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"Holonic scheduling concepts for C2 organizational design for MHQ with MOC"

Organizational Issues

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Holonic scheduling concepts for C2 organizational design for MHQ with MOC

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ABSTRACT

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Keywords: holonic reference architecture (HRA), maritime headquarters (MHQ), maritime operations centers (MOC), strategic level control (SLC), operational level control (OLC) and tactical level control (TLC), Markov decision process (MDP), group technology (GT), nested generic algorithm (NGA).

I. INTRODUCTION

Motivation

The term *maritime headquarters* refers generically to those Navy operational-level commands with the capability to assess, plan, and execute at the operational level of war and the term is inclusive of the commander, the staff and the facilities [1] (see Fig. 1). The Navy's new concept of incorporating MHQ with MOC emphasizes standardized processes and methods, centralized assessment and guidance, networked distributed planning capabilities, and decentralized execution for assessing, planning and executing missions across a range of military operations. In this paper, we seek to model the coordination issues inherent in the MHQ with MOC via a three-level holonic reference architecture that links tactical, operational and strategic levels of decision making. Here, we show that the C2 coordination issues at the three levels, viz., strategic, operational and tactical levels, associated with future plans, future operations and current operations can be modeled and addressed by using the proposed holonic architecture.

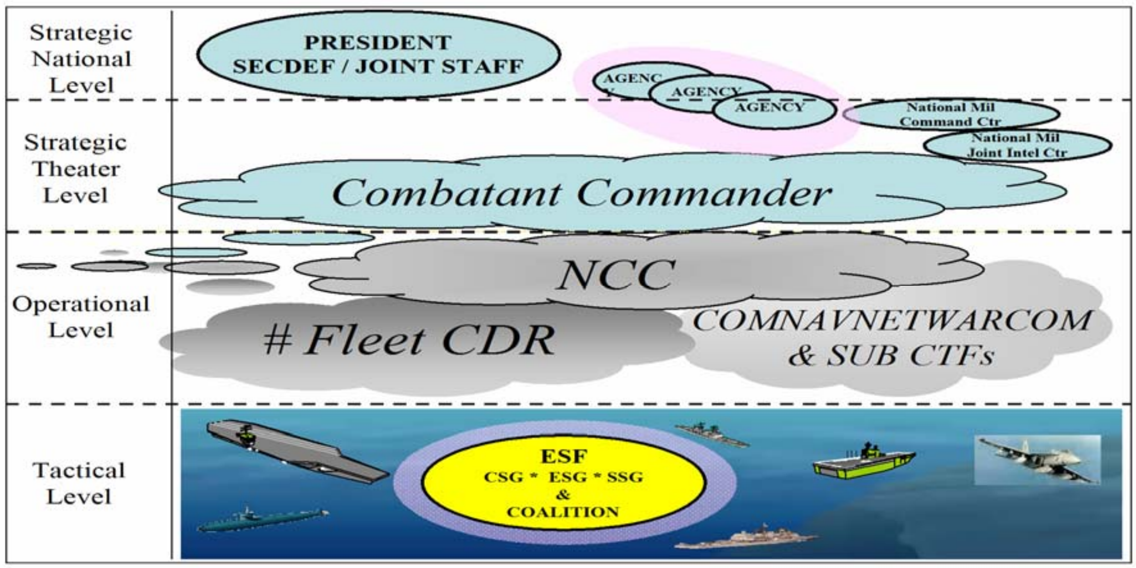

Figure 1. Maritime headquarters focusing on operational command (adopted from [2]).

Related research and new contributions

Our previous research on C2 organizational design has included the modeling and synthesis of organizational structures at the tactical level to achieve a set of command objectives, such as maximizing the speed of command, minimizing coordination, balancing workload, and so on. Levchuk et al [3-5] developed the following three-phase process to design mission-congruent organizations:

Phase I: The first phase of the design process determines the task-asset allocation and task sequencing that optimizes mission objectives (e.g., mission completion time, accuracy, workload, asset utilization, asset coordination, etc.), taking into account task precedence constraints and synchronization delays, task-resource requirements, resource capabilities, as well as geographical and other task transition constraints. The generated task-asset allocation schedule specifies the workload of each asset. In addition, for every mission task, the first phase of the algorithm delineates a set of non-redundant asset packages capable of jointly processing a task. This information is later used for iterative refinement of the design, and, if necessary, for on-line strategy adaptation.

Phase II: The second phase of the design process combines assets into nonintersecting groups, to match the operational expertise and workload threshold constraints on available DMs, and assigns each group to an individual DM to define the DM-asset allocation. Thus, the second phase delineates the DM-asset-task allocation schedule and, consequently, the individual operational workload of each DM.

Phase III: Finally, Phase III of the design process completes the design by specifying a communication structure and a decision hierarchy to optimize the responsibility distribution and inter-DM control coordination, as well as to balance the control workload among DMs according to their expertise constraints.

Each phase of the algorithm provides, if necessary, feedback to the previous stages to iteratively modify the task-asset allocation and DM-asset-task schedule. Phase I of the design process essentially performs mission planning, while Phases II and III construct the organization to match the devised courses of action.

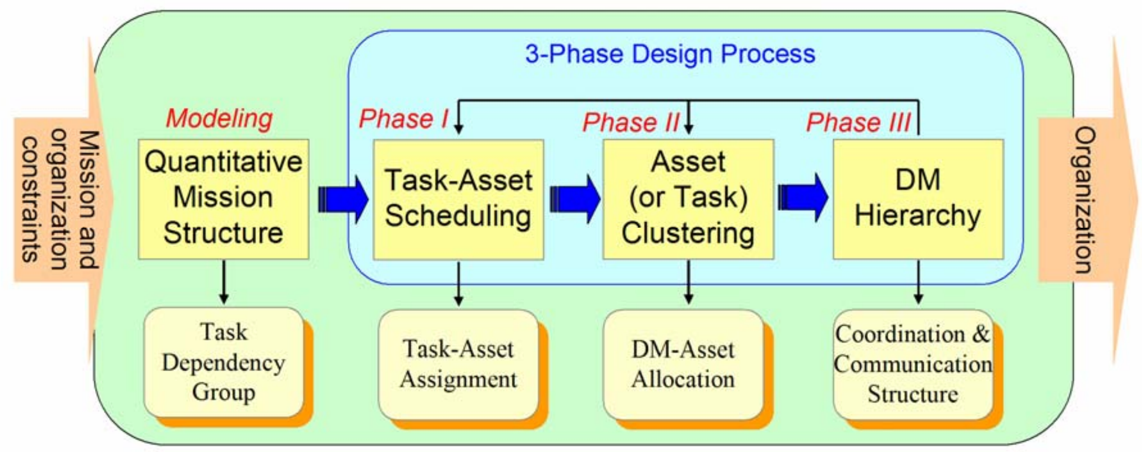

Figure 2. Three-phase organizational design process.

A C2 architecture can be organized as a hierarchy, heterarchy, or a holarchy. This paper employs the holarchical structure because it overcomes the limitations of both hierarchical and heterarchical structures.

Hierarchy: Traditional C2 hierarchy keeps authority and information at the center. Koestler [9] observes that most of the complex systems are organized hierarchically: the control flow is typically top-down and the feedback information is bottom-up. The decision makers at the upper level define tasks and coordinate lower level units, while decision makers at the lowest level execute the tasks. One of the many merits of a hierarchical C2 structure is that it provides unity of command, which refers to the principle that a subordinate should have one and only one superior to whom he or she is directly responsible. Because military power is the product of multiple capabilities, a centralized C2, as an embodiment of the principle of unity of command, is essential to effectively fuse these capabilities. However, hierarchical control assumes deterministic behavior of the components [10]. Studies indicate that a fixed, vertically integrated hierarchy has the following drawbacks [11]: (a) limited ability for reconfiguration to novel situations; (b) slower response and limited immediate intelligent actions in the face of a major disturbance due to the rigidity of a hierarchy; and (c) limited propagation of bottom-up information due to a multi-level bureaucratic structure.

Heterarchy: The conventional alternative to hierarchy is heterarchy. A heterarchial structure has the attributes of distributed intelligence, diversity, self-organization, and lateral accountability [12]. In a heterarchical structure, decision makers (DMs) communicate as peers; there are no fixed supervisor/subordinate relationships. Each DM has equal right of access to resources and independent modes of operation. Coordination among DMs is realized by using a market mechanism, such as the 'contract net protocol' or the 'request for bid' protocols, etc. Most heterarchical systems have no central controller. Some inherent capabilities of heterarchy include self-configuration, flexibility, fault-tolerance, reduced complexity, and emergent behaviors [13]. However, except for a few applications, heterarchical architectures are not widely used due to the following drawbacks: (a) limited performance due to the absence of global information; (b) unpredictability of organizational behaviors; (c) sensitivity of system performance to coordination protocols; (d) the low efficiency of market-based negotiation mechanism resulting in a slow decision process; (e) limited emergent behaviors; and (f) potential for chaotic behaviors.

Holarchy: A hybrid organizational structure, termed the holonic structure or the holarchy, is proposed in order to overcome the drawbacks of both the hierarchy and the heterarchy. The holonic structure combines features of these two structures, and addresses key requirements of C2 organizational structures operating in dynamic and uncertain situations. The term 'holonic' is derived from the word 'holon', and was introduced by Koestler in the context of social and living organisms [9]. This word is a combination of the Greek 'holos' meaning whole, with the suffix 'on' which, as in proton or neutron, suggests a particle or part. The holon, then, implies a combination of 'wholes' and 'parts'. Thus, 'holons' refer to autonomous self-reliant units, which hold a degree of independence and are able to manage contingencies without interference from their superiors. A holonic modeling concept is used as a means for the synchronization of both the physical view and informational views ensuring interoperability in an enterprise context [15].

Accordingly, a holarchy refers to a hierarchy of self-regulating holons with the following advantages [10]: (a) ability to model and control very complex systems; (b) high resilience to internal and external disturbances; (c) adaptability to changes in the environment. Within a holonic organization, holons can dynamically create and change hierarchies. They can be both autonomous, as well as cooperative. That is, holons can handle circumstances and incidents based on their own knowledge and information available without interference from superiors; at the same time, holons can still receive instructions or be controlled by their superiors. This combined hierarchical and heterarchical behavior ensures effectiveness in complex C2 operations.

Yu et al [6, 7] employed concepts from group technology and nested genetic algorithms to solve holonic coordination problem in a two-level structure (operational and tactical levels) involved in planning and executing a single mission. The focus was on asset allocation and task scheduling problem for the ESG. Herein, we consider three-level structures (viz., strategic, operational, and tactical levels) for MHQ with MOC facing multiple simultaneous or sequential missions. Consequently, the holonic scheduling concepts for C2 organizational design considered here can be applied to the coordination problems in MHQ with MOC; these link the tactical, operational and strategic levels.

The contributions of this paper are three fold. The three-level architecture gives the solution to the C2 coordination problem involving a higher level authority (e.g., combatant commander at the strategic level), in addition to operational and tactical levels. The second contribution is that the paper gives a solution approach for the multi-mission planning problem at the operational level. The third contribution is that the paper shows how holonic organizational structures may be employed for the USN's complex and distributed coordination problem involving MHQ with MOC.

Organization of the Paper

This paper is organized as follows. Section II explores our three level C2 organizational design model, and introduces a holonic reference architecture (HRA). Section III shows two coordinating decision layers (e.g., the SLC-OLC layer and the OLC-TLC layer). An operational model for holonic scheduling is discussed through an illustrative example in section IV. Herein, the processes of centralized assessment and guidance, distributed and collaborative planning, and decentralized execution are evident in that it employs centralized decision making at the strategic level via a Markov Decision Problem (MDP), collaborative planning at the operational level in terms of specifying the mission task graphs delineating mission phases and precedence/synchronization constraints on tasks, and negotiation mechanisms at the lower level to resolve scheduling conflicts. Finally, the paper concludes with a summary of key findings and future research directions in section V.

II. STRUCTURE OF HOLONIC C2 REFERENCE ARCHITECTRUE

Three-level Control Architecture

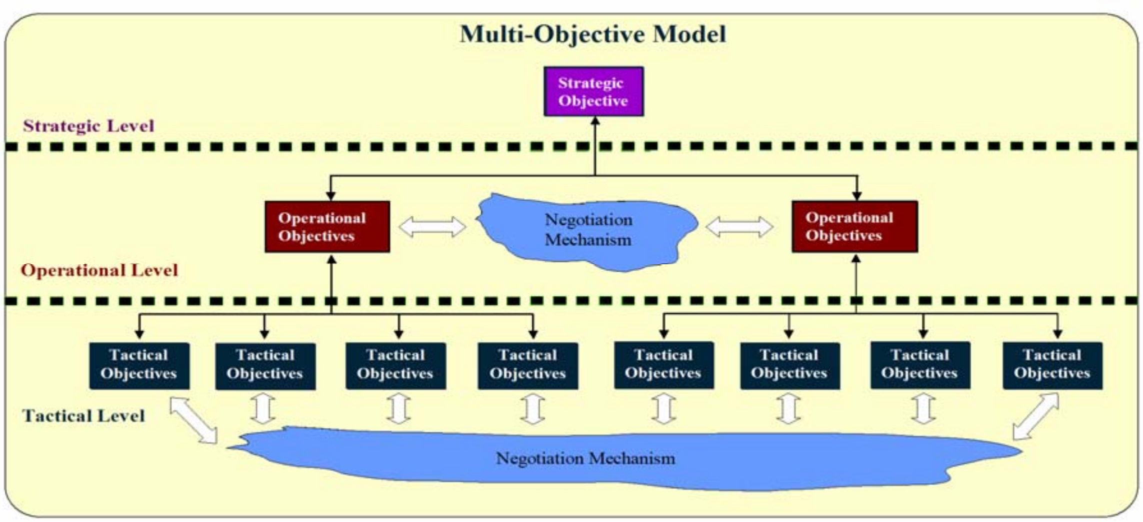

Figure 3. Three level holonic reference control architecture.

Within the scope of decentralized C2 requirements, the control architecture should be distributed, abstract and generalized. The control is *abstract* in the sense that the assumptions on the internal structure and the behavior of other DMs should be least restrictive. The *generalized* control requires that a holon be cloned from certain basic structures. The distributed control should also be both *reactive* and *self-organizing*, i.e., control is able to respond to environmental disturbances and adapt to changes during the mission execution process. We categorize the C2 architectural concepts into three levels as shown in Fig. 3.

Strategic Level Control (SLC) Architecture

The SLC architecture provides a structure for establishing mission objectives and guidance for future plans. At this level, the process is focused on national/international objectives. It gives strategic-level guidance to MHQ commanders assigning mission priorities and resolving mission conflicts as they arise during subsequent planning and operations. This level also decides the time sensitivity of multiple missions and ensures that the missions meet the strategic objectives. We model the strategic guidance using MDP. The MDP decides on the sequence of missions with the national level constraints (i.e., political, military, economic, social, information and infrastructure constraints). That is, the MDP decides which missions should be executed in parallel and which ones should be executed sequentially.

The SLC architecture is built around six types of basic holons: Strategic holon (STH), national/international intelligence holon (NIIH), mission sequence decision holon (MSDH), security coordination holon (SCOH), guidance holon (GUH), and strategy communication holon (SCOMH). Each of these holons is responsible for one aspect of strategic level control.

Operational Level Control (OLC) Architecture

The OLC architecture provides facilities for mission decomposition (i.e., generating the task graph), deliberate planning (future plans and future operations), command, inter-holon coordination/negotiation. At this level, the process is focused on meeting the strategic guidance of the SLC by integrating and synchronizing key objectives at all levels of war. It seeks to produce an initial force structure that places the subordinate units at the right place and at the right time prior to mission execution. During the current operations, it monitors the real-time mission execution and its effects, and adjusts the initial plan, if needed, to ensure that the mission is successfully completed. It also has a negotiation mechanism to resolve conflicts among multiple missions (simultaneous or sequential); however, it still requests guidance from the strategic level when conflicts are irresolvable via the negotiation mechanism, and provides C2 based on this guidance.

The OLC architecture is built around six types of basic holons as well: Operational holon (OPH), intelligence holon (INH), planning holon (PLH), coordinating/negotiation holon (CONH), promulgating holon (PRH), and communication holon (COMH). Each of these holons is responsible for one aspect of operational level control.

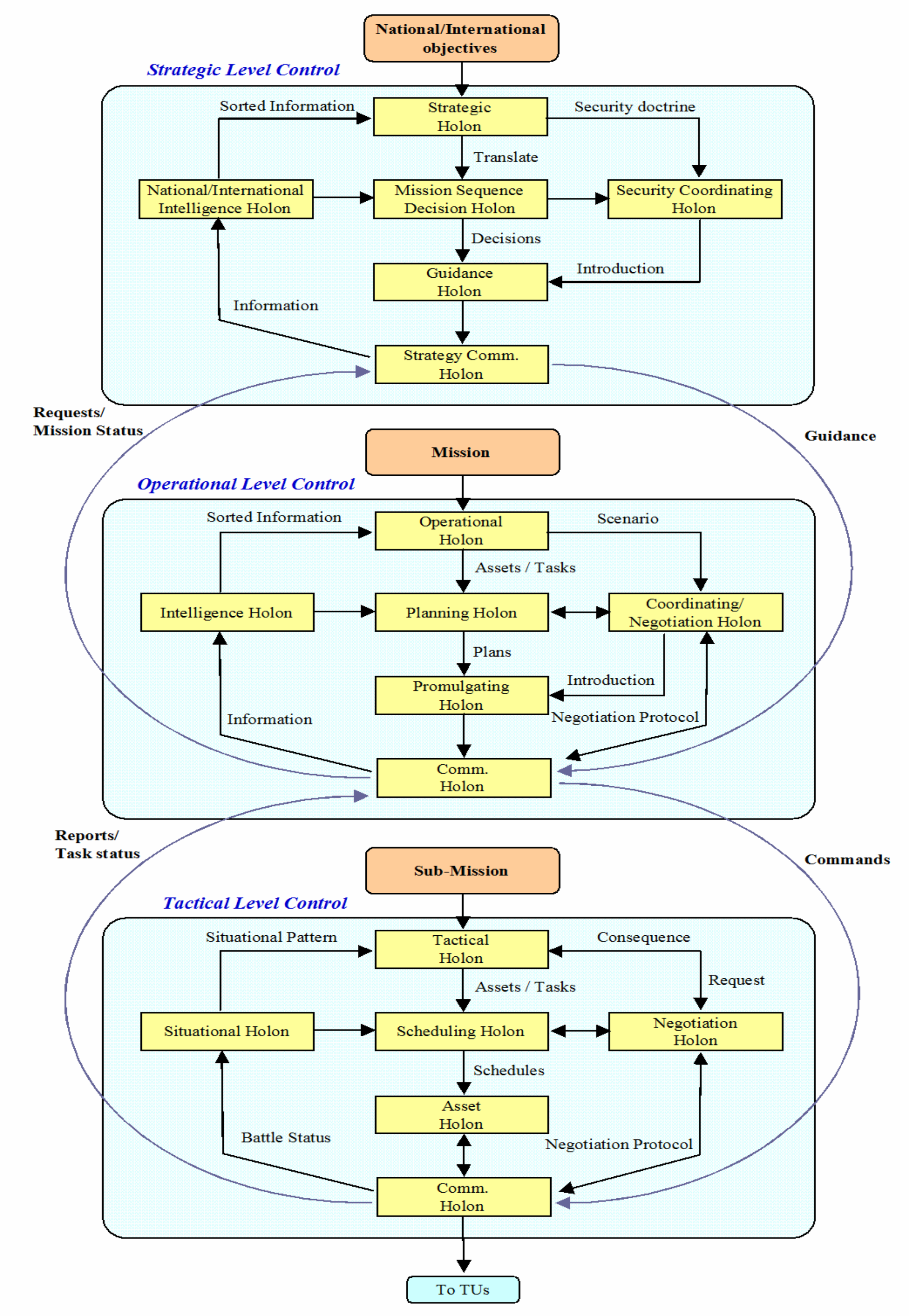

Figure 4. Three level control architecture.

Tactical Level Control (TLC) Architecture

The TLC architecture encapsulates the functional holons that execute the assigned sub-missions or tasks. This tactical process involves local task scheduling, battlefield pattern recognition, and negotiation mechanism. It also provides an interface to the physical assets. The TLC architecture can have more than one TLC instance (TLC unit); the numbers of instances are decided by deliberate planning in the OLC architecture. The TLC units can be dynamically added or deleted according to the perceived mission environment. A negotiation mechanism is provided for the TLC units to resolve conflicts among themselves, or to provide coordination as needed.

The TLC architecture is concerned with mission execution, given the allocated assets by the OLC holons. The TLC architecture is comprised of six holons: Tactical holon (TAH), situational holon (SIH), scheduling holon (SCH), negotiation holon (NEH), asset holon (ASH), and communication holon (COMH).

Coupling the three-level architecture, there are two coordinating decision layers at the SLC-OLC and the OLC-TLC interfaces. The first decision layer (the SLC-OLC layer) is used for coordinating multiple missions, and the second decision layer (the OLC-TLC layer) resolves conflicts in task scheduling and asset allocation for each mission. Task status reports from subordinate holons at the TLC are sent up to holons at the OLC. The monitoring and supervision of the overall progress of the mission and adjustment of tactical action is promulgated to lower level holons. If missions are in conflict at the OLC, the OLC requests the SLC to obtain strategic guidance, and then the SLC gives guidance to resolve the conflict(s) and yet achieve long-term strategic objectives.

III. TWO COORDINATING DECISION LAYERS

SLC-OLC layer

We model the optimization problem of strategic guidance of deciding on the sequence of missions (simultaneous or sequential) subject to the national level constraints (i.e., political, military, economic, social, information and infrastructure constraints) as a Markov decision problem (MDP). A MDP is specified by state space, action set, action-dependent state transition probabilities, and a reward structure.

State space, *X*: The mission environment is assumed to have n_h states. Each state, *x(k)* defined at the beginning of a decision epoch *k*, denoting a combination of missions, is assumed to belong to a set, $X = \{x_h\}_{h=1}^{n_h}$. We consider a scenario where the SLC needs to dynamically decide on a state-dependent mission policy that decides on the sequence of multiple missions to be planned at the OLC. The combination of military operations, such as peacekeeping, HA/DR (Humanitarian Assistance and Disaster Relief), stability operations, and major combat operations constitute the states of MDP. If there are *M* possible operations, and if let $z_i \in \{0,1\}$ denote the status of operation *i*, where z_i =1 denotes the presence of an operation and 0 implies its absence, state x_h is denoted by an M-dimensional binary vector $[z_1, z_2, ..., z_M]$. Table 1 shows the different states (one for each row), along with the operational attributes (presence, absence) characterizing them.

x_h	Peacekeeping	HA/DR	Stability Ops.	Major combat Ops.
x_1	1	1	1	1
x_2	1	1	1	0
x_3	1	1	0	1
x_4	1	1	0	0
x_5	1	0	1	1
x_6	1	0	1	0
x_7	1	0	0	1
x_8	1	0	0	0

Table 1. State space denoting combinations of military operations.

Action set, *U*: an action $u_j(k)$, also defined at the beginning of a decision epoch k, in state x is assumed to belong to the set $U_k(x) = \{u_j\}_{j=1}^{m(x)}$, where $m(x)$ is the number of possible ways of executing the mission combinations in state x. For example, if M_x is the number of mission combinations in state x, and we allow only a two step parallel and sequential missions wherein $l \geq 2$ missions are executed in parallel and the remaining $(M_x - l)$ are executed sequentially (the latter will be sequenced in the order of their priority so that the remaining $(M_x - l)$ missions can only be executed only one way), the cardinality of action set is:

$$|U_k(x)| = 1 + \sum_{l=2}^{M_x} \binom{M_x}{l}. \tag{1}$$

Evidently, the cardinality of action set increases exponentially with the number of mission combinations. In the following, for simplicity of exposition and with no loss in generality, we allow $l=1$ (sequential) *or* $l=M_x$ (parallel) so that the cardinality of $|U_k(x)| = 2$ and $U_k(x) = \{Parallel, Sequential\}$.

State transition probabilities, $\{P(x(k+1) | x(k), u_j(k))\}$: given (current) state $x(k)$, and action $u_j(k)$, the probability of $x(k+1)$ being the next state is denoted by $P(x(k+1) | x(k), u_j(k))$. In this scenario, each mission operation has its own transition probability matrix, and the transition probabilities among states are computed by multiplying the corresponding elements from these local transition probability matrices. For example, consider a HA/DR with two operational states *S = {HA/DR yes, HA/DR no}*. Here, *yes* implies that the operation needs to be executed, and *no* implies that the operation is irrelevant. The state transition matrices for the HA/DR operations for parallel and sequential execution are shown in Table 2. As seen from this table, the transition probability from 'HA/DR yes' to 'HA/DR no' is higher, if the MHQ with MOC executes this operation in parallel with other operations. Also, because of the higher resource requirements for parallel execution of missions, there is a higher probability of transitioning from the ‘HA/DR no’ state to the ‘HA/DR yes’ state.

Action	Parallel		Sequential	
Op. states	HA/DR yes	HA/DR no	HA/DR yes	HA/DR no
HA/DR yes	0.3	0.7	0.4	0.6
HA/DR no	0.1	0.9	0.01	0.99

Table 2. The operation state transition matrix for *HA/DR*.

Assuming that the stochastic matrices for stability operations and the major combat operations can also be represented in a manner similar to *H* (in fact, identical in this example), we can obtain the overall state transition matrix among the MDP states as:

$$P(x(k+1)\,|\,x(k),u_j(k))=\prod_{i=1}^{M}P(z_i(k+1)\,|\,z_i(k),u_j(k))\,. \qquad (2)$$

The resulting state transition probability matrix of the MDP for simultaneous mission execution is computed as shown in Table 3.

x_h	x_1	X_2	x_3	x_4	x_5	x_6	x_7	x_8
x_1	0.027	0.063	0.063	0.147	0.063	0.147	0.147	0.343
x_2	0.009	0.081	0.021	0.189	0.021	0.189	0.049	0.441
x_3	0.009	0.021	0.081	0.189	0.021	0.049	0.189	0.441
x_4	0.003	0.027	0.027	0.243	0.007	0.063	0.063	0.567
x_5	0.009	0.021	0.021	0.049	0.081	0.189	0.189	0.441
x_6	0.003	0.027	0.007	0.063	0.027	0.243	0.063	0.567
x_7	0.003	0.007	0.027	0.063	0.027	0.063	0.243	0.567
x_8	0.001	0.009	0.009	0.081	0.009	0.081	0.081	0.729

Table 3. The state transition matrix of MDP (Action = Simultaneous).

Reward structure, $\{R(x(k),u_j(k))\}$: Another important part of the MDP is the reward formulation. The reward is a surrogate to the probability of mission success. The immediate reward for taking action $u_j(k)$ in state $x(k)$, $R(x(k),u_j(k))$, is calculated as follows. The contribution of each operation to the reward is assumed to be different because of their priorities. For example, the reward for the major combat operation is larger than that of the HA/DR, because the major combat mission is assumed to have a higher priority to the national security than a HA/DR mission. An example of national level reward matrices for various operations is assumed to be as shown in Table 4.

Operations	Political	Military	Economic	Social	Infra.	Inform.	Sum
HA/DR	0.5	0.5	0.75	0.75	0.75	0.25	3.5
Stability Ops.	1	1	0.5	0.5	0.5	0.5	4
Major Ops.	1.5	1.5	0.25	0.25	0.25	0.75	4.5

Table 4. The national level reward matrices for various operations.

We can obtain the overall reward for each state-action pair as:

$$R(x(k),u_j(k)) = \sum_{i=1}^{M} R(z_i(k),u_j(k))\ . \tag{3}$$

The resulting reward matrices for the MDP states are computed as shown in Table 5.

x_h	Simultaneous	Sequential (Simultaneous×90%)
x_1	12.00	10.80
x_2	7.50	6.75
x_3	8.00	7.20
x_4	3.50	3.15
x_5	8.50	7.65
x_6	4.00	3.60
x_7	4.50	4.05
x_8	0.00	0.00

Table 5. The reward matrices.

Policy, π : the best action to be taken in each state at each decision epoch.

The objective is to determine an optimal policy, i.e., a mapping from states to actions, such that the value function (expected total reward) is maximized. The value function of an initial state *x* = *x(0)*, for policy π is denoted as:

$$V^{\pi}(x) = E^{\pi}[\sum_{k=0}^{N-1} R(x(k),u(k)) + R(x(N))], \tag{4}$$

where N is the number of decision epochs.

The optimal state-dependent mission policy for this problem is computed by dynamic programming [16] and is shown in Table 6. Since state 1 has many missions (major combat operation, stability operation, and HA/DR) to execute, the concomitant action policy involve sequential mission processing.

x_h	x_1	x_2	x_3	x_4
π	Sequential	Simultaneous	Simultaneous	Simultaneous
x_h	x_5	x_6	x_7	x_8
π	Simultaneous	Simultaneous	Simultaneous	Simultaneous

Table 6. The mission policy of each state.

OLC-TLC layer

In our previous work [6], we formulated and solved a two-level coordination problem at the OLC-TLC layer by employing concepts from group technology (GT) and nested genetic algorithms (NGA). In this formulation, a task, derived from mission decomposition, is an activity that entails the use of relevant resources, and is executed by one or more decision makers (DMs) at the tactical level to accomplish the mission objectives. The DM is an entity with information-processing, decision-making, and operational capabilities that can control the necessary resources to execute the tasks. A DM also communicates with other DMs, and cooperates on task execution by sharing his resources. The resources are carried by assets with given resource capabilities, ranges of operation and velocities. The organization consists of a set of DMs, the assignment of assets to DMs, and the coordination structure among DMs.

For concreteness, we consider the following process for planning and executing a mission. A set of tasks with specified resource requirements, locations, and precedence relations need to be processed by the organization. The tasks are assigned to DMs based on the fit between the resource requirements of tasks and the resource capabilities of DMs. The assigned DMs select and send their assets to the locations where tasks appear in order to execute them with minimum lead time and maximum accuracy. In a situation wherein a DM assigned to a task must utilize the assets from another DM, they must coordinate to synchronize the operations of their assets (e.g., arrival time of assets at the task location). Only when all the assets needed to process a task have arrived, the task execution begins. Therefore, the delays in task execution are primarily due to synchronization. In order to minimize the overall task completion time, the synchronization delays should be minimized. In addition, the task execution accuracy should be maximized. We note that minimizing the inter-DM coordination delay ("between group delay") outweighs the intra-DM coordination delay ("within group delay"), since there is a "barrier" between any two DM cells. However, there are always some exceptional tasks that need to be processed by more than one DM. Due to these exceptional tasks, the inter-DM coordination delays are inevitable. A tradeoff between internal and external coordination workload is a key aspect of our design approach.

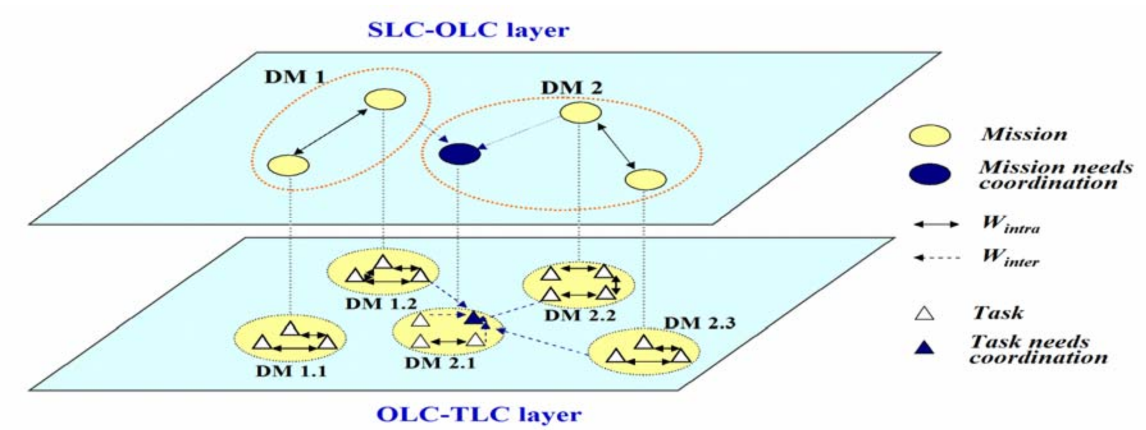

Figure 5. Illustration of the problem to be solved.

IV. OPERATIONAL MODEL FOR HOLONIC SCHEDULING

A Holonic Scheduling Model

In our previous work [7], the two-level (OLC-TLC) model for the C2 holonic reference architecture (HRA) for planning and executing a single mission was considered. The model included the mission and its decomposition into a task graph, planning, and task scheduling. Those elements of the model are also used in this work, and are extended to include multiple missions at the SLC level. We consider the following example for illustrative purposes.

Missions: MHQ with MOC is assigned to complete two military missions, which occur in geographically separated areas, e.g., mission 1: capturing a seaport to allow an introduction of follow-on forces (major combat operation), mission 2: rescue activity after a hurricane in the homeland (HA/DR). Fig. 6 shows the geographical situation in this area [8]. We assumed that the missions are reproduced using the tasks in [6]. Here, the odd numbered tasks of [6] are categorized as mission 1 and the even numbered tasks of [6] are categorized as mission 2.

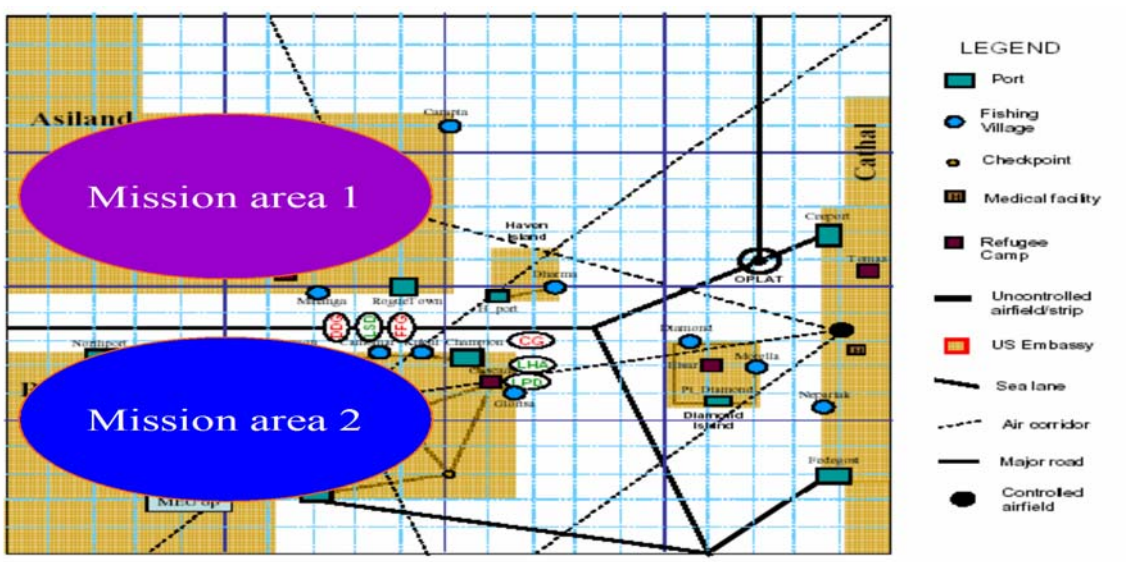

Figure 6. Notional mission areas.

Multi-mission sequence planning (Future Plans): The mission sequence decision holon (MSDH) at the SLC level manages multiple missions; it provides guidance for future plans by specifying the sequence of missions (simultaneous or sequential) to be planned and executed using MDP (see Fig. 7). The mission state 3 is the initial state where MHQ with MOC is tasked to execute a major military operation and an HA/DR. From the optimal MDP policy, missions 1 and 2 should be executed simultaneously, while mission 1 has a higher priority if the two missions are in conflict because it has larger national level reward value than mission 2 in Table 4.

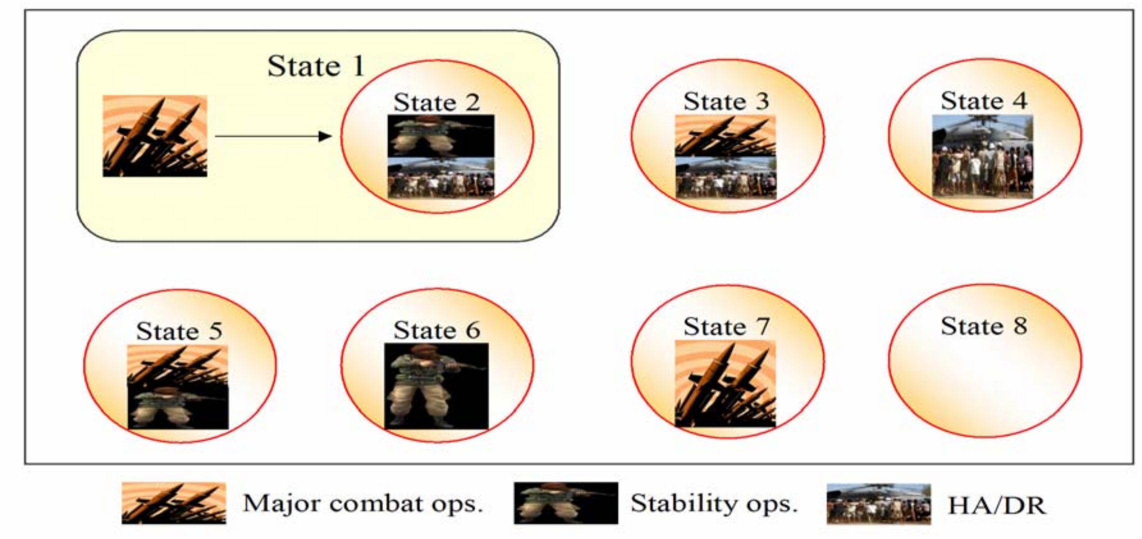

Figure 7. The mission sequence as computed by the MSDH in the SLC architecture.

Mission Decomposition (Future Operations): The operational holon (OPH) in each mission unit at the OLC level provides plans for future operations; it devises plans for the missions that include the mission decomposition and the task precedence constraints as shown in Fig. 8.

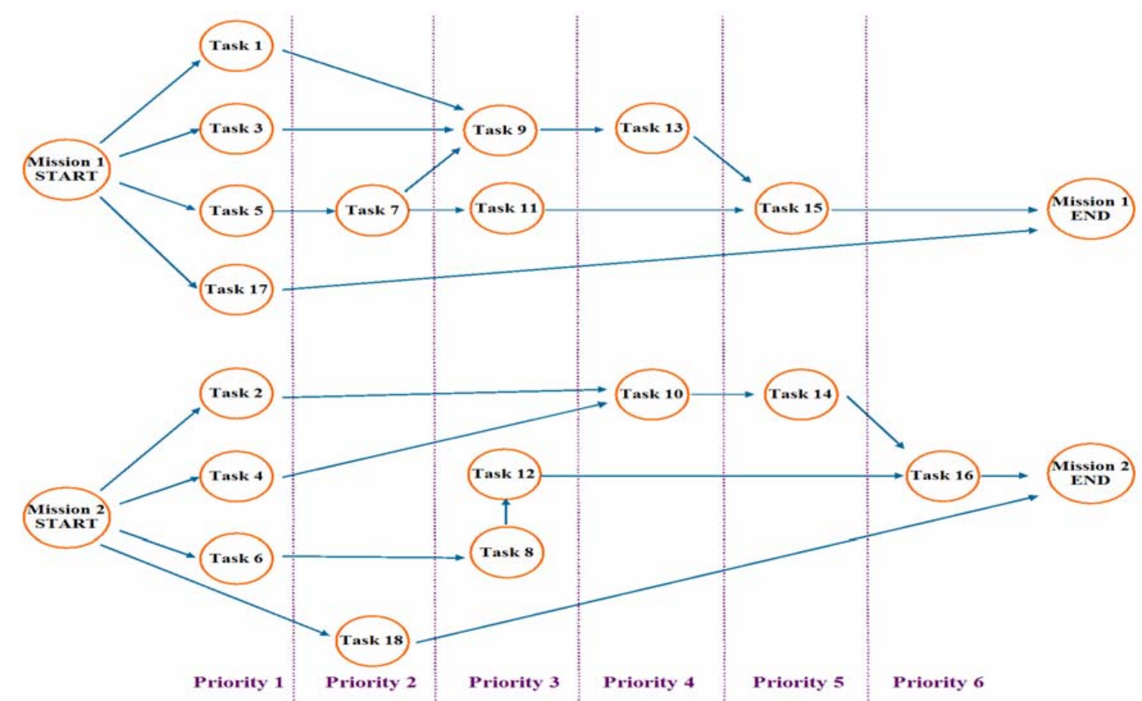

Figure 8. Mission decomposition from the OPH in the OLC architecture.

Deliberate Planning (Future Operations): The planning holon (PLH) in each mission unit at the OLC level also provides a future operations plan by allocating the tasks and assigning assets to these tasks after the mission is decomposed by the operational holon (OPH). The group technology (GT) and the nested genetic algorithm (NGA) developed in [6] are used to solve the task-asset assignment problem with the objective of minimizing both the internal and the external workloads of the system (see Fig. 9). Here an entry of 1 in element (*i*, *j)* denotes that the corresponding asset in row *i* is assigned to the task in column *j*. These plans specify the optimal number of TLC units for each mission, the task assignment to each TLC unit, and the asset allocation to each TLC unit.

Holonic Scheduling (Current Operations): The holonic scheduling process at the OLC involves interactive coordination and synchronization between holons from both the TLC and the OLC for the current operations. The holonic scheduling process involves interactive coordination and communication between holons from both the OLC and the TLC, e.g., the CONH (coordinating/negotiation holon) in the OLC and the SCH in each TLC unit. The holonic scheduling is comprised of two elements: the OLC-TLC coordination layer and the SLC-OLC coordination layer.

Assets *(i)*	Mission 1									Mission 2								
	Tasks *(j)*									Tasks *(j)*								
	3	15	11	13	17	1	5	7	9	16	18	6	12	14	2	4	8	10
1	1	1								1	1							
15											1							
18		1								1	1							
19		1								1								
3												1						
7			1	1	1							1	1	1				
11																		
14			1				1						1					
17				1	1						1							
20												1						
2						1									1			
10						1									1			
12						1									1			
16						1												
4							1											
5								1									1	
6																		
8								1	1							1	1	
9									1								1	1
13																		1

Task Unit

Figure 9. The asset allocation plan created by the PLH in the OLC architecture.

(i) The OLC-TLC coordination is carried out by the coordinating/negotiation holon (CONH) at the OLC and the scheduling holon (SCH) in the TLC. The CONH at the OLC first decomposes the future operations plans (Fig. 8 and 9), and then distributes them among the TLC units. Then each SCH at the TCL makes the sequencing decisions based on local information, local objectives and constraints. We assume that each TLC unit seeks to find a schedule that minimizes the makespan of the task. The distributed schedule for the current operation is shown in Fig. 10.

Negotiation mechanism provides communication among the TLC units when coordinating on the execution of a task. Information and commands are exchanged by the use of a negotiation protocol, in which the schedule of certain assets executing cooperative tasks can be determined by negotiation. In this example, the TLC unit TU2 will negotiate with TU3 on mission 1 before it sends its asset 14 to coordinate on task T5.

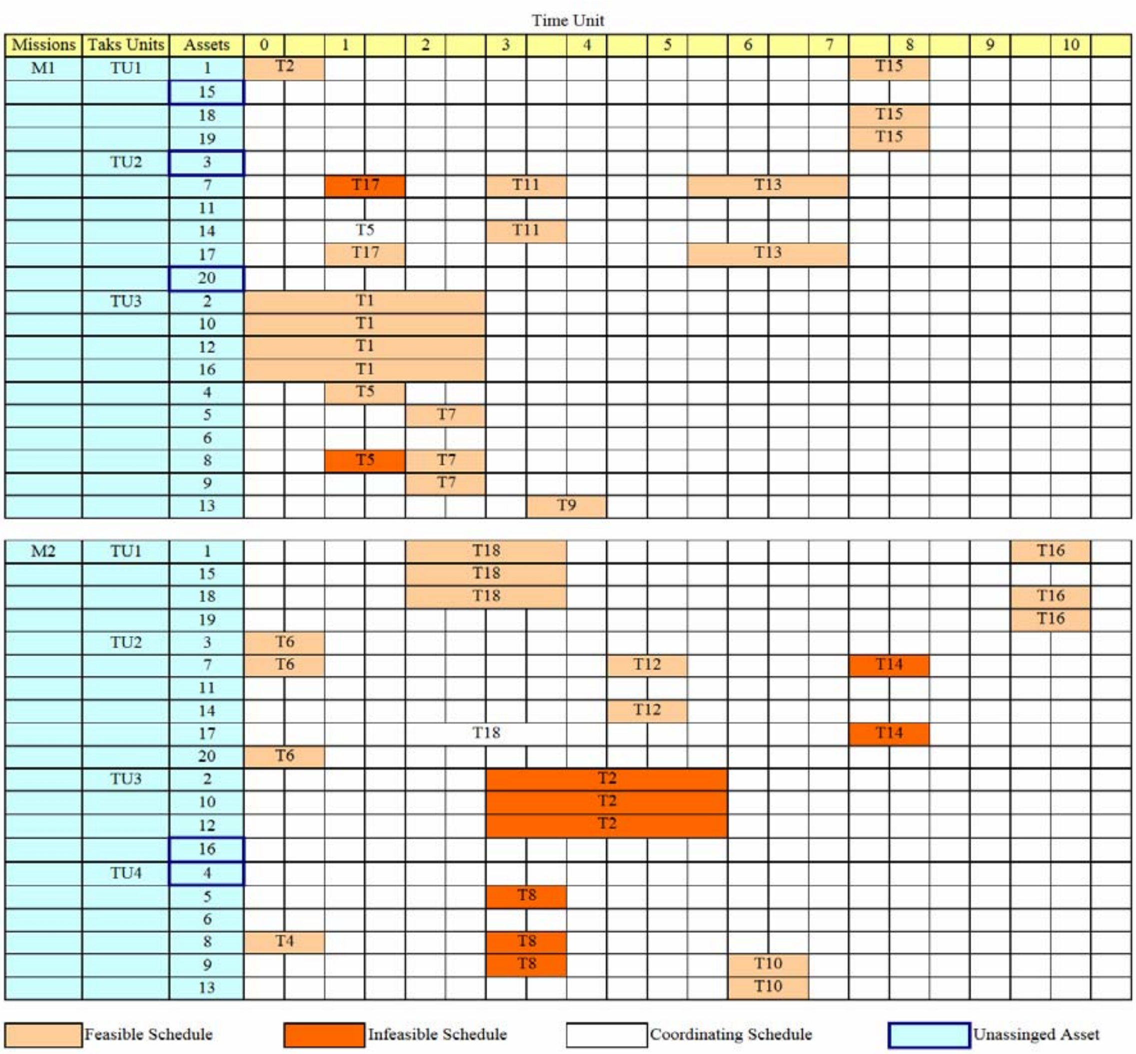

Figure 10. The schedule created by the OLC-TLC layer.

(ii) The SLC-OLC coordination is carried out by the security coordination holon (SCOH) in the SLC and the planning holon (PLH) in the OLC architecture. This involves setting mission priorities and sequencing of missions. For example, we may notice that the schedule for task 17 and task 5 is infeasible, because assets 7 and 8 experience travel and logistics delays in moving to mission area 1 after completing tasks 4 and 6 at mission area 2. The infeasibility of the global schedule can be detected by the SLC-OLC layer. The re-scheduling procedure begins by setting a higher priority to mission 1 based on future plans; and it generates a feasible global schedule; consequently, it also advises the OLC-TLC coordination layer (related TLC units) to adjust their local schedules by changing the constraints, for example, the constraint for the starting time of tasks 17 and 5 would be changed from 1 to 2; followed by removing unassigned assets in each mission, for example, assets 15, 3, 20 of mission 1 and assets 16 and 4 of mission 2 are unassigned; this means that those assets are assigned for only one mission. Finally, each related TLC holon regenerates the schedule based on new constraints. Fig. 11 shows a feasible Gantt chart after the scheduling process is completed at the SLC-OLC coordination layer.

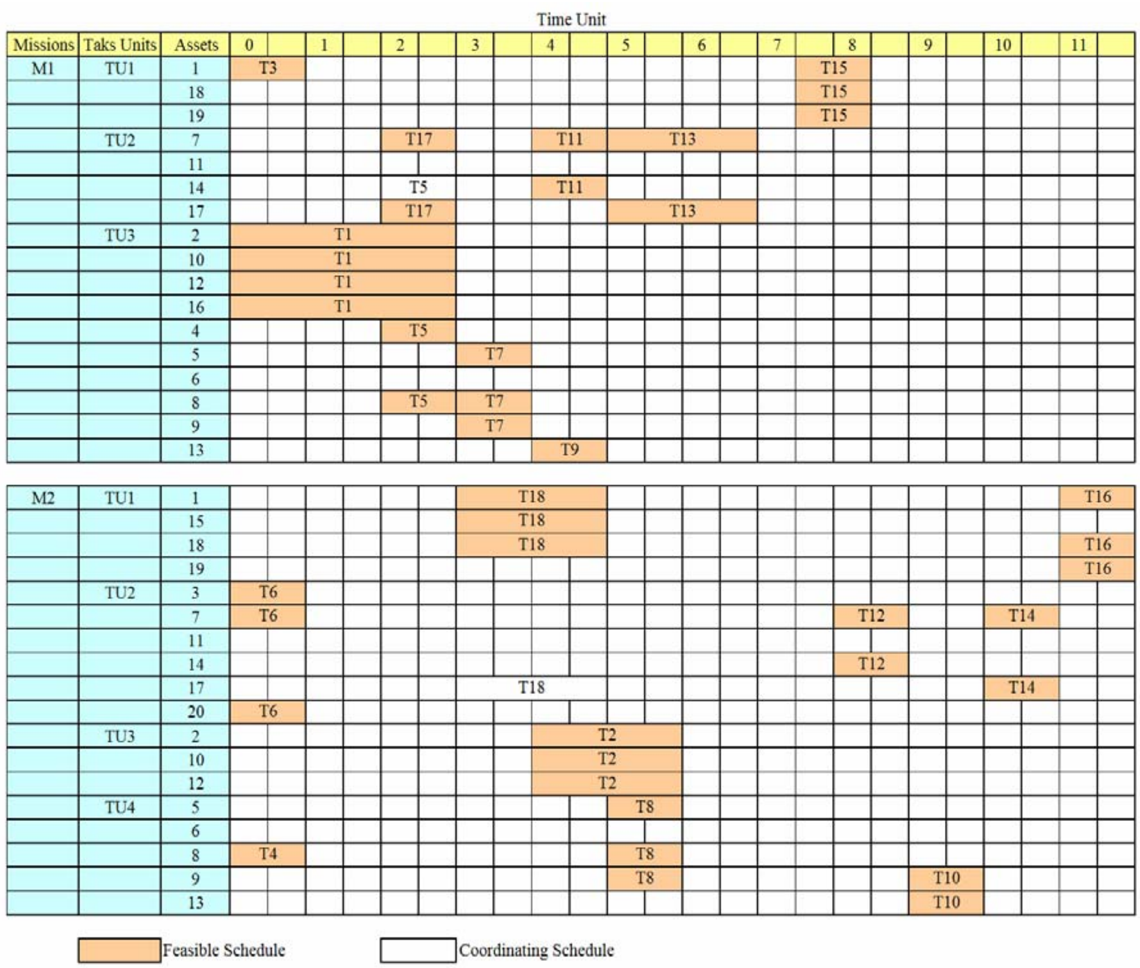

Figure 11. The schedule created by the SLC-OLC layer.

Adaptation to Contingencies: Dynamic Holonic Scheduling Model

Now we consider a dynamic holonic scheduling model assuming that a new military mission is added in ongoing missions at time 3 (after finishing tasks 1, 3, 5 and 17 in mission 1 and tasks 4 and 6 in mission 2) in Fig. 11. The new mission, i.e., mission 3 is a stability operation which seeks to provide security in the unstable mission area 2 due to high possibility of terrorist activity after a hurricane, and also to prevent civilian populations from interfering in mission area 1. In addition to this, we also assume that assets 1, 10, 12 and 16 were disabled during the execution of task 1 of mission 1 (however, we assume that task 1 was completed). Mission 3 is constructed by selecting the tasks at random in [7], then changing those task numbers for a new mission, e.g., the task numbers 1, 4, 5, 8, 9, 12, 13, 16 and 17 are selected and renumbered as 21, 24, 25, 28, 29, 32, 33, 36 and 37, respectively.

The MHQ commander begins rescheduling the current operations by recognizing that the current mission state 3 (including a major combat operation and a HA/DR) transitions to state 1 (adding a stability operation to mission state 3). Now, the optimal MDP policy of the MSDH (mission sequence decision holon) at the SLC level shows that mission 1 should be executed first, followed by this, missions 2 and 3 should be executed simultaneously. In case of conflict, mission 3 has a higher priority than mission 2, because of its lager national level reward value in Table 4.

The operational holon (OPH) at the OLC level decomposes mission 3 and modifies current mission decomposition considering the mission sequence (see Fig. 12).

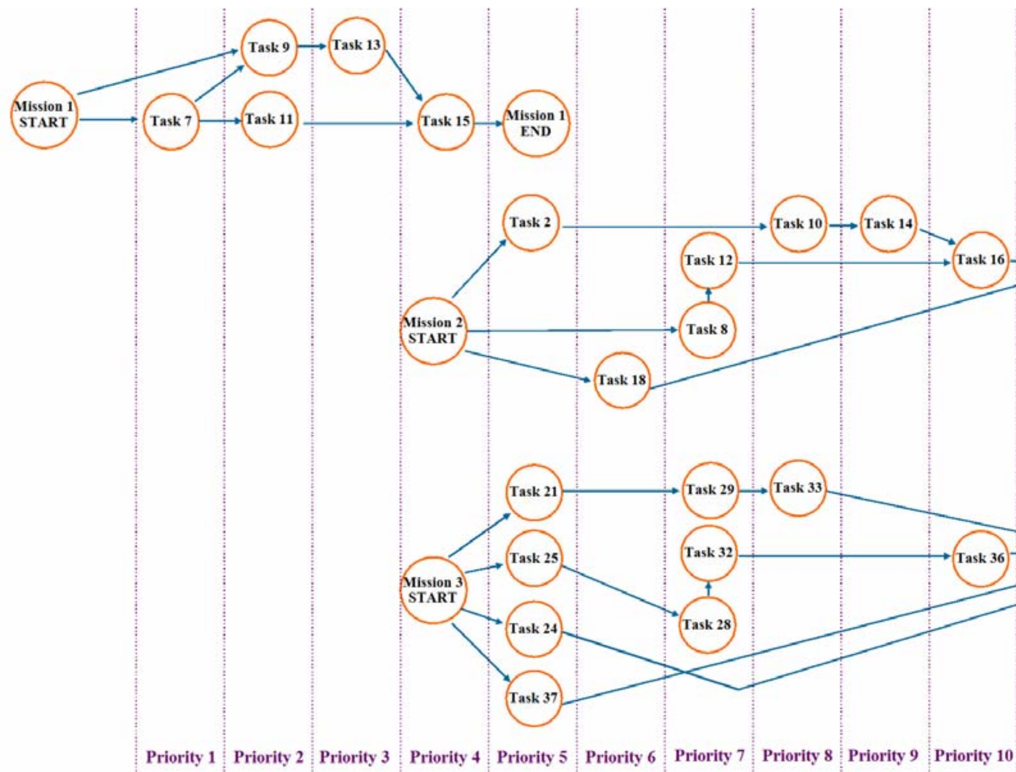

Figure 12. Mission decomposition with three missions

The planning holon (PLH) at the OLC level assigns assets to these tasks after the mission is decomposed by the operational holon (OPH) (see Fig. 13). Here some assets are unavailable while executing task 1, so other assets having the same or similar resource capability substitute for those assets, e.g., assets 8, 9 and 10 (Close air support 1, 2 and 3) in [6].

Figure 13. The new asset allocation plan after some asset breakdown.

The OLC-TLC coordination modifies the distributed schedule for current operations at time 3 (see Fig. 14). Missions 2 and 3 begin after completing mission 1 (recall that the strategy is such that mission 1 is sequential, while missions 2 and 3 are simultaneous) considering the travel and logistical delays of assets 1, 18 and 19 from mission area 1 to mission area 2. Based on negotiation mechanism, the TLC unit TU2 will negotiate with TU1 on mission 2 before it sends its asset 17 to coordinate on task T18.

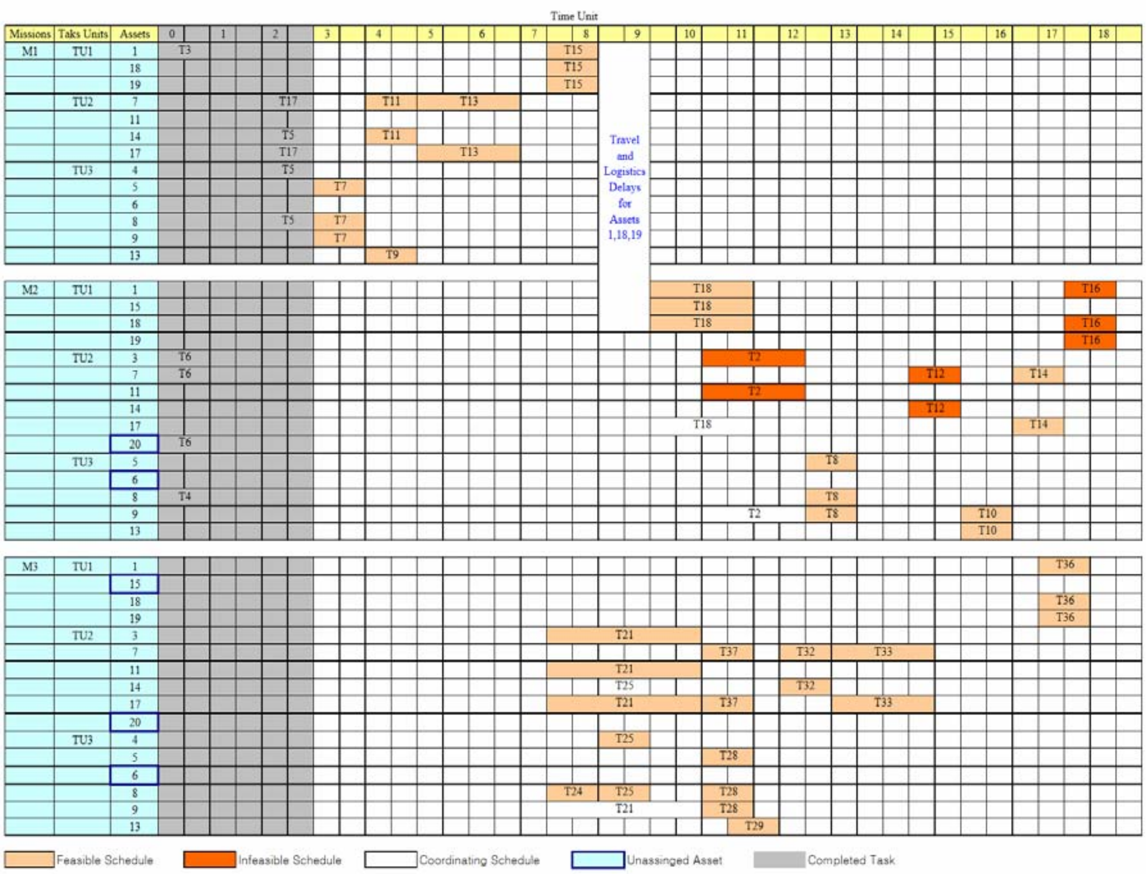

Figure 14. The schedule modified by the OLC-TLC layer at time 3.

The SLC-OLC coordination involves again setting mission priorities and sequencing of missions as in the previous example. Fig. 15 shows a new feasible Gantt chart after the planning process at the SLC-OLC coordination layer.

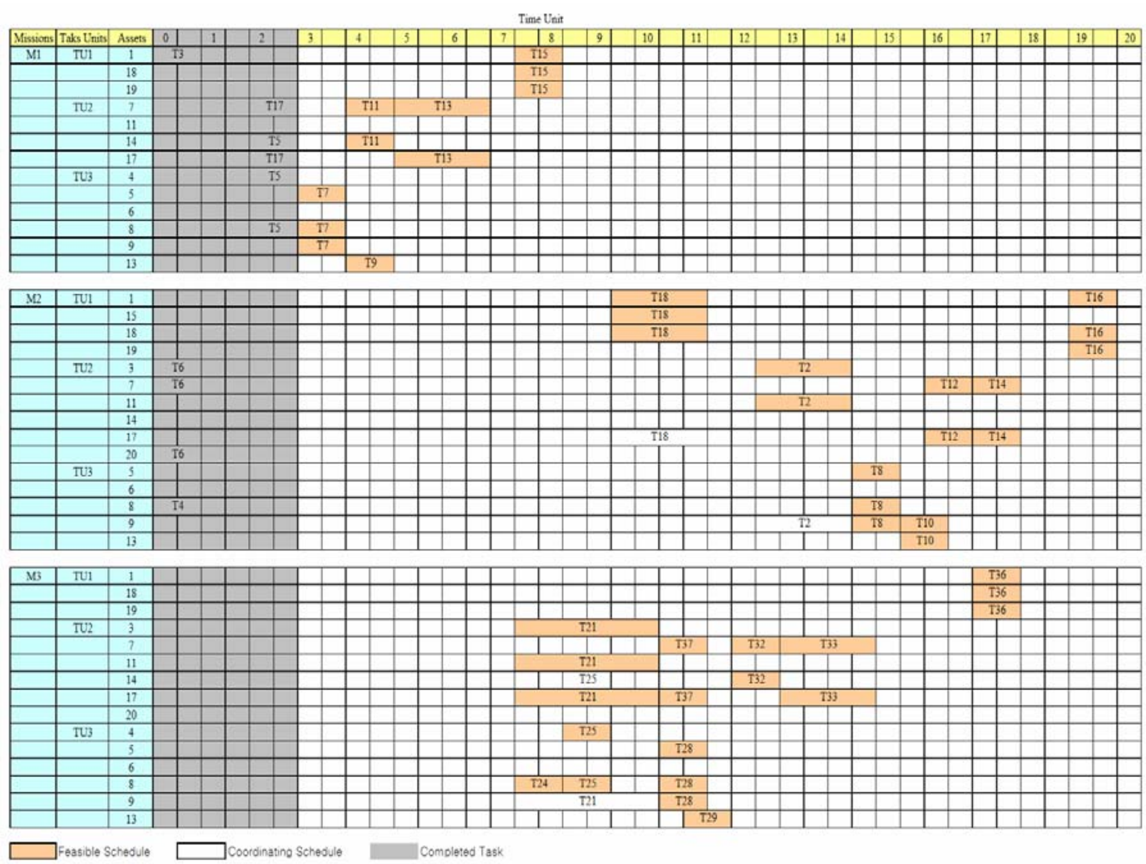

Figure 15. The schedule modified by the SLC-OLC layer at time 3.

V. CONCLUSIONS AND FUTURE WORK

The Navy's new concept of incorporating MHQ with MOC emphasizes standardized processes and methods, centralized assessment and guidance, networked distributed planning capabilities, and decentralized execution for assessing, planning and executing missions across a range of military operations. In this paper, we have presented a C2 holonic reference architecture that is applicable to Navy MHQ with MOC for assessing, planning and executing multiple missions and tasks across a range of military operations.

We modeled the coordination issues inherent in the MHQ with MOC via a three-level holonic reference architecture that links tactical, operational and strategic levels of decision making. Here, we showed that the C2 coordination issues at the three levels, namely strategic, operational and tactical levels, associated with future plans, future operations and current operations can be modeled and addressed by using the proposed holonic architecture. We also showed how the three-level architecture can adapt to contingencies, such as the onset of new missions and asset breakdowns.

There are some extensions of the research presented here. The first is the use of goal-action attainment graphs to represent strategic objectives, and then converting them into MDPs as we had done in our earlier work [17]. The second is the problem of eliciting or learning the reward structure and transition probabilities for the MDP from subject matter experts or from historical data.

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Holonic Scheduling Concepts for C2 Organizational Design for MHQ with MOC

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Outline

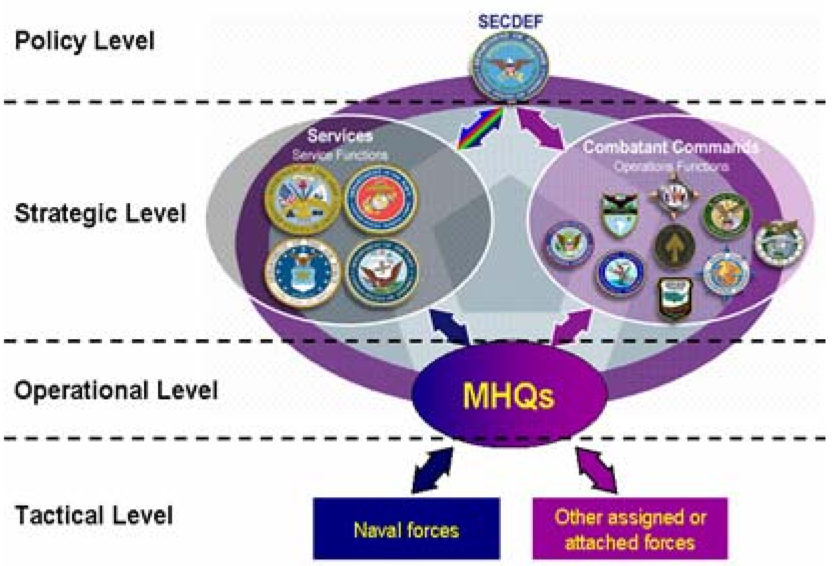
- **Introduction**
  - Motivation and Objectives
  - Holonic C^2 Structure
  - C^2 Requirements for MHQ with MOC
- **Holonic Reference Architecture (HRA)**
- **Two Coordinating Decision Layers**
  - Strategic – Operational Level Control (SLC-OLC) Layer
  - Operational – Tactical Level Control (OLC-TLC) Layer
- **Application to a Multi-mission Scenario with Contingencies**
- **Summary**

Introduction

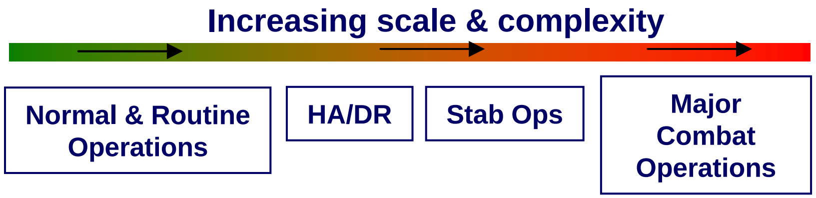
- **Motivation**
  - Maritime Headquarters with Maritime Operations Center (MHQ/MOC) motivated by identified C^2 gaps in recent national-level crises, e.g., September 11, operation Iraqi freedom (OIF), and humanitarian assistance and disaster relief (HA/DR) during Katrina
  - MHQ/MOC* is the Navy's new concept at the **operational level** with the capability to *assess*, *plan*, and *execute* multiple missions

- **Objectives**:
  - How to **sequence** multiple missions and **coordinate** tasks across a range of military operations**?
  - How to **link tactical**, **operational** and **strategic** levels in assessing, planning and executing multiple missions?

* MHQ/MOC

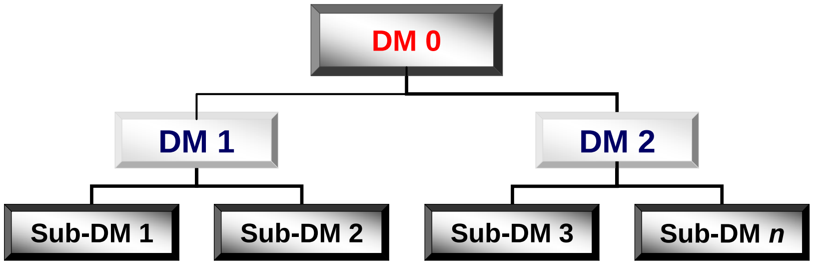


** Range of military operations

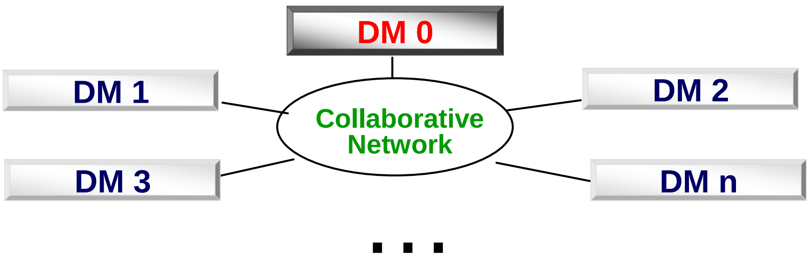


Holonic C2 Structure

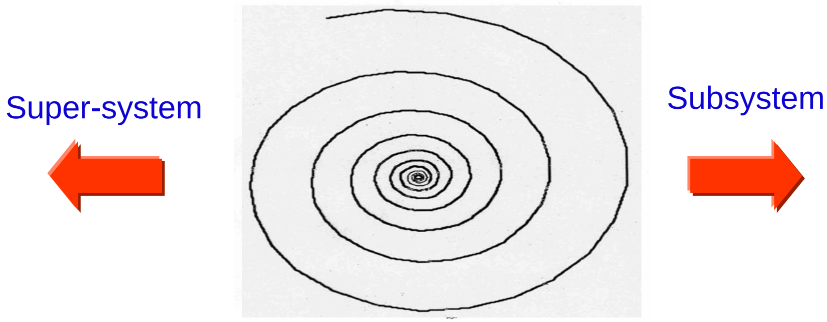
- **Traditional C2 Structures**
  - **Hierarchy**
    - **Pros**: provides **unity of command**
    - **Cons**: slow response and limited immediate intelligent actions due to a multi-level bureaucratic structure



  - **Heterarchy**
    - **Pros**: provides **fast response** to local disturbances
    - **Cons**: limited performance due to absence of global information

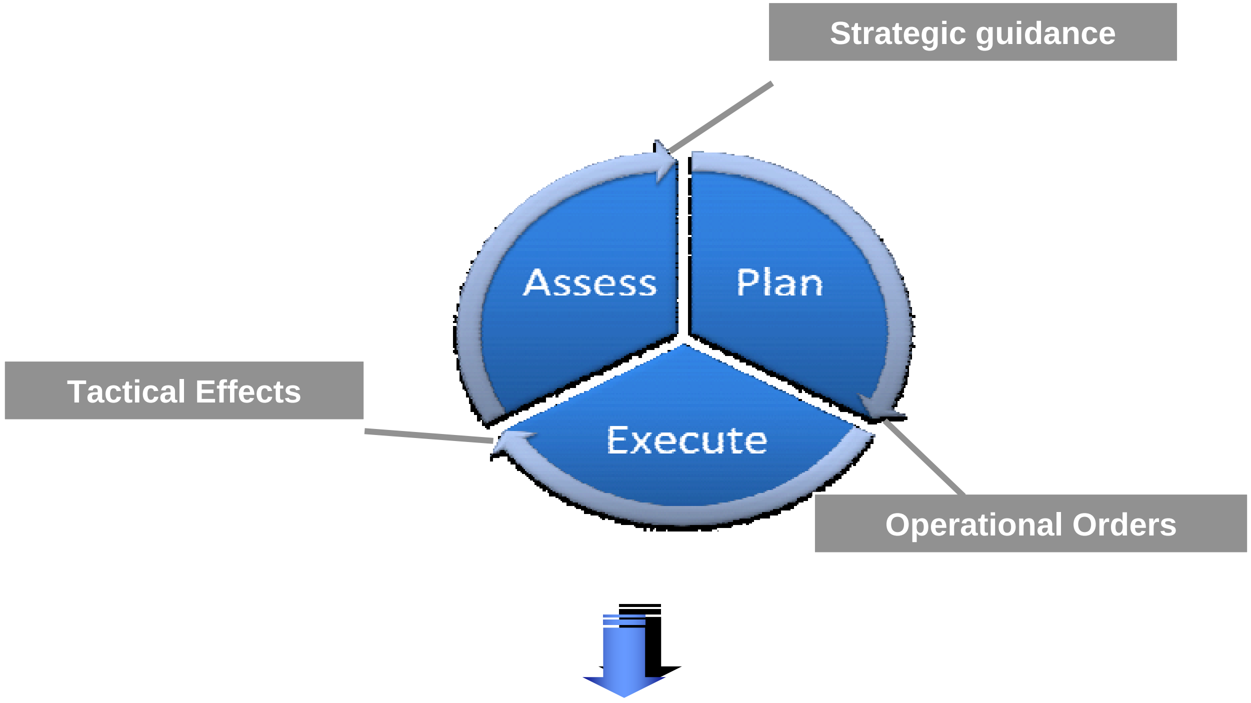


- **Holonic C2 Structure**: overcomes drawbacks of hierarchy and heterarchy
  - **Holons** are **autonomous self-reliant units**: have a degree of **independence** and **handle contingencies** without asking higher authorities for instructions
  - **Advantages**
    - Enables the creation of very complex systems ⇒ complex organizations such as MHQ/MOC
    - Highly resilient to the internal and external disturbances
    - Adapts to the changes in the environment with which it interacts ⇒ dynamic changes in the mission and/or organization
    - Maintains **unity of command**



C2 Requirements for MHQ/MOC

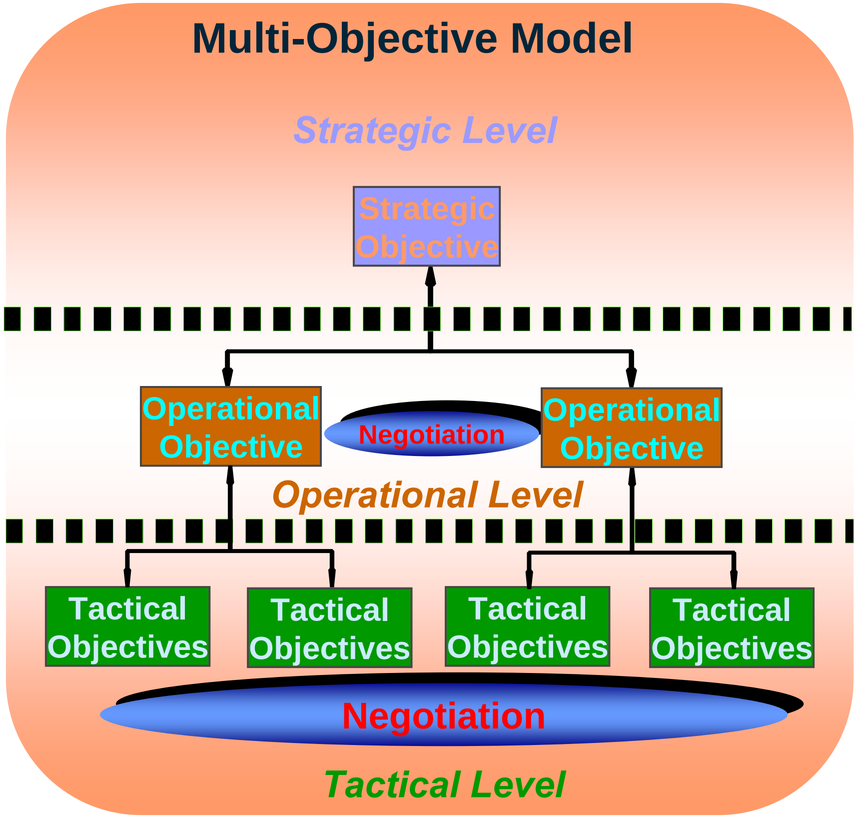
- **C2 Requirements for MHQ with MOC**
  - Centralized assessment
  - Networked distributed planning
  - Decentralized execution



Key MHQ/MOC issue: how to link tactical, operational and strategic levels

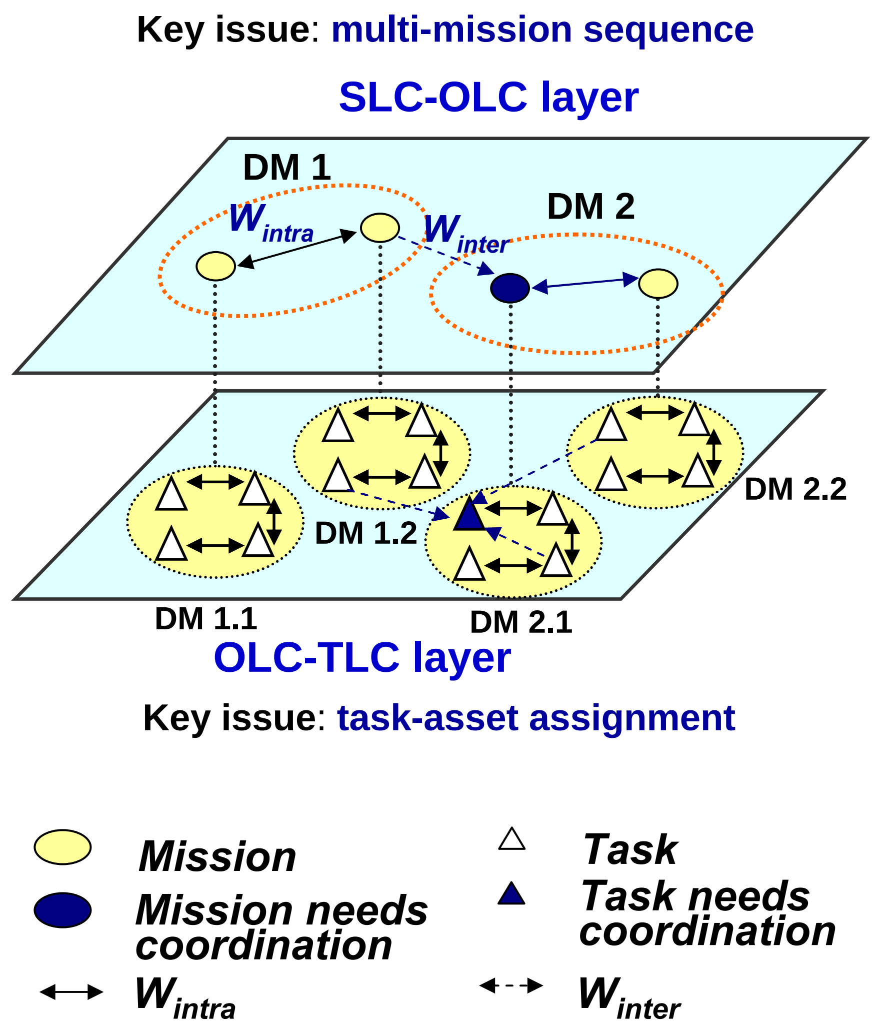
Holonic Reference Architecture

- **Strategic-level control (SLC)**
  - Centralized assessment / guidance, mission assignment
  - Provides a structure for establishing mission objectives and guidance for future plans
- **Operational-level control (OLC)**
  - Networked distributed collaborative planning /dynamic and adaptive re-planning
  - Provides facilities for mission decomposition (i.e., generating the task graph), deliberate planning, command, inter-holon coordination/ negotiation
- **Tactical-level control (TLC)**
  - Decentralized execution
  - Encapsulates the functional holons that execute the assigned tasks



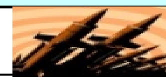
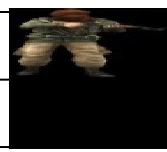
Two Coordinating Decision Layers

- **SLC-OLC layer**: coordinates multiple missions (simultaneous or sequential)
  - If missions are in conflict at the OLC, the OLC requests the SLC to obtain strategic guidance to resolve the conflict and yet achieve long-term strategic objectives
- **OLC-TLC layer**: performs asset allocation for each mission and resolves conflicts in task scheduling
  - Task status reports from subordinate holons at the TLC are sent up to holons at the OLC
  - Monitor and supervise mission progress and promulgate adjustments to tactical actions to lower-level holons



SLC-OLC Layer

- **Key Issue:** How to sequence multiple missions?
- **Approach:** Formulated as a Markov decision problem
  - **State:** combination of missions

State	HA/DR	Stability Ops.	Major combat Ops.
x_1			
x_2			
x_3			
x_4			
x_5			
x_6			
x_7			
x_8			

- **Action**: process missions in *sequential* or *parallel* mode
- **Policy**: The best action to take in each state at each decision epoch

- **Overall Transition probability**: from constituent mission transition probabilities

$$P(x(k+1) \mid x(k), u(k)) = \prod_{i=1}^{M} P(z_i(k+1) \mid z_i(k), u(k))$$

where *M* is the number of missions

- **Reward Structure**: Surrogate measure to the probability of mission success in terms of the national level resources

$$R(x(k), u(k)) = \sum_{i=1}^{M} R(z_i(k), u(k))$$

x_h	Simultaneous	Sequential	x_h	Simultaneous	Sequential
x_1	12.00	10.80	x_5	8.50	7.65
x_2	7.50	6.75	x_6	4.00	3.60
x_3	8.00	7.20	x_7	4.50	4.05
x_4	3.50	3.15	x_8	0.00	0.00

- **The expected reward of policy π starting at $x(0)$:**

$$J_\pi(x) = E[R(x(N)) + \sum_{k=0}^{N-1} R(x(k), u(k))]$$

where *N* is the number of decision epochs

OLC-TLC Layer

- **Key Issue:** How to allocate assets for each mission and resolve conflicts in task scheduling?
- **Approach:** use group technology and nested generic algorithm to assign assets to tasks (Yu *et al.* IEEE T-SMCA, January 2006)
  - Tasks are assigned to assets based on the fit between the resource requirements* of tasks and the resource capabilities** of assets
  - Tasks are assigned to decision makers (DMs) based on the fit between the resource requirements of tasks and the resource capabilities** of DMs
  - In order to minimize the overall task completion time, synchronization delays should be minimized
  - Minimizing the inter-DM coordination delay (**between group delay**) outweighs the intra-DM coordination delay (**within group delay**), since there is a larger **barrier** between any two DM cells
  - A tradeoff between internal and external coordination workload is the key here

* Resource Requirements

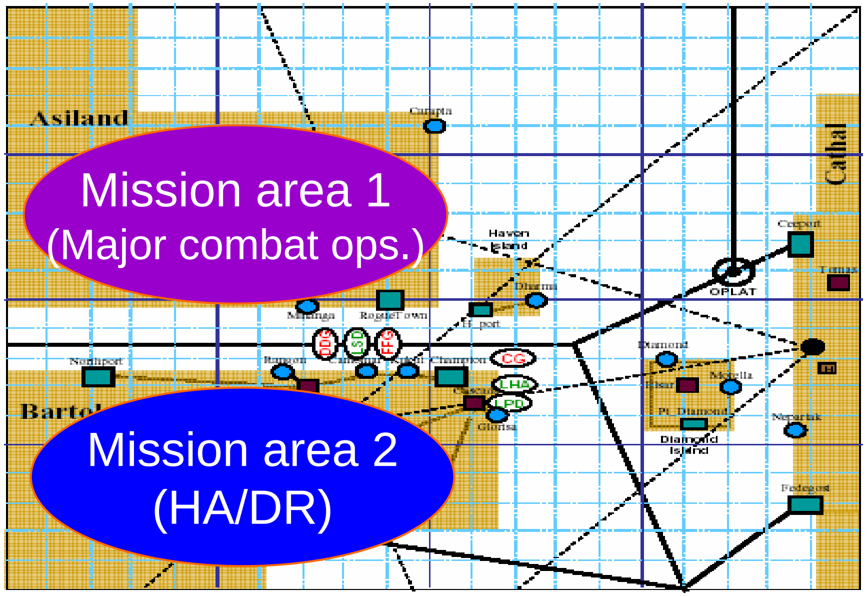
		Resource Requirements				
ID	Task Name	R1	R2	R3	time	locations
1	T1	1	0	1	1	(0,0)
2	T2	1	0	1	1	(2,1)
3	T3	1	1	0	1	(1,1)
4	T4	1	1	0	1	(1,0)
5	T5	0	1	1	1	(2,0)
6	T6	0	1	1	1	(0,1)

** Resource Capabilities

		Resource Capabilities			
ID	Asset Name	R1	R2	R3	velocity
1	A1	1	0	0	1
2	A2	1	0	0	1
3	A3	0	1	0	1
4	A4	0	1	0	1
5	A5	0	0	1	1

Multi-mission Sequencing

Mission Space



Future Plans

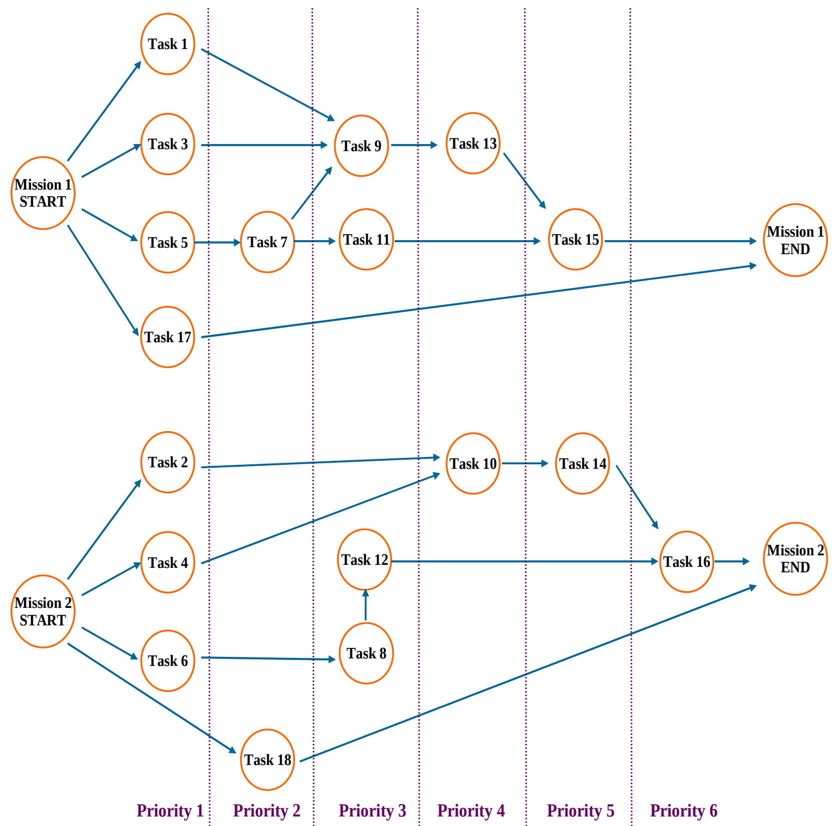
- Multi-mission sequencing provided by SLC-OLC layer: **parallel** execution of both missions

mission 1 

mission 2 

Mission Decomposition

- Operational holon at the OLC decomposes the mission as a task precedence graph



Task-Asset Assignment

- **Task-Asset Assignment Solution**
  - Conflicts in Task-asset assignment are resolved by OLC-TLC layer

Time Unit

Missions	Taks Units	Assets	0	1	2	3	4	5	6	7	8	9	10	11
M1	TU1	1	T3							T15				
		18								T15				
		19								T15				
	TU2	7			T17		T11	T13						
		11												
		14			T5		T11							
		17			T17			T13						
	TU3	2	T1											
		10	T1											
		12	T1											
		16	T1											
		4			T5									
		5				T7								
		6												
		8			T5	T7								
		9				T7								
		13					T9							
M2	TU1	1				T18								T16
		15				T18								
		18				T18								T16
		19												T16
	TU2	3	T6											
		7	T6								T12		T14	
		11												
		14									T12			
		17				T18							T14	
		20	T6											
	TU3	2					T2							
		10					T2							
		12					T2							
	TU4	5						T8						
		6												
		8	T4					T8						
		9						T8				T10		
		13										T10		

Feasible Schedule

Feasible Schedule | Coordinating Schedule

Handling Mission Contingencies

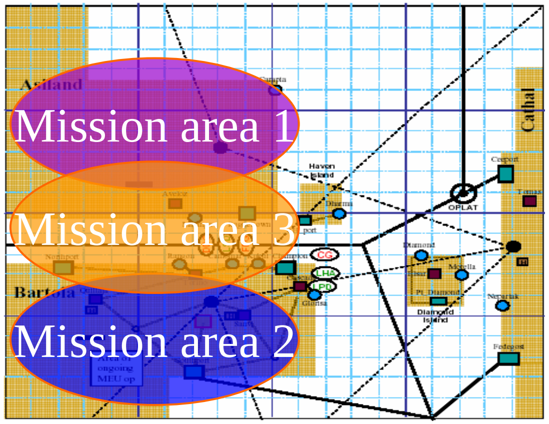
- **Contingencies**: a new military mission is added to ongoing missions at time 3
  - **Mission 3** (**stability operations**): Provide security in the unstable mission area 2
  - **Asset breakdown**: assets 2, 10, 12 and 16 were disabled during the execution of task 1 of mission 1; but, task 1 is completed

- **Mission space**

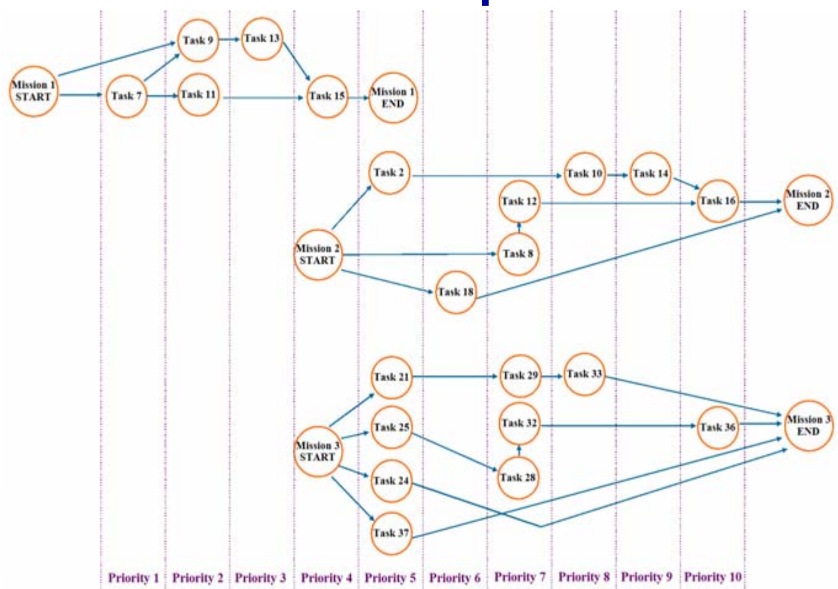
Major combat operation

Stability operation

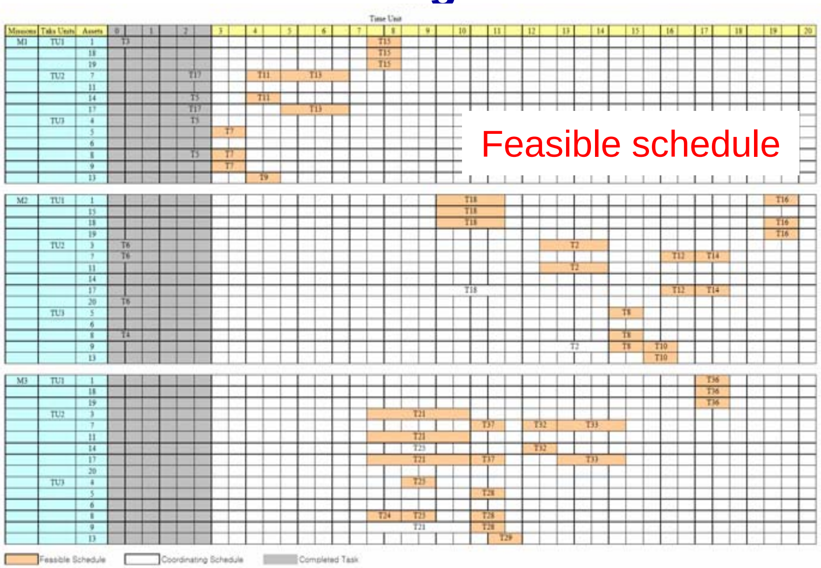
HA/DR
(humanitarian assistance/ disaster relief)



- **Multi-mission sequence solution**



- **Task-asset assignment solution**



Summary

- We showed that the proposed C^2 holonic reference architecture (HRA) can be applied to the Navy's new MHQ with MOC linking tactical, operational and strategic level controls
  - Strategic Level Control (SLC): centralized assessment
  - Operational Level Control (OLC): networked distributed planning
  - Tactical level control (TLC): decentralized execution
- The C^2 HRA provides an approach to the multi-mission planning problem at the operational level
- A multi-mission scenario showed that the C^2 HRA exhibits the capability to detect and recover from schedule infeasibility and to adapt to contingencies, such as the onset of new missions and asset breakdowns