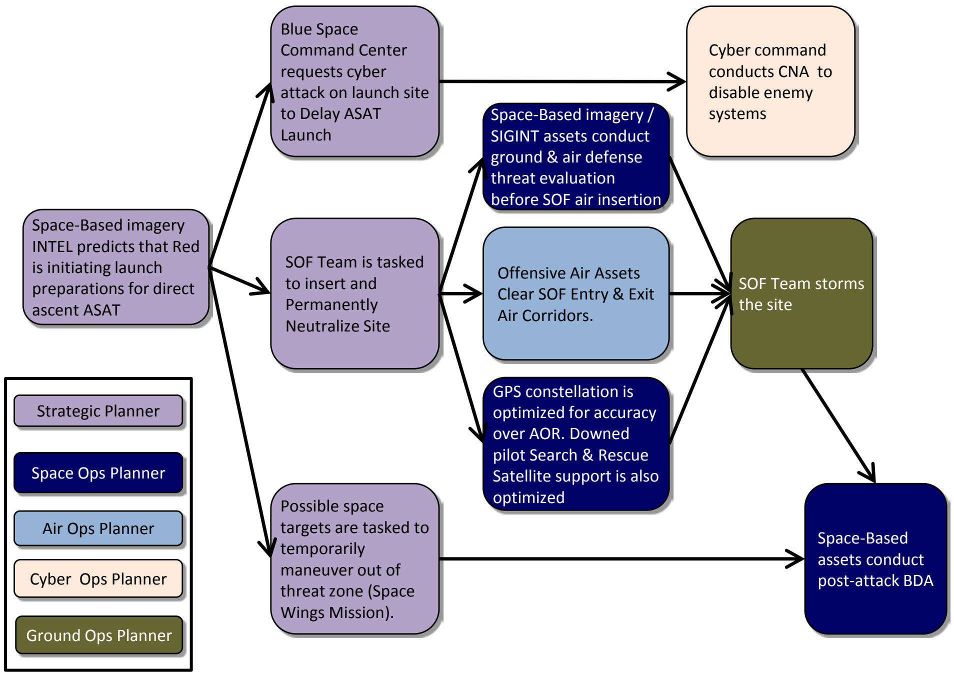

Figure 8: Cross-domain LTE vignette calling for coordinated air, ground, cyber, and space missions, triggered by a notional direct ascent ASAT threat.

The Cornerstone team coordinated with an AFRL integrated C2 experimentation team who assisted with integration into the ACS SOA environment and administered the execution and data collection for the experiment conducted at AFRL Rome. We designed four LTE threads to exercise different aspects of the software described earlier. The purpose, metrics, and results for each thread are described in Table 1.

Table 1: Summary of Cornerstone LTE threads, metrics, and results

Thread	Purpose	Metrics	Results
1. Cross-Domain Mission Processing	Verify successful end-to-end processing of mission requests for air, cyber, space.	Recall, Accuracy: % of expected data reported, % correct output	100% recall and accuracy verified by air, cyber, space subject matter experts for four missions (ten trials)
2. Constraint Processing	Verify detection of violation of no-strike target constraint	% correct trials	100% expected violations reported (ten trials)
3. Run-Time Performance	Establish baseline system and service-specific average run-time and memory usage.	Goal: < 30 sec end-to-end runtime	15 sec for initial trials but run-time increased over the course of 50 trials due to memory leak in object cache (fixed after LTE)
4. Dynamic Model Extension	Verify successful run-time extension of planner capability model.	% correct trials, # unexpected errors	100%, 0 errors: no planners found initially, cyber-planner found after model extension (ten trials)

The purpose of the first thread was to exercise the end-to-end system workflow for mission request processing, ensuring coverage of all three domains (air, cyber, space). The deployment configuration for Cornerstone included the Arlington team's cyber-planner, which was used to generate options for cyber-mission requests. The cyber-planner was fully integrated with

Cornerstone in that it supported automated and live human-in-the-loop interaction, via the Cornerstone Planner Interface Service. For air missions, we pre-loaded the Plan Repository with a 50-mission dataset adapted from the previous DARPA JAGUAR program. For space missions, we authored the OPIR mission artifacts by hand using an XML editor. To ensure correctness and accuracy of output data, we assembled a Subject Matter Expert (SME) team consisting of analysts with experience in each domain to analyze pre-verified mission output and identify salient XML data elements to use as a ground truth basis for comparing LTE output. During the LTE, the SME team verified that Cornerstone mission output contained 100% of expected data elements, and no inaccurate or unexpected output data was detected from manual inspection of all output. Likewise, the SME team verified that the no-strike constraint violations in the second LTE thread were successfully reported by RMS for all trials.

The third thread was administered and analyzed primarily by the AFRL LTE team. This thread used the same mission request sequence as the first thread, but with many automatic repetitions and logging of the timing of key web service entry and exit points. This was done to characterize run-time performance. This thread duplicated the first thread's end-to-end run-time latency of 15 sec, well under our goal of 30 sec. However, over the span of fifty-repetition trials, they observed that run-time linearly increased with each repetition and garbage collection activity tended to spike more frequently on the later repetitions. They also found that RMS and PM Service run-times increased linearly, while DTS performance remained flat throughout all trials. The Cornerstone team traced this issue to a memory leak in the PM Service object cache, associated with the ACS JBOSS methods. The leak was fixed shortly after the LTE and new performance tests verified constant run-time even after thousands of trials in a row.

For the fourth and final thread, we tested whether Cornerstone could process a dynamic extension of a planner capability model within the MMS. Each trial featured a mission request for a "Neutralize" effect that was processed in two stages, a "before" stage and an "after" stage:

- Before the dynamic extension, Neutralize as an effect was not included in any of the domain planner models and hence requests to neutralize a target should yield no candidate planners.

- After the dynamic extension, RMS should suggest the cyber-planner as a candidate because its capability model was extended to include the Neutralize effect type.

For all trials, we verified that the correct output occurred for the "before" and "after" stages. However, for trials in which the ACS JBOSS environment was not restarted between trials, the "before" behavior incorrectly matched the expected "after" behavior for the second and subsequent trials because the MMS models were apparently retaining the model extension from previous trials. Subsequent ontology refactoring and initialization logic improvements after the LTE fixed this problem; however, this points to a curious challenge designing and deploying dynamically changing services; a subject of future experimentation.

We also conducted some exploratory tests. For example, the cyber SME intentionally entered invalid dates on the cyber mission option and verified that Cornerstone's semantic reasoner detected the error and raised an exception. After correcting the dates and resending the option, Cornerstone correctly accepted the response rather than dropping the request. We also verified the correct locations of geospatial air, cyber, and space mission data using Google Earth to display the results of a Keyhole Markup Language (KML) mission data translator. Finally, we successfully ran Thread 1 via an alternate client configuration, in which the air, cyber, and space clients were run as separate processes. This verified that Cornerstone services could support a distributed planning environment, which is the most likely configuration for the eventually deployed system.

8 Future Research

Having achieved a successful end-to-end prototype in Phase 2, future plans for the final Phase 3 experiment with Cornerstone (Nov 2011-Jan 2013) include, by service:

- Integrate Cornerstone with BAE Systems' DARPA JAGUAR automated air mission generator and CACI's AFRL-sponsored Air-Space-Cyber Universal Client as the space tasking order mission management and visualization tool. Develop additional data translators within the DTS.

- Extend RMS to support a negotiation protocol in which Cornerstone users collaborate with domain planners to request minor adjustments to options to synchronize missions across domains.

- Extend MMS to support dynamic registration of new domain planners. Improve the dynamic extension mechanism to support on-the-fly loading of new ontology segments and translators (i.e., to support a new external domain planner).

- In the PM Service, expose finer-grained CRUDF access to additional object types as appropriate.

Over the course of Phase 3, we are also planning to develop a more rigorous test harness to allow for generation of a large number of test artifacts and help scale Cornerstone processing to handle hundreds or thousands of missions.

BAE Systems has also begun work on a follow-on project entitled Synchronized Constraint-based Optimization, Repair, and Assembly (SCORA), which will add automation support via optimal search algorithms. Semantic reasoning is being used for selection of mission options that best fulfill a set of desired effects. SCORA will also use plan repair techniques to automatically synchronize multiple cross-domain missions, and it will add a capability to assemble and publish a complete integrated battle plan.

9 Conclusion

To address the challenge of coordinating complex multi-domain operations among air, cyber, and space domains and their multitude of security domains, AFRL has sponsored the development of a shared representation and suite of coordination and synchronization planning web services under the Cornerstone project. BAE Systems has successfully prototyped and demonstrated the utility of this collaborative approach via services for request management, plan management, and dynamic model management. We have successfully integrated Cornerstone with an existing cyber-planner, and have plans to incorporate air and space planners in Phase 3. AFRL's Phase 2 Limited Technology Experiment verified successful end-to-end mission request processing and constraint checking and established baseline metrics for run-time performance. Most importantly, Cornerstone demonstrated the ability to add and extend capability models on-the-fly to support new mission effects. When taken to its fullest potential, Cornerstone's approach to plan and model management promises to yield significant cost and time savings in interoperations, and increase C2 agility in deployed environments. As we make progress, we plan on including all Joint domains available to a commander.

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