

Title: **Supporting Adaptive C2 Structures in Time-critical Environments**

Suggested Topics:

Topic 5: Organizational Issues

Topic 8: C2 Architectures

Topic 3: Modeling and Simulation

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Abstract

As technological advances allow automation of many operations, human operators supervise systems with increasing breadth of scope. In these complex environments, decisions regarding resource assignment to tasks, goal prioritization and coordination strategies during unexpected events become unwieldy as the problem spaces grow.

In this paper, we describe the development of technology to support teams of operators controlling teams of unmanned vehicles (UVs) in their global resource planning and re-planning. These teams include a several coordinating Littoral Combat Ships, a mixture of autonomous vehicle types, typically with a range of differing capabilities, and management by multiple human operators attempting to achieve several high-level goals. Using the results of a Cognitive Work Analysis, we extend our work in organization design and analysis to give real-time support to the operators.

Introduction

Recent military experiences with AVs [Autonomous Vehicles] have consistently demonstrated their value in a wide range of missions, and anticipated developments of AVs hold promise for increasingly significant roles in future naval operations.

- NRC Committee on Autonomous Vehicles in Support of Naval Operations 2005

In the 2005 report quoted above, the NRC recommended that the Navy pursue development of technologies to accelerate the introduction of unmanned aerial vehicles, uninhabited combat air vehicles, unmanned ground vehicles, unmanned surface vehicles, and unmanned undersea vehicles. This development would support major Navy missions such as long-dwell standoff intelligence, surveillance, and reconnaissance (ISR), ship-based tactical surveillance and weapons targeting, damage assessment, communications support, and detection of threats from an array of possible traditional and non-traditional sources. In a realistic version of any of these missions involving, for example, several coordinating Littoral Combat Ships (LCSs), there would be a mixture of autonomous vehicle types, typically with a range of differing reasoning capabilities, and they would be managed by multiple human operators attempting to achieve several high-level goals. This perspective highlights a number of major challenges in technology development if such complex human-UV systems are to be effective.

One challenge is to develop algorithmic or software support to optimally allocate unmanned vehicle assets and objectives across the different human operators within the overall team in order to effectively accomplish the high-level mission goal(s), and to then effectively plan the details of mission execution at the local UV level (e.g., detailed routes, objective execution sequence) given these resource allocations. In addition, these software tools must be able to re-plan at the local and global level when there are changes to the mission goals, when unanticipated events arise, or when the available assets or the nature and number of human operators change.

To support collaboration of the multiple human operators with UVs also requires an advanced interface that clearly indicates what decisions have been made in terms of task assignments, the state of task execution for each UV-assigned responsibility, and an overall global picture of the current operational environment. This interface should enable each human participant to have a clear idea of the current mission and world state without introducing unnecessary information or

detail that increases workload. All these technologies must then work seamlessly together to enable effective collaboration for accomplishing critical Naval missions within the necessary constraints of time and available resources.

As one component of a phase I SBIR effort (Collaborative Optimization System for Mixed Initiative Control (COSMIC)), we began developing a technology to provide this computational team planning support. The goals of COSMIC in phase I were to develop specifications for a dynamic team planning component that could optimally allocate objectives and unmanned vehicle assets to human operators and designs for embedding this capability in an interaction environment that would greatly facilitate the ability for those operators to collaborate in accomplishing their assigned objectives. Both of these primary aspects of COSMIC were, in turn, derived from an in-depth understanding of the possible space of human coordination during complex UV missions achieved through the technique of Cognitive Work Analysis (CWA).

Illustrative Use Case

To demonstrate our approach, we introduce a use case describing littoral combat ships (LCSs) supporting a Carrier Strike Group on Maritime Interdiction Operations and Mine Clearing missions. LCSs are intended to be easily configured for different types of target missions through the use of various pre-defined mission packages (mine counter warfare, anti-submarine warfare, and surface warfare). Each of these mission packages, as well as those that are tentatively planned for later development, rely heavily on the use of a mixture of different types of unmanned vehicles to accomplish their objectives, including underwater, surface, and aerial assets. They also closely adhere to the future Navy goals of reduced manning and highly networked forces.

The target scenario involves several LCSs coordinating to accomplish two competing high-level missions, with overall control residing in a remotely located Sea Combat Commander aboard a Carrier as part of a Carrier Strike Group (CSG). The target location for this group is a dangerous strait in the Middle East bordering a U.S.-hostile country. The LCS/CSG force is deployed in the designated MIO OP AREA and conducts surveillance of likely transit routes using sensors and aerial assets. Off board systems such as acoustic arrays and USVs may also assist surveillance efforts. Fire scouts are equipped with either EO or IR sensors to identify tracks and to enable 24/7 operations. Multiple LCSs may participate in this, depending on the nature of the threat posed. Each LCS has two Firescouts equipped with Hellfire missiles and two Spartans with Hellfire missiles and deck guns. In addition, one of the mission packages (for LCS2 and LCS4) has several unmanned underwater vehicles for mine hunting and undersea mapping. The carrier has overall operational control and also controls additional UV assets (high altitude ISR vehicles, UCAV, USVs, UUVs).

The strait has high volumes of commercial ship traffic and is located near a hostile country. That country is currently under arms embargo by the United States. Evidence indicates other countries have been trying to smuggle arms to the hostile country in defiance of the U.S. embargo. The U.S. intends to increase its presence in the strait by bringing in one of its Carriers. An advanced fleet of four LCSs is tasked with clearing the strait of any potential threats before the Carrier enters, including mines, small diesel submarines, and fleets of small boats (10 meter “go fast” boats). In addition, the LCSs have a second mission of investigating any reports of potentially belligerent ships which may be transporting weapons and terrorists in defiance of the embargo. Maritime

interception has been ordered as a means to investigate these types of suspicious vessels. At the start of the scenario, two possible Targets of Interest (TOI) have been identified which have entered the Area of Responsibility (AOR) and these targets need to be put under surveillance and investigated. The Area of Responsibility has been subdivided into two roughly equal subareas, AOR Alpha and AOR Bravo. LCS1 and LCS2 are assigned to AOR Alpha and LCS3 and LCS4 are assigned to AOR Bravo.

There are two different versions of the LCS with different mission package configurations:

- LCS1 and LCS3 have the Maritime Interdiction Operations Mission Package. This includes three Vertical Take-off UAVs (VTUAV) equipped with Hellfire missiles and radar and two Unmanned Surface Vessels (USVs) with Hellfire missiles and deck guns. VTUAVs are equipped with either EO or IR sensors to identify tracks and to enable 24/7 operations.
- LCS2 and LCS4 have the Area Clearing Mission Package, which includes: – 3 VTUAVs, 1 USV, 1 RMV, 1 BPAUV, 1, and 1 Advanced Deployable System (ADS).

The Carrier has overall operational control (Command Information Center or CIC is located there) and also controls additional UV assets (two Maritime HALE ISR vehicles, UCAVs, USVs, UUVs).

Personnel in the relevant chain of command include:

- Commander – On Carrier in CIC, in charge of all LCSs and Carrier UVs
- Mission Manager – one on each LCS; in charge of overall LCS mission
- UV Manager – one on each LCS, in charge of all UV assets for LCS mission

During the scenario, there are scripted losses of both unmanned vehicle assets (e.g., a hostile vessel destroys a VTUAV) and loss of communications with a key human operator (communications are disabled for LCS1). These disruptions were included to create challenges for the COSMIC Team Planner. The Mission Commander and the various LCS UV Mission Managers must handle the coordination required to hand-off assets and assume new mission objectives while minimizing disruption to current operations and goals. Thus, this use case scenario captures the functionality that must be present in COSMIC to provide a new level of team coordination from both the planning and user interface perspectives.

Cognitive Work Analysis (CWA) Approach

To ground this work in the products of informative, operator-centered evaluations, Aptima and the University of Iowa applied techniques drawn from Cognitive Work Analysis (CWA), an innovative, in-depth method for capturing the information that exists in the battlespace at differing levels of granularity and the use of this information in planning and monitoring the ongoing progress of the mission. The CWA approach applies engineering processes and techniques to capture the work domain as a system, to identify the constraints that affect the actions that can be taken within that system, and to model the human’s interaction with the system and collaborative team members as control processes. Because of its fundamental engineering-based approach, it provides a natural foundation for the development of automated planning systems. As this approach tightly links human decision making and action with the parameters typically captured in

such systems, it can be used to ensure that the models that underlie these systems are intuitive to human operators.

Introduction to CWA

Unlike traditional task analysis techniques, CWA is a process that is unique designed to capture both the *design of systems* to fit the human operator, such as the COSMIC team planner, and the *design of the interaction between teams of humans and new technological systems*, such as the COSMIC team planner, in meeting mission objectives (Vicente, 1999). The CWA process applies a suite of analyses, which are used to capture the work domain and the operator characteristics that affect performance in that domain. This two-pronged approach provides the tools needed to identify the objectives and decision processes that must be completed for a given mission, as well as the information that supports these objectives and processes, regardless of whether the information will be used and tasking will be completed by a human operator or an automated system.

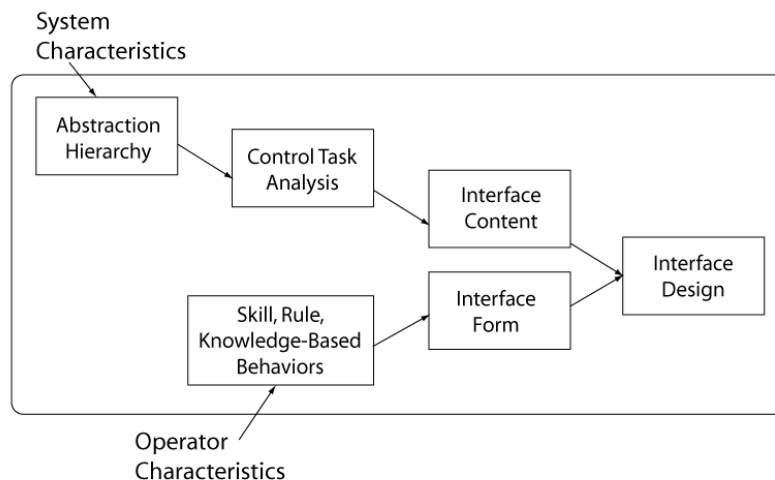


Figure 1. The outlined cognitive work analysis process, adapted from Lee (1995).

As shown in Figure 1, the CWA approach derives information requirements and the resultant interface design from both operator characteristics (skills, rules, knowledge) and total system characteristics (which includes the environment, technology, and mission context). This approach represents the mission environment in terms of *constraints* (i.e. what is *not* possible in the environment of interest) and *affordances* (i.e. what *is* possible in the environment), thus serving as a strong framework for building the COSMIC team planner, discussed in greater detail in subsequent sections. This mapping of the mission environment provides a shared information-space supporting collaboration between humans and automated mission planning tools. The analyses from this technique directly support both the development of COSMIC planning model and the design of its interface to support interaction with this model. CWA has already been successfully applied to the design of numerous military and non-military systems (Bisantz and Roth, 2001; Linegang and Lintern, 2003; Naiker and Sanderson, 2001; Dinadis and Vicente, 1999), and Aptima and the University of Iowa have helped to pioneer this effort (Lee and Moray, 1994; Lee and See, 2004; Stoner, 2004; Stoner & Wiese, 2003), particularly in the development of interfaces for the control and management of unmanned vehicles and robotic assets.

These processes, defined in Figure 1 above, can be applied to support the development of a resource allocation and planning model, such as COSMIC. We will focus our discussions to insights gained from an abstraction hierarchy, shown in the box on the left of Figure 1, which can be derived through a work domain analysis

Work Domain Analysis

The work domain analysis is used to produce the abstraction hierarchy, a hierarchical framework that links the very detailed physical properties of an environment to the abstract functional purposes that those detailed information properties support. The result of the work domain analysis is a very detailed map of information requirements, which are parsed along two continua, represented by the vertical and horizontal dimensions in the hierarchy.

The vertical dimension of the hierarchical framework represents the abstraction levels of a system, and layers information from granular components to high-level system functions. For the purpose of COSMIC, the system refers to the littoral combat environment, and the entities contained within. The layers of abstraction include:

1. **Functional purpose:** This level contains a description of the primary objectives of the system, traditionally captured in the military domain as mission objectives.
2. **Abstraction functions, values, and priorities:** This level identifies the resources and values that need to be minimized, maximized, or conserved to meet the defined objectives. Priorities may be captured in the expeditionary unit mission environment as the balance between the risk of UV detection and the reward of critical Intel collection.
3. **General functions:** This level of abstraction identifies the functions or mechanisms that are required to realize the abstract functions and meet the objectives outlined in the functional purpose level. Examples from the expeditionary unit environment would include the sensor footprint of a UV, or the window of opportunity to access a target of interest.
4. **Physical functions:** The physical function level of abstraction identifies the capabilities provided by physical devices in the work domain or environment. Examples include the status of a UV or the capabilities of its sensor.
5. **Physical form:** The lowest level of abstraction describes the specific physical components that exist in the environment. The location, configuration, condition, and physical attributes of objects in the system define categories at this level. Examples include the LCS ship, a UV, and weather conditions.

The horizontal dimension of the hierarchical framework represents the decomposition of the system. Three levels of resolution are defined along this dimension, including the system, subsystem, and component levels of decomposition.

Applying Cognitive Work Analysis to Collaborative UV Management

Aptima and the University of Iowa conducted the processes described above to capture and represent the information requirements and decision processes of the roles outlined in the use case

above. In capturing the information requirements, the analysis team constructed the COSMIC abstraction hierarchy, designed to identify and organize information present in the littoral combat environment at multiple levels of abstraction and system granularity, shown in Figure 2.

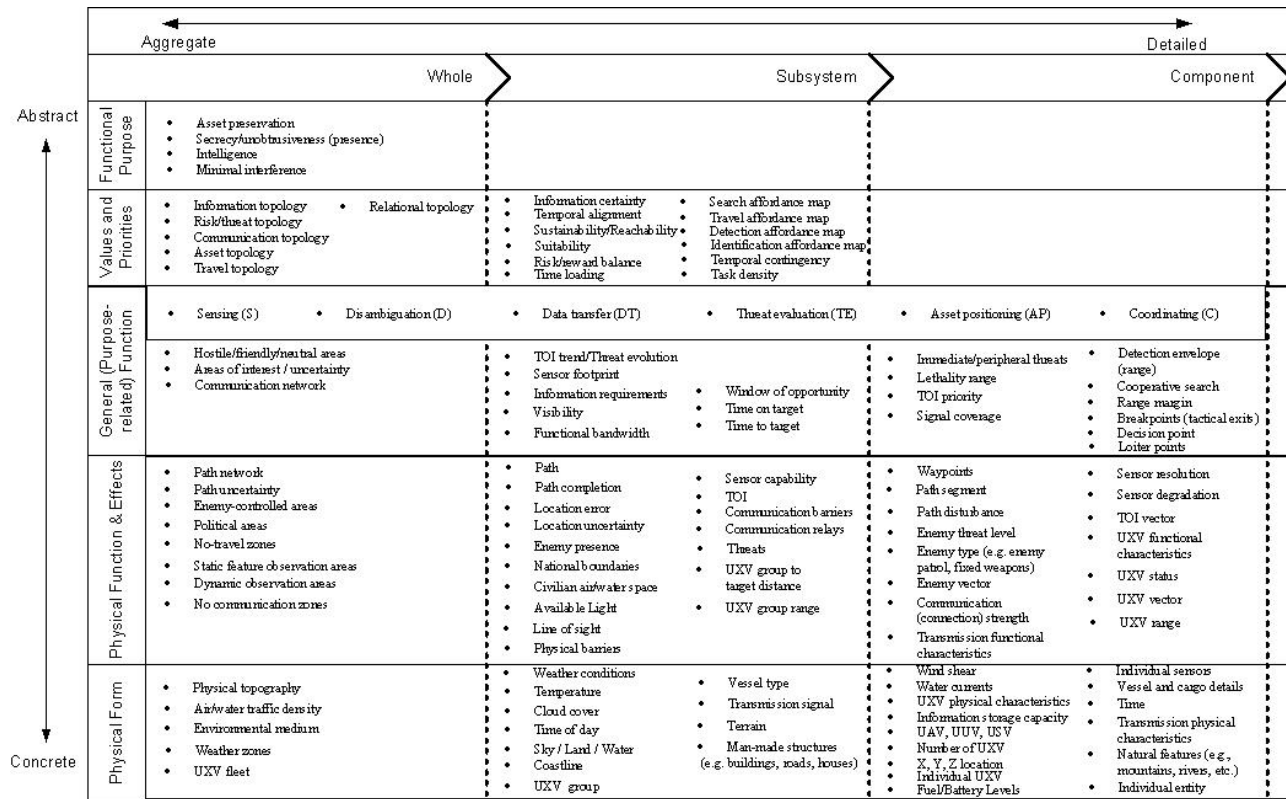


Figure 2. Abstraction decomposition representation of collaborative, unmanned vehicle management for littoral command.

Through the analysis, four primary objectives (captured as *functional purposes*) were identified and mapped to the upper left corner of the hierarchy: (1) **preservation** of assets, (2) **secrecy** of assets, (3) **intelligence** gathering, and (4) **minimal interference** with other mission tasks or vehicle operation. Tersely stated, the analysis indicated that vehicle managers are concerned primarily with gathering the intelligence needed to meet mission objectives, while preserving the secrecy and ensuring the safety of his assets and the assets and objectives of other blue force entities.

Within the effort, Aptima and the University of Iowa linked each of these four objectives to information requirements at increasing levels of granularity (e.g., *secrecy* is linked to *visibility*, which is linked to *line of sight*, which is linked to *UV vector*), which map to lower levels of the hierarchical framework. As a result, the team generated a representation of the information in the work domain, clustered by each of the four objectives. The varying levels of granularity of this information, reflected in the five rows in the abstraction hierarchy, support the grouping of information from specific tactical data (i.e., UV fuel capacity) to higher level strategic data (i.e., enemy trend evolution). This capability to flexibly group and cluster information by

mission function is a critical capability for developing innovative display designs and automated models.

Because of the collaborative nature of the environment, and the multiple roles that use the information contained within the hierarchical representation shown in the figure, the project team conducted an additional analysis to focus on the distribution of this information across roles that could support coordination and collaboration among multiple UV teams. The hierarchical representation allows the key roles to be mapped directly onto the information they need to accomplish tasks. The information associated with each role is relevant for display design and communication interaction. Information that is necessary to multiple roles must be available to each role, either through direct communication between roles or in a central display representation. The mapping is shown in Figure 3.

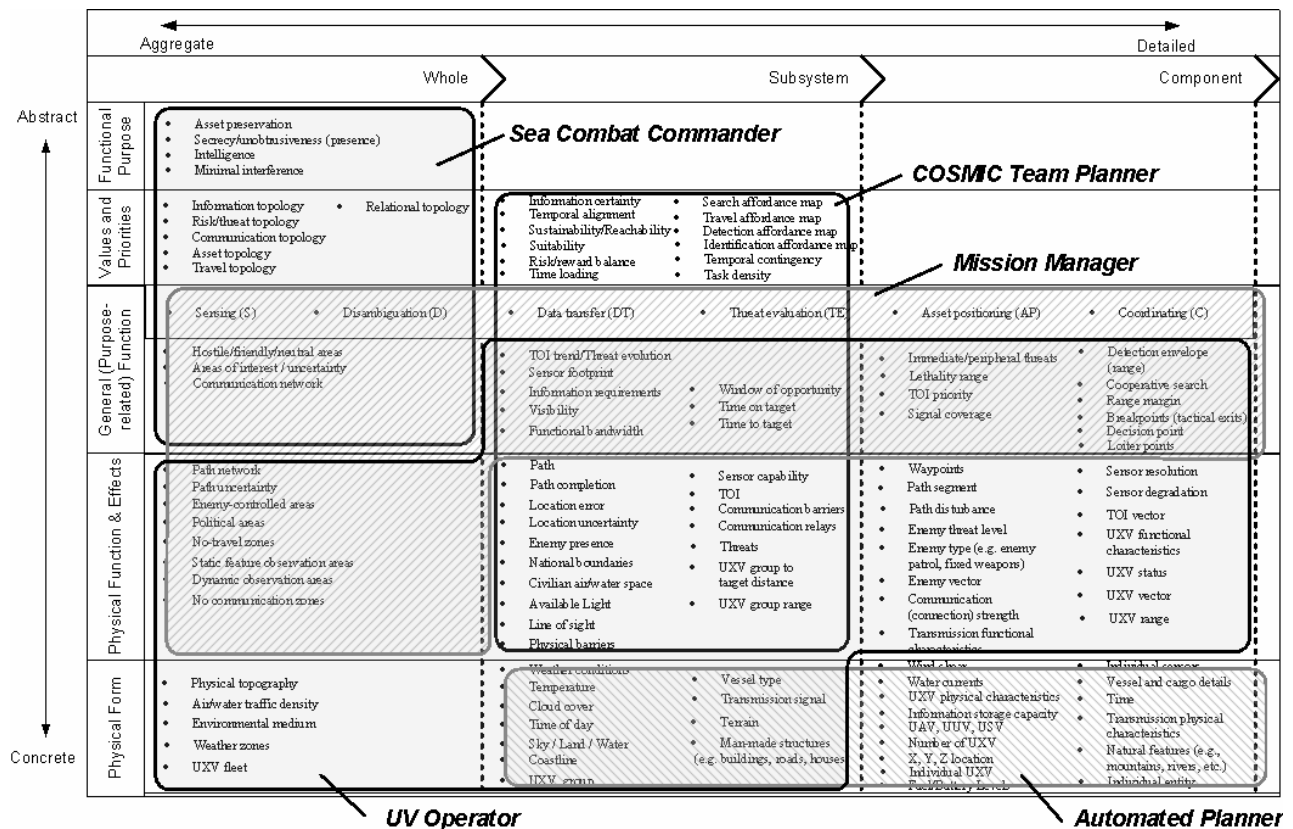


Figure 3. Abstraction decomposition representation mapped to key roles and technologies.

Because Figure 3 also illustrates all the roles overlaid onto the same work space representation, it reveals the instances where information is needed by multiple roles, and thus should be shared across roles. Note that one of the identified roles is that of the COSMIC team planner, discussed in detail in the following section. The team planner uses information related to the values and priorities and general functions associated with the vehicles and planning space as a whole, using this information to support collaborative planning and task-resource matching across multiple LCSs. Furthermore, the abstraction hierarchy links each of the constructs captured within the COSMIC team planner cell (see Figure 3), with the information that defines it. For example, sustainability and reachability of a vehicle, is defined in part by the time to the target (located in

the general function row of the Team Planner cells), which is mapped to path, location, physical capabilities, and other relevant constructs. Thus, this representation can serve as a strong framework for capturing the granular elements of the domain which are necessary for comprising the parameters of the team planner model, as it evolves in future research.

Developing the Cosmic Team Planner (CTP)

Our system to support the team of UV-team operators builds on Aptima’s experience developing MOST (Models of Organizations, Systems, and Technologies), an automated environment for engineering human organizations for a specific mission or a set of missions to achieve superior performance. MOST derives an organizational design to optimize the set of user-defined performance criteria, quantified via a multi-variable objective function. That is, MOST utilizes the underlying quantitative structure of a set of interrelated mission tasks that must be completed under time constraints to design the “best” team structure for accomplishing those tasks (Levchuk et al., 2003).

The tasks represent the courses of actions that serve two functions: (1) they are efficiently combined to achieve mission goals, according to the mission plan; and (2) they are used to respond to (unanticipated) mission events that constitute either threats or opportunities. Successful execution of a set of tasks in a specific course of action results in achieving the concomitant target (sub)goal. The mission plan typically specifies both the combined functional requirements and the alternatives for achieving commander’s intent (the latter being expressed as a set of objectives or high-level goals).

MOST automates a multi-phase allocation model that consists of three pieces (Figure 4a): (i) the *tasks* that must be accomplished and their interrelationships (the “mission”); (ii) the external *resources* needed to accomplish those tasks (e.g., UAVs, ISR resources), and (iii) the human *agents* (decision makers; e.g., UV operators) who will control resources to execute tasks. The MOST organizational design process is, in simplest terms, an algorithm-based allocation between these three parts. Individual task execution is modeled by accounting for human *workload* constraints and the impact of workload, experience, and learning on task execution accuracy. Team processes are modeled using agent interactions in the form of communication, including (i) decision/action, (ii) command, (iii) information request/transfer, and (iv) task execution synchronization. The organizational structures (information transfer and command responsibility) also serve as a medium for this communication.

The **MOST** process (Fig. 4b) starts with quantitative mission and organization definitions (Phase A), and proceeds to identify the optimal task-resource scheduling (Phase B), operator-resource assignment (Phase C), team coordination and communication strategy (Phase D) and the supporting structures (Phase E). The **MOST** method is algorithm-based, but it relies on allocation heuristics and on the judgment of subject matter experts to frame the design problem in a meaningful way, including decomposing an overall mission (or goal) into specific tasks, specifying the relationships between tasks, specifying the resources needed to complete the tasks, specifying the criteria to be optimized for the team, and specifying the task scheduling and communication rules employed by human agents modeled in MOST (Levchuk, et al., 2002a; 2002b)

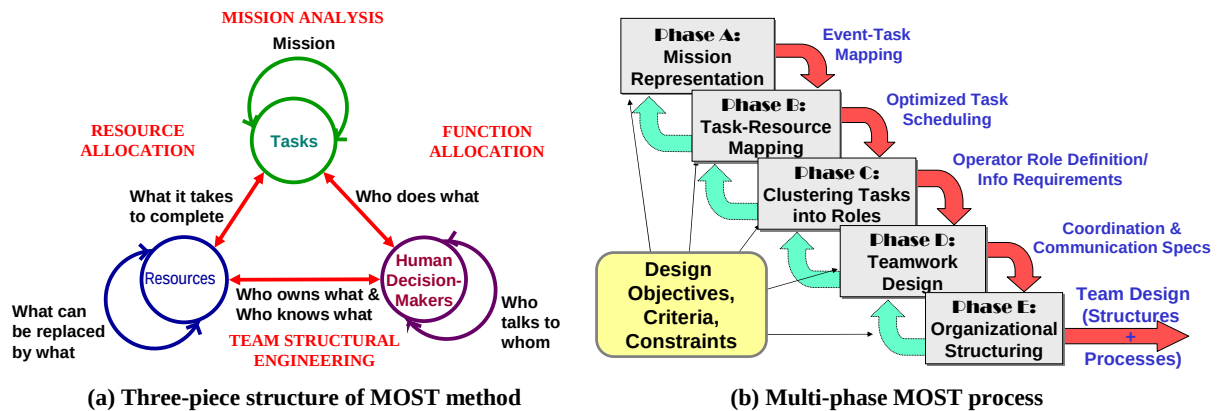


Figure 4. MOST Team Optimal Design methodology

Dynamic Team Replanning

The MOST technology and its algorithms have proven effective in designing novel, successful organization structures for C2 environments (Levchuk, et al., 2007; Entin, et al., 2007). The problem COSMIC is working to solve, however, has added a new level of complexity to the organization design challenge. In addition to initial organization structuring and scheduling, we are working to build a system that dynamically adapts the organization to changes in the environment, mission goals and available resources. This means that if one operator of a team of UV assets becomes overloaded during the execution of part of a mission, we want to evaluate the options for reducing his workload. These may include handing off control of one of his assets (along with its tasking) to another operator or simply re-delegating some of his tasking to another, similarly-equipped LCS operator. Another alternative could be to move an LCS to a new area of responsibility in order to allow him to support an overloaded LCS in that same area.

This system must be able to monitor mission progress, evaluate new possible team configurations, and communicate the implications of new allocations to the users. These dynamic reconfigurations must take into account the disruption caused by adding a new asset and/or tasking to an operator already in progress on his mission. Additionally, the user-interface and collaboration support for these operators must be able to allow immediate situational awareness update and sharing in order to ensure that a smooth handoff is possible. These requirements, above and beyond the advance mission pre-planning for which optimization to create a centralized plan work well, motivate the integration of our MOST approach with the CWA analyses described above.

An initial formulation of these planning algorithms, adapted to be run at any point during a mission, are described in the next sections. As we present these models, we discuss possible, radical, future changes that would further incorporate the CWA work. For Phase I of COSMIC and its Cosmic Team Planner (CTP), we focused on the problems of (1) allocating objectives (or tasks) to UVs (assets or resources), and (2) assigning these UVs to the available LCSs (decision-makers). Motivated by the complex, dynamic environment of the UV operators working on teams of LCSs, we expand the mission-based design focus of MOST to support real-time team structure adaptations to changes in mission priorities and asset health.

Asset-task Assignment and Scheduling

The first step in our Phase I two-step allocation process consists of the assignment and scheduling of objectives and UV assets. We adapt the formulation of Levchuk, et al. (2002) to the domain of UVs and their assets, resulting in the following formulation:

Given:

$$w_{im} = \begin{cases} 1, & \text{if UV asset } m \text{ is assigned to objective } i \\ 0, & \text{otherwise} \end{cases}$$

$$x_{ijm} = \begin{cases} 1, & \text{if UV asset } m \text{ is assigned to process objective } j \\ & \text{after processing objective } i \\ 0, & \text{otherwise} \end{cases}$$

$$a_{ij} = \begin{cases} 0, & \text{if objective } i \text{ must be completed before objective } j \text{ can start} \\ 1, & \text{otherwise} \end{cases}$$

T = the upper bound on mission completion time

r_{ml} = the number of units of capability type l available on UV asset m ($l=1,...,L$, where L is the number of capability types)

R_{il} = the number of units of capability l required for successful processing of objective i ($l=1,...,L$, where L is the number of capability types)

t_i = the estimated processing time of objective i

d_{ij} = the distance to be traveled between objectives i and j

v_m = the maximum velocity of UV asset m

s_i = the calculated starting time of objective i

and objective function:

Y = mission completion time (time when the last task is completed).

We minimize the mission completion time, so following [Levchuk, et al., 2000], the problem can be written:

$$\begin{aligned}
& \text{minimize } Y \\
& \text{subject to :} \\
& \left\{ \begin{array}{l}
\sum_{j=0}^N x_{ijm} - w_{im} = 0, \quad i = 1, \dots, N; m = 1, \dots, K; \\
\sum_{j=0}^N x_{jim} - w_{im} = 0, \quad i = 1, \dots, N; m = 1, \dots, K; \\
\sum_{i=0}^N x_{i0m} = \sum_{j=0}^N x_{0jm} = 1; \\
s_i - s_j + x_{ijm} \cdot \left(\frac{d_{ij}}{v_m} + a_{ij} \cdot T \right) \leq a_{ij} \cdot T - t_i \\
\quad i, j = 1, \dots, N; m = 1, \dots, K; \\
\sum_{m=1}^K r_{ml} \cdot w_{im} \geq R_{il}, \quad i = 1, \dots, N; l = 1, \dots, L; \\
s_i - Y \leq -t_i, \quad i = 1, \dots, N; \\
0 \leq Y \leq T; s_i \geq 0; x_{ijk}, w_{ik} \in \{0,1\}
\end{array} \right.
\end{aligned}$$

This is a mixed-integer programming (MIP) problem, the solution of which is known to be NP-hard. Moreover, even relaxing the integrality constraints on the binary variables w_{im} , and x_{ijm} gives a linear programming problem in which the number of variables is equal to $K(N+1)^2 + N+1$, the number of equality constraints is equal to $2K(N+1)$ and the number of inequality constraints is equal to $KN(N-1) + L(N+1)$. This makes it hard to find solutions to even average-sized scheduling problems. We have therefore had success implementing a heuristic, multidimensional dynamic list scheduling (MDLS) algorithm to find the UV asset - objective allocation and mission schedule by sequentially assigning objectives to UV assets until the objective list is exhausted (Levchuk, et al., 2002).

We note that the inputs to this algorithm include task locations, requirements and priorities (dependencies) as well as asset capabilities and the environmental information necessary to calculate measures such as travel times to objectives, etc. These correspond primarily to the physical function and general function levels of information in the Abstraction Decomposition (Figure 3). The CTP is performing a role of converting this lower-level data into plans for use and dissemination by the Sea Combat Commander.

Asset-LCS Assignment

Once objectives are allocated to UVs and scheduled, we assign the UVs to LCSs. We assume that each LCS contains one manager who oversees the local team of UVs. Whereas previous asset-to-decision maker assignments have been viewed strictly as clustering problems, COSMIC presented a new challenge at this stage. The opportunity for dynamic, mid-mission asset hand-off or reassignment meant we needed to explicitly address the problem of reducing the disruption to the LCS mission managers caused when assets changed hands. In an extreme case, when the fleet of UVs owned by an LCS need to be distributed across the other LCS's (due to system failure of some kind aboard the first LCS), a considerable level of disruption is possible.

One could imagine a number of objective functions that a commander might wish to employ for this assignment problem. In the future, we will consider a possible extension to a system that would allow the commander to choose from among a limited set of objective functions, based on the immediate circumstances at the time of CTP use. Here, we minimize the maximal weighted LCS Manager coordination workload, where workload is a sum of *internal* and *external* coordination loads. Although our Phase I Use Case did not allow for two LCS managers to coordinate in the accomplishment of a single task, this is a possibility allowed for in this formulation. We find, therefore, that the LCS managers in our Phase I Use Case currently only accrue internal workload (the burden of managing their UV assets and objectives), and in the formulation below all of the y_{nmi} remain equal to zero. Other alternatives for objective functions of interest would include minimizing the peak workload over the mission horizon or minimizing the difference between the highest workload LCS manager and the lowest workload LCS manager.

To incorporate the desire to reduce disruption caused by mid-mission hand-offs of UV assets and objectives, we introduce a penalty function in this Phase I formulation. Here, as we work to minimize the workloads, we are penalized for accomplishing this change by imposing radical changes in the arrangement. By variation of the weight, λ , we are able to tune the penalty's strength according to our preferences.

We formulate this problem of decomposing the mission into clusters as the following integer programming problem:

$$\begin{aligned} & \text{minimize } C_W + \lambda \left(\frac{1}{2} \sum_{j=1}^D \sum_{m=1}^K (z_{mj} - \hat{z}_{mj})^2 \right) \\ & \text{subject to} \\ & \left\{ \begin{array}{l} \sum_{m=1}^D z_{mj} = 1, \quad j = 1, \dots, K \\ y_{nmi} \geq w_{ji} \cdot z_{mj}, \quad m, n = 1, \dots, D; i = 1, \dots, N; j = 1, \dots, K \\ y_{nmi} \geq w_{ji} \cdot z_{nj}, \quad m, n = 1, \dots, D; i = 1, \dots, N; j = 1, \dots, K \\ C_W \geq W^I \cdot \sum_{j=1}^K z_{nj} + W^E \cdot \sum_{m=1, m \neq n}^D \sum_{i=1}^N y_{nmi}, \quad n = 1, \dots, D \\ z_{nj}, y_{nmi} \in \{0, 1\} \end{array} \right. \end{aligned}$$

where

C_W = the maximal weighted coordination workload

λ = the weight on the disruption penalty

$$y_{nmi} = \begin{cases} 1, & \text{if } DM_n \text{ and } DM_m \text{ coordinate over objective } i \\ 0, & \text{otherwise} \end{cases}$$

$$w_{im} = \begin{cases} 1, & \text{if UV asset } m \text{ is assigned to objective } i \\ 0, & \text{otherwise} \end{cases}$$

$$z_{mj} = \begin{cases} 1, & \text{if LCS } m \text{ is assigned to UV asset } j \\ 0, & \text{otherwise} \end{cases}$$

$$\hat{z}_{mj} = \begin{cases} 1, & \text{if LCS } m \text{ was assigned to UV asset } j \text{ in the previous assignment} \\ 0, & \text{otherwise} \end{cases}$$

W^I, W^E = the weights on the internal and external workloads, respectively, when they are summed

D = the number of LCS's

N = the number of objectives

K = the number of UV assets

Due to the complexity of the problem, we currently implement a genetic algorithm–based evolutionary algorithm to probabilistically search the space of possible solutions for the optimal solution. Given the limited size of the Use Case scenario, this was a sufficient approach for our Phase I prototype implementation. In future phases, we will investigate more tailored solution techniques for the problem.

By providing this LCS-Asset-Objective assignment, the CTP and associated interface can serve as a communication tool between the Sea Combat Commander and the LCS Mission Managers. As we continue to refine and enhance the CTP algorithms, this module will grow to hold, shape and act upon the Values and Priorities (see Figure 3) guiding the decisions of the Sea Combat Commander.

Conclusion and Future Work

In the reported effort, Aptima worked to build a prototype model designed to support the rapid allocation of UVs to meet the needs of collaborative mission managers supporting littoral combat. This prototype model was designed to serve as a proof-of-concept of the extension of our modeling approaches to this challenging domain. The model was constructed leveraging products generated from a Cognitive Work Analysis, which was conducted collaboratively with the University of Iowa. The product of this analysis captures the information requirements used by individuals at varying levels of the command hierarchy and by technologies, such as the COSMIC team planner.

This analysis can be extended to develop additional key requirements for the team planner in future iterations. We can do this by applying the information requirements for the team planner to the development of the planning algorithms, such that the COSMIC team planner will more completely capture the elements defined within the CWA and create computational methods for considering their implications to mission success. By capturing these critical components of the work domain, which serve as the informational link between the Sea Combat Commander and the UV Mission Manager, the COSMIC team planner can serve as a tool to support collaboration between these individuals. In a second potential extension, the CWA can be used to identify the general tasking demands placed on the vehicle operators, mission operators, and mission

managers. By capturing the temporal alignment of tasked objectives across the course of the mission for a single vehicle, as well as the fleet of vehicles that are managed by the operator, the project team can derive and project the workload of individuals over time. This workload information can be used, within the COSMIC team planner, to establish plans that optimize operator demand while minimizing disruption to ongoing tasks.

By applying the products of the CWA to the development of the COSMIC team planner in these key areas, the project team has ensured that the output of the automated planner will have utility to the human operators using the plans and that the interactions between the team planner and the human operators have been well-defined.

In leveraging the products of this described analysis, we will explore the following options to be evaluated for inclusion in future versions of the CTP:

- New **objective functions**, such as the ability to minimize *peak* workload rather than cumulative workload or variance in workloads, would allow high-level commanders to choose a function at run-time to tailor the analysis to a particular concern for the current situation
- Expanding the types of objectives and mission guidelines to allow multiple UV Assets and even multiple LCS's to participate in accomplishing a single objective, where appropriate
- Including analysis of coordination requirements and costs between LCSs when cooperating together to accomplish a single goal
- Allowing an LCS to temporarily task a UV asset belonging to a different LCS, **without making a permanent handoff**, and accounting for the workload to each operator in this decision

The proposed refinements will continue to enhance the robustness of the designed model in supporting the challenges encountered by operators, thus increasing their effectiveness and opportunities for mission success.

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