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Final Report, Contract N00014-14-P-1185 (CDRL 0003, Data Item C001): PDS Preparation and Planning

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1 Executive Summary

PRELIM (Predictive Relevance Estimation from Linked Models) draws on semantic models provided by some members of the PDS team to generate forecasts and estimates of value of information (VOI) for use by other members of the team.

The central challenge in proactive decision support is to anticipate the decision and information needs of decision-makers, in the light of likely future developments in a scenario. In many cases, this anticipation does not require sophisticated forecasting, but can be triggered by simple decision rules (e.g, "If a typhoon is moving toward the Philippines, identify the state of Humanitarian Assistance/Disaster Recovery resources within a 1000 mile radius"). Such an approach corresponds to automation of elements of recognition-primed decision-making [4]. However, some cases may go beyond patterns that are readily learned from past experience, and require a forecasting mode of reasoning that in people is called explanation-based reasoning [11]. Several conditions that require proactivity and prediction, including

- The need to preposition assets, materiel, or information because of intrinsic timelags;
- Indications of unlikely but high value future events that cannot yet be perceived (the typical indications and warnings scenario);
- Estimation of second and third order responses in developing Blue COAs.

This document summarizes the technical work done on Contract N00014-14-P-1185 to advance the PRELIM vision. It includes

- a short narrative that describes how someone would benefit from using the PRELIM technology as part of a Proactive Decision Support System;
- a technology roadmap that describes the science / technology that needs to exist to realize the PRELIM vision;
- a description of the science research and/or theory that needs to be done to create make these technologies real.

2 Use Narrative

One situation that requires predictive reasoning is making effective use of digital communications in DIL (disrupted, intermittent, limited) bandwidth environments. We present a tactical use case that shows the reality of this requirement and illustrates PRELIM's value. This is only an example; PRELIM can be applied to more strategic-level decisions as well, and the PRELIM team is eager to support any of the scenarios discussed at the planning workshop.

Many likely military scenarios require inserting troops into littoral regions that we do not control. The proliferation of Anti-Access/Area Denial (A2/AD) capabilities such as anti-ship cruise missiles (ASCMs) and anti-ship ballistic missiles (ASBMs) can place our blue-water assets at risk even 1000 miles from shore. To respond to these threats, the US Marine Corps (USMC) has been experimenting with CONOPS for long-range insertions via V-22 and other air platforms [3]. The insertion flight can last as long as seven hours, during which events on the ground can make obsolete the situation awareness (SA) and mission plans that were current when the raid force boarded the aircraft. The USMC has been experimenting with providing troops on the insertion vehicle with tablet computers that can be updated with SA during flight, allowing replanning. However, the comms channel to the aircraft (typically Link-16) is intrinsically limited, and in the case of active hostilities may be further degraded by jamming or interference with satellite communication. Because of this DIL environment, it is not feasible to provide the raid force with all the information available in the combat operations center (COC) overseeing the operation.

Background: Consider the scenario in Figure 1. Two raid forces (RFs) are en route to Littoral Penetration Site (LPS) 1. RF1 is to disable a ASCM battery at OBJ A, then secure an airfield at OBJ B for incoming F35s. RF2 will secure a bridge at OBJ C to block Red reinforcements and maintain the transportation infrastructure for later Blue use. A previously emplaced SEAL team has deployed unattended ground sensors (UGS) in the vicinity of OBJ A.

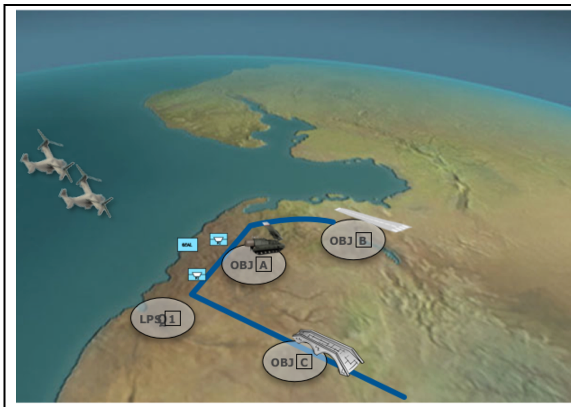

Figure 1: CONOPS for long-range insertion mission

During the insertion flight, these sensors report strong vibrations in the vicinity of OBJ A. This MASINT could indicate the removal of the ASCM battery, or the arrival of strong reinforcements, or simply a civilian construction vehicle moving over the nearby road.

Before PRELIM: With no communications between the insertion aircraft and the COC, the RFs land without knowledge of the MASINT and its implications, and may face either unexpected reinforcements or a missing target that has been moved to another location. With current communications technology and without PRELIM, the COC must manually select which information to send to the RFs, and there is limited ability to do rapid evaluation of second and third order Red responses in replanning the insertion mission.

With PRELIM: Table 1summarizes how events might unfold with PRELIM, interacting with the COC and the conventional Navy Information Technology (IT) framework. PRELIM monitors the mission plan against arriving ISR, recommending that the COC disregard some items, but calling attention to the UGS MASINT as potentially disruptive. Its forecasts guide the issuing of a priority information requirement (PIR) to the SEAL team, then assesses the impact of their report to enable the COC to replan and update the Raid Forces, so that they land ready for the current situation on the ground.

3 Technology Roadmap

In this section, we review the D2REEM metaheuristic, which is the core of PRELIM, and summarize its technical components. Then we discuss how those components may be realized in the PDS program.

Table 1: Evolution of insertion mission with PRELIM. Time is relative to landing at LPS.

Time	Event	Raid Force	COC	Navy IT	PRELIM
-7	Launch	Board V-22	Makes go/no-go decision Continuous monitoring for abort conditions	Provides C2 data including current plan, track feed, METOC forecasts, ship readiness, …	Loads current mission plan; Monitors context information (C2); Assesses mission plan against context
-6	Numerous ISR hits (NTM, HUMINT, …)	Not distracted with irrelevant traffic	Reviews hits	Link 16	Determines that new information does not impact current mission
-5	MASINT from embedded SEALs identifies heavy movement in AOO			MASINT via Link-16	
		RF 1 & 2 receive status updates	Notifies COC		Recognizes potential mission impact
-5			Review, approve, PIR		Forecasts likely Red location over time; Reports high-relevance IRs & affected futures to COC
		RF 1 receives status updates			Reports high-relevance IRs & affected futures to Raid Team
-4	PIR results available	Warning order to RF 1; status confirmation to RF 2	Replans mission for RF 1 Adjusts sync matrix for other units	Link-16 warning order to RF 1	
-3	Revised mission plan available	RF 1 revises tactics en route RF 2 reviews original plan	Reviews revised tactics	Link-16 between RF 1 and COC	Monitors against revised plan
0	Insertion	Both teams land, ready for the current situation		Link-16	Continues to monitor and update force on the ground

3.1 Overall Roadmap: the D2REEM Metaheuristic

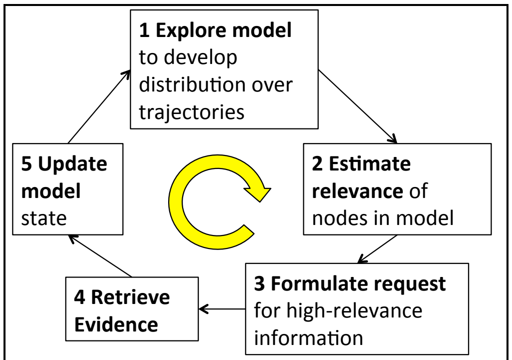

Figure 2: The D2REEM Metaheuristic

PRELIM is based on the D2REEM metaheuristic, an innovative approach to matching complex semantic models with data [10]. D2REEM stands for "Dynamic Data Relevance Estimation by Exploring Models." It supports any graphical model with these characteristics:

- The *edges* express required semantic relations among the *nodes*;
- *Partial matches* are meaningful (the graph may express a range of alternatives of interest that we wish to disambiguate from the data);
- A meaningful *subgraph* corresponds to a *trajectory* through the graph;
- The probability that this trajectory visits a node depends on *evidence* attached to the node.

Table 2 shows a number of examples of such graphs,

Figure 2 outlines the overall flow of algorithms that implement this metaheuristic:

1. The system *explores* a graphical model to develop a statistical distribution over possible trajectories through the model, reflecting the evidence available on the model's nodes.
2. It *estimates* the relative relevance of the nodes in the model based on this distribution.
3. It *formulates a request* for additional evidence for the nodes identified as most relevant.
4. It *retrieves* this evidence, whether by querying existing data or by deploying sensors to gather additional intelligence.
5. It *updates* the model with the new evidence.

Naïve matching of a complex model against data is combinatorially prohibitive, but iteration of the D2REEM cycle retrieves evidence in a best-first process that is linear in the size of the model.

3.2 Required Science and Technology

We outline the required science and technology for each of the five components of D2REEM, and for the antecedent step of constructing the model in the first place.

Table 2: Examples of Graphical Models that D2REEM can exploit

Graph	Nodes	Evidence	Edges	Subgraph
Geospatial lattice [6]	Locations	Sightings	Physical adjacency	Trajectory
Narrative graph [9] or HMM	Statements about the world "Start" node	For or against the statement	Temporal sequence	Path from "Start"
Hierarchical task network [8]	Actions	For or against the action	1. Subtasks 2. Sequence constraints	Path through leaf nodes
Social network [2]	People or organizations	Data on resource of interest	Potential resource flow	Path through the network
Argument graph [12]	Statements	For or against the statement	Rhetorical relations	Path through the network

Model Construction.—While graphical semantic models offer great leverage for reasoning, their construction is often expensive and slow. A number of technologies are available to help reduce the cost and speed the production of model, including Bayesian model learning from examples, and fusion of model fragments into a more complex model [5]. The "LI" in PRELIM ("Linked") refers to the potential for connecting existing models of different types (e.g., causal graphs, hierarchical task networks, and geospatial representations) into more complex and expressive structures. PRELIM can readily process such linked models, but automating the linking is a challenging research problem.

Model Exploration.—A wide variety of technologies are available to explore a graphical model and yield candidate trajectories. These include probabilistic inference (as in a Bayes network or a Markov transition system), high-level semantic reasoning, and Monte Carlo sampling. The technology we prefer, polyagent simulation [7], is a variety of Monte Carlo tree search [1]. Its advantages include speed (the ability to generate multiple trajectories quickly) and expressiveness (since each agent traversing the graph can carry its own state and behavioral preferences).

Relevance Estimation.—Given a distribution over alternative trajectories through the graph, we seek to estimate the relevance of each node. A node is highly relevant if additional evidence for or against that node would make a large change in the distribution of trajectories; it is less relevant if additional evidence would make little change to the distribution. Our preferred approach to relevance estimation is genetic search over the set of nodes, using information-geometric measures to evaluate alternative candidate sets of nodes.

Request Formulation.—Having identified a highly relevant node in a graphical model, we need to formulate queries to available information repositories or taskable sensors that will return information to increase or decrease our belief in the state of affairs represented by the node, and thus modulate the probability that trajectories will include this node. The most direct approach to this task is to include construction of such queries, or of query elements (such as relevant keywords or search conditions), in the task of constructing the node in the first place. Alternatively, candidate queries may be retrieved from the language used in representing the node.

Evidence Retrieval.—Given a query, a wide array of database mechanisms and sensor allocation schemes can be invoked to search for the desired information.

Model Updating.—The evidence returned by queries needs to be attached to the nodes that led to the queries in the first place, along with an assessment of whether the query increases or decreases the probability of trajectories that include the node.

3.3 Realizing PRELIM's Technical Components

SoarTech's efforts in PRELIM focus on *Model Exploration* and *Relevance Estimation* (steps 1 and 2 of the D2REEM cycle) to provide short-term forecasts and estimates of information value in support of Naval decision-makers.

PRELIM works with other performers in the overall PDS program as a forecasting and information valuation service that accepts world and mission models with supporting data and produces forecasts and relevance estimates for information not yet in hand (Figure 3). The efforts of other performers in effect close the overall D2REEM loop. In particular,

- Various PDS modeling services will do *Model Construction*, including *Model Updating* (D2REEM step 5) as new evidence becomes available. PRELIM does include optional tasks to explore the linking of heterogeneous model types.
- Various PDS performers are focusing on presentation services. We anticipate that human watchstanders will do *Request Formulation* (D2REEM step 3), including information source identification, for highly relevant nodes that PRELIM identifies.
- Various PDS performers are focusing on information management, and thus are in a position to support *Evidence Retrieval* (D2REEM step 4).

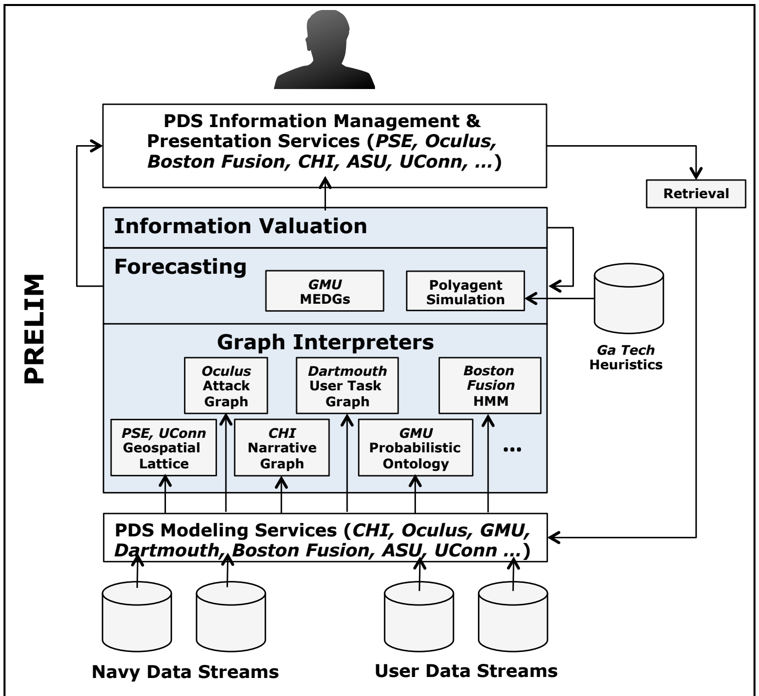

Figure 3: PRELIM in the context of the PDS program

4 Opportunities for Scientific Advance

PRELIM offers a number of opportunities for significant scientific discovery, summarized in Table 3.

Table 3: PRELIM Objectives and Potential Scientific Impact

Function	Objective	Scientific Impact
Information Valuation	1. Define & compute measures of information value that support proactive collection management.	Develop an approach to model-based value of information estimation that is semantically richer than current methods
		Develop visualization methods for information gaps that are cognitively accessible to operators
Prediction	2. Generate distributions over possible futures of the world as a function of available information.	Demonstrate ability to forecast over multiple model types with a single prediction engine
		Develop hybrid Monte Carlo/Bayesian forecasting methods
		Develop visualizations of forecasts in graphical models that allow users to focus attention without losing the big picture
Model Linking	3. Define formal linkages between different model types.	Develop a canonical representation for semantically rich models that subsumes a wide range of graph types
		Develop mathematical theory mapping model types to one another

5 Description of All Tasks Performed

Under this project, the P3 team has:

- Prepared and presented workshop materials, and participated in a planning workshop
- Prepared the use narrative, technology roadmap, and opportunities for scientific advance documented in the previous sections of this report
- Filed the required status reports.

6 Accomplishments of the Program

In collaboration with other members of the PDS program, the P3 project has developed a collaborative vision (Figure 3) for applying the D2REEM metaheuristic in the context of a broader architecture for proactive decision support.

7 Recommendations for Future Technology and Research

The P3 team recommends that ONR develop a Proactive Decision Support technology that incorporates the technical insights presented earlier in this report, and addresses the scientific questions detailed in Section 4.

8 Breakdown of Contract Costs

Labor and Indirect Costs: $52,578

Travel: $3312

Other ODCs: $0

Fee: $4052

Total: $59,942

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