# CONCEPTS FOR AUTONOMOUS COMMAND AND CONTROL

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Abstract: The new Department of Defense (DOD) transformational doctrines for future battlefield operations emphasizes the need to more aggressively pursue program developments with unmanned systems technologies. Currently, there are ongoing Battle Experiments testing and assessing the operational performance of these technologies. These experiments in turn are uncovering current and future capability gaps that need to be fulfilled with aggressive research, engineering, test and evaluation. The Innovation Center at SPAWAR Systems Center, San Diego, has established a research and development process to better address Future Naval Capability gaps in the areas of both, Intelligent Autonomy and Autonomous Command and Control for Unmanned Systems. In this paper we report our research on two important components concepts for AC2: 1) Autonomous Resource Allocation, 2) Autonomy and Commanders Intent, and 3) A discussion on Self organizing C2.

## 1 INTRODUCTION

Sea Power 21 is a Naval vision that seeks to transform defense processes and modernize technologies for the battlefields of the future. The greatest challenges to transforming Naval doctrines from the industrial age to the information age has been the development of a clear notion of the value that distributed command architectures bring to modern combat Fig1. Distributed command architectures bring increased update speed of situational awareness. Each modernization step in C4ISR technology that enables faster horizontal integration is one step closer to a fully distributed command structure allowing for near real-time transmission of intent from the Commander on downwards resulting in better Situational Awareness of the Battlefield. Intention awareness is therefore an integral part of distributed command architecture and must be properly established in the information environment where faster and optimum execution of mission objectives is needed.

The fundamental infrastructure enabling command and control (C2) is undergoing a revolutionary change. The assumptions embedded in traditional C2 such as a centralized decision authority and well-defined hierarchy are being reassessed, especially in light of mission areas that involve coalition operations and the emergence (and dependence) on a ubiquitous IT capability (Alberts, 2007). While moving away from traditional C2 to a net-centric environment represents unique challenges, the prevalence of unmanned systems must also be considered within the context of emerging architectures and concepts. If properly architected, unmanned C2 systems should meld seamlessly into the operational environment augmenting and working in concert with C2 for manned units. Most investment in autonomy is being made at the platform level. This work focuses on the next level of autonomy- that is, the autonomous interaction of autonomous platforms to achieve pre-specified objectives.

The DoD Definition for *C2* is given (Joint Publication, 2002) as *the exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission.*

*Autonomous* is defined as *not controlled by others or by outside forces; independent and independent in mind or judgment; self-directed.*

Considering these definitions, Autonomous Command and Control (AC2) can be defined as *the independent, self-governed exercise of authority and direction over the assigned forces in the accomplishment of the mission*.

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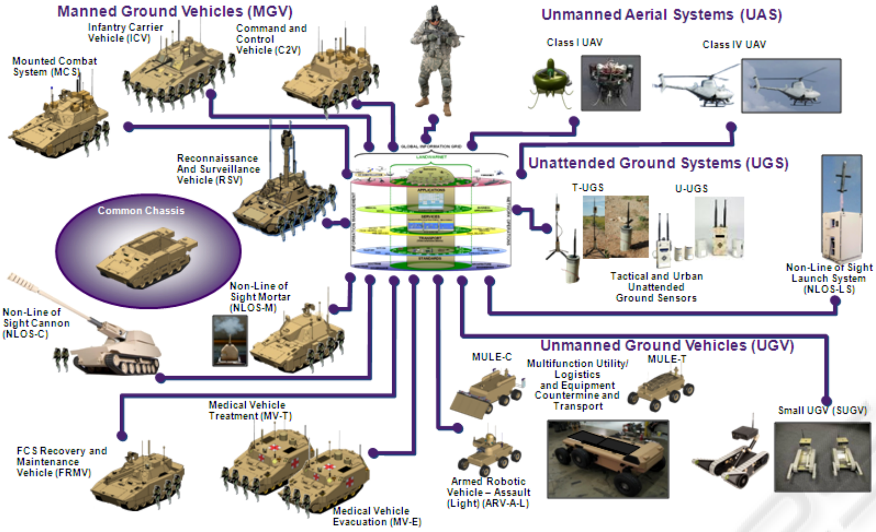


Figure 1: Unmanned Systems in DODs Transformational Information Architecture. (http://www.army.mil/fcs/).

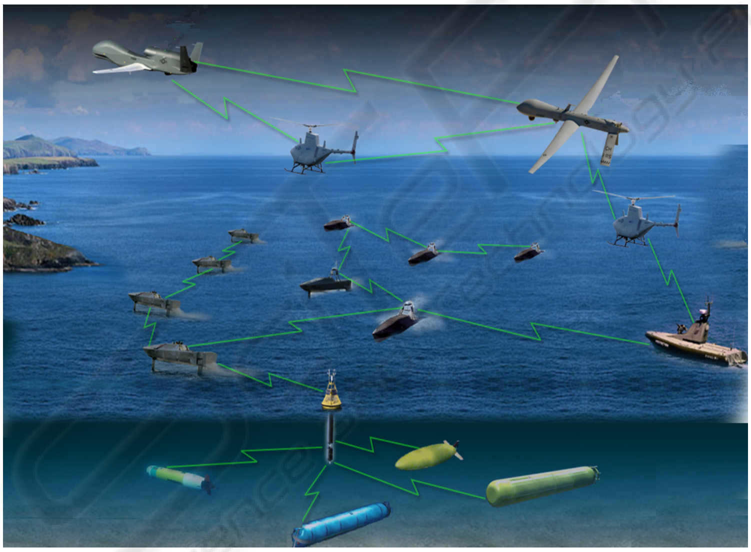


Figure 2: Autonomous Command & Control (AC2) for Self Organizing Unmanned Systems.

The prevalence of unmanned systems has increased dramatically across the DoD services in recent engagements. In addition, user acceptance has become well established over this time ensuring that unmanned platforms will remain pervasive in future conflicts. Recently released Master Plans for both USVs (UUV, 2007) and UUVs (UUV, 2004) allude to the need for *autonomous group/cooperative behavior* to achieve the desired mission objectives for these types of systems. Fig. 2 illustrates the self organizing concepts of a disparate set of unmanned platforms.

The capabilities required to achieve AC2 include:

- Self-Organizing C2
- Translate Commander Intent to Executable Missions
- Autonomous Allocation and Management of Resources
- Machine Learning from Training/Experience
- Near Real-Time Analysis for predicting future C2 actions
- Seamless Interoperability of C4ISR Systems

- Sufficient BW and communications
- Autonomous Platforms and Sensing
- Level 3, 4 Fusion

The first three bullets are elaborated on in the following sections. While critical to achieving AC2, the remaining topics are advancing under a myriad of other efforts. For example, the seamless interoperability of C4ISR systems is being addressed under next-generation C2 efforts which are focused on providing a Service Oriented Architecture (SOA) to the warfighter. In addition to architecture, mobile add-hoc networks (MANET) are being studied to determine the best methodologies to achieve self-forming/self-healing networks and provide desired QoS levels. Bandwidth utilization will continue to improve with spectrum management, compressed sensing, along with novel routing and radio capabilities. Higher levels of sensor fusion are being rigorously investigated in order to ascertain enemy course-of-action analysis, turn data into understanding and wisdom, and autonomously improve sensor fusion capability. Autonomous sensing is also in the critical path as that dovetails with the allocation and management algorithms that are incumbent in AC2. Finally, significant investment continues in imbuing individual platforms with autonomy and analyzing the benefits of shared information/awareness.

## 2 SELF ORGANIZING C2

The key attributes of next-generation C2 include agility, focus, and convergence (Alberts, 2007). Agility is the ability of distributed platforms to self-synchronize and organize into an appropriate C2 topology in a dynamic manner. Self-synchronization will determine the decision rights across the platforms, and, in effect, serve as part of the cost function in the formation of the C2 topology. It is imperative that any self-organizing C2 topology yield deterministic behavior(s). The salient features that should be used to automatically determine an appropriate C2 topology remain to be discovered. Intuitively, the decision space could include the number of assets, the information capacity of the assets, the connectivity bandwidth between assets, and mission and environmental complexities. For purposes of discussion, C2 topologies are characterized in (Figure 3) as centralized, localized, and distributed. If, for example, a key component for determining C2 topology is the number of assets in the area of interest, then thresholds could be configured to trigger the formation a different topologies as exemplified in Figure 4. In addition to determining the salient factors, there is significant challenge is in determining the threshold functions.

A more effective approach may consider decomposing the problem such that these lower-level categories are mapped into the higher levels characterizations of information distribution, interaction patterns, and allocation of decision rights such as discussed by Alberts (Alberts, 2007). This hierarchical decomposition may serve to simplify the complexities involved in determining effecting AC2 topologies.

## 3 COMMANDER'S INTENT

The understanding of Commanders Intent (CI) clearly demonstrates that although the concept of intent has been in our doctrine for quite a while, confusion still exists and there is little empirical investigation into the process of communicating intent.

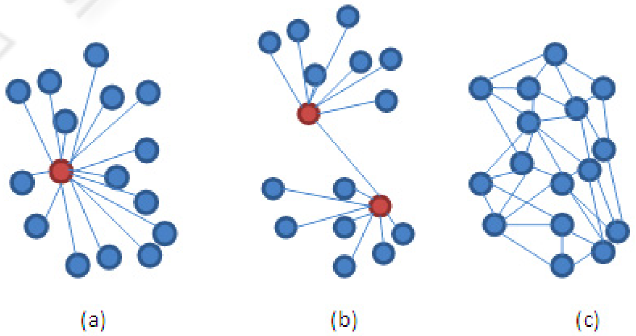


Figure 3: C2 Topologies: (a) Centralized, (b) Localized, and (c) Distributed.

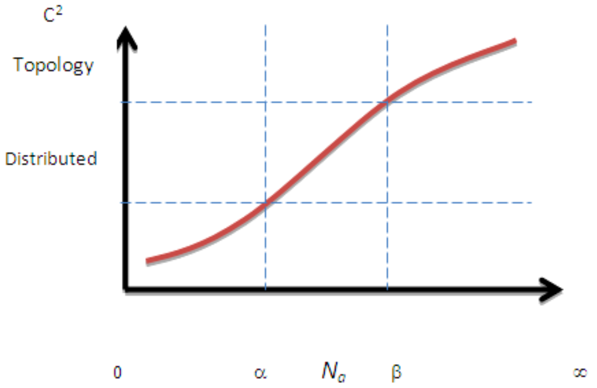


Figure 4: A notional mapping between the number of assets in the region of interest and the most effect C2 Topology.

CI has long been used to guide the actions of subordinates, but has only recently been formally included in doctrine. CI first appeared in US Army Field Manual in 1982 (GPO, 1982). During the 1970s, when the military tended to centralize decision making; however, failed hostage missions and similar events signaled the need to empower subordinate players on the scene. A model of today concept of CI can be traced to Army doctrine writers that used the German army's Aftragstaktik (Silva, 1989) first introduced in the early 19th century. The word means "mission-oriented" reflecting the developments in response to the French Revolution. This mission oriented methodology was the realization that battle is marked by confusion and ambiguity and that trust between superior and subordinate is the cornerstone of mission-oriented combat. Today, CI consists of a brief directive, usually in written format with a purpose, a method, and an endstate for any given operation. It is also the single unifying focus for all subordinates elements or groups of a command structure which are dedicated to different activities (communication, Intelligence, surveillance…) but which cooperate/collaborate to achieve mission effectiveness and success.

## 3.1 Concepts for Automating Commanders Intent (CI)

Automating Commanders Intent (CI) and military courses of action are very complex and difficult activities. These activities should take into consideration environmental information, predictions, the end state targeted and resource constraints. Automating Commanders Intent involves solving simultaneously planning and scheduling problems. In this section we provide 1) an approach to transforming CI objectives into an algebraic form, 2) a discussion on task scheduling, optimization, and resource allocation.

### 3.1.1 Algebraic Representations of CI

An approach to transforming CI into an algebraic form can best be described by the flow diagram Figure 5. As mentioned above, a CI consists of a brief directive containing objective statements. The first transformation (formalization) of these statements is done by utilizing a formal specification language such as the one provided by Berzin & Luqi (Berzins and Luqi, 1991). Formal statements of objectives and constraints are then stored permanently on a database. A Natural Language Processing (parsing) function aided by a Naval Lexicon provides formal unambiguous objective statements for encoding; the encoder creates an algebraic representation of these objectives creating what we call elementary actions. The elementary actions together with proper task scheduling algorithms, multi-objective optimization functions, and resource allocation methods provide a framework for automating Commanders Intent.

### 3.1.2 Task Scheduling & Optimization

We suggest a task (course of action) approach to automating Commanders Intent based on evolutionary algorithms that use multi-objective optimization methods and support resource constrained CI development with both cardinal and ordinal objectives.

During the development step, the commander analyses the relative combat power of friendly and enemy forces, and generates the CI.

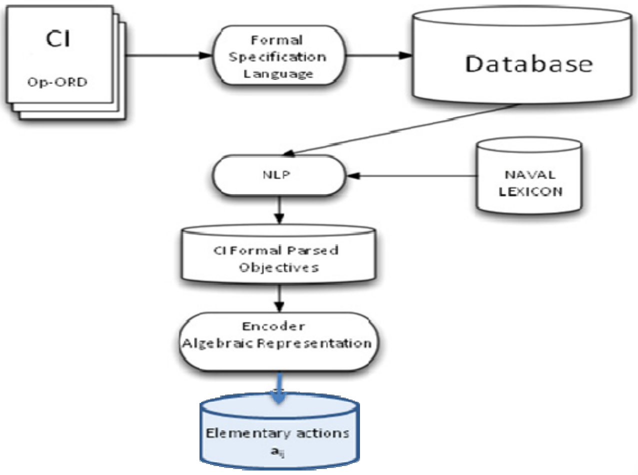


Figure 5: An approach for transforming CI into a formal algebraic representation.

During the mission analysis, the objectives are identified, assigned, and tasks (courses of action) are implemented to perform the mission. These tasks can be decomposed into sub-tasks. Tasks and sub-tasks can be represented by means of a hierarchical structure –a Graph. Synchronization analyses leads to identifying temporal and spatial relationships between elementary tasks. The automating algorithm must consider all available resources and capabilities and assign them to tasks. Synchronizing tasks then requires scheduling of all tasks according to resource availability, deployment constraints, and task relationships. We provide a task (courses of action) planning model as a multiple mode resource-constrained scheduling problem (MRCPS) since, from a methodological point of view planning and scheduling are not much different. Our model consists of representing generic activities (tasks with specific combinations of resources) into elementary (or primitive) actions interrelated to accomplish the mission objectives. This process implies the identification of the tasks (when and where), precedence relationships, the pool of available resources with their localization, and the objectives of the mission. An objective is then represented as an oriented time-space graph of tasks. Figure 6.

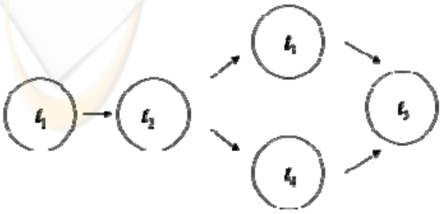


Figure 6: An Objective represented as a task.

Depending on the combination of resources allocated and the actions in the scheduler, different courses of action networks could be obtained, such as the one above. They constitute variants (or alternatives) of a mission with different evaluations on objectives. Solving CI and courses of action planning problems is NP-Hard. But a feasible process for automating CI with respect to multiple objectives for resource allocation may include evolutionary algorithms (EA) with meta-heuristic approaches or a method that addresses the multi-objective aspect of resource-constrained scheduling problems in which all objectives are combined into one single scalar value by using weighted aggregating functions. The search is then performed several times to find a compromise solution that reflects these preferences. Another approach is to generate the set of compromise solutions in a single execution of the optimization such as done by multiple-objective Evolutionary Algorithms. In this section, we provide a construct for the tasking and resource allocation associated with a CI that can be implemented using multiple-objective EAs. Evolutionary Algorithms are able to deal simultaneously with multiple solutions for solving multi-objective optimization problems allowing a set of potential Pareto optimal solutions to be found in the same iteration.

Here is our construct: Multi-objective CI can be characterized by a set of tasks, a set of resources, precedence relationships, resources, constraints and global performance functions $F_z$ shown in Figure 7.

Once a CI has been decomposed into its requisite tasks, the question of which autonomous unmanned system should be responsible for executing each particular task still remains. Many techniques for

Optimize: $F_z, z = 1,\dots,Z$

s.t. $t \in D$

s.t. $R \in D$

Use vector of tasks $t = \{t_1, t_{2,\dots,} t_n\}$ having the following attributes for each task $t_i$ :

Define starting and ending time [ $\tau_b(i)$ , $\tau_f(i)$ ]

Define earliest and latest starting and ending time [ $\tau_s(i)$ , $\tau_e(i)$ ]

Define type and quality of resources required, represented by a set $\boldsymbol{R}$ composed of renewable and nonrenewable resources available in limited quantities, i.e:

$R_k(t_i) = \{r_{1i}, r_{2i}, \dots, r_{mi}\}$ is the $k^{th}$ set of resources required to accomplish the task $t_i$ .

Consider set of predecessors {PR} characterized by the tasks that temporally and /or spatially precedes $t_i$

Use resources $\boldsymbol{R}$ having the following attributes:

Define starting and ending time of availability $[t_{rs}(k), t_{re}(k)]$

Define localization of resources (*x,y,z*)

Define types of resources.

Define other specific characteristics such as “mean speed of (for mobile resources)”, reliability, etc.

Figure 7: A construct for multi-objective task optimization for low size problem (~10actions).

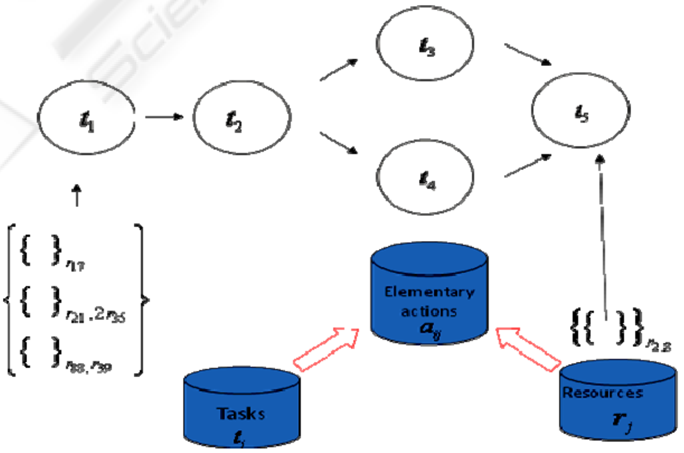


Figure 8: Summary of the main concepts needed for Commanders Intent Automation.

multi-robot task allocation are included in the works of Parker (Parker, 1998), LePape (Le Pape, 1990), and others (Botelho and Alami, 1999). Mataric (Gerkey and Mararic) provides a thorough review of several Multi-Robots Task Allocation Frameworks.

## 4 AUTONOMOUS RESOURCE ALLOCATION

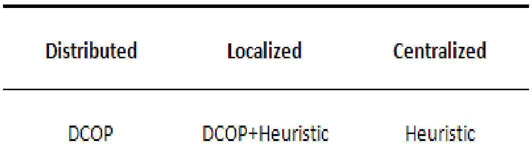
Another key attribute of next-generation C2 is convergence (Alberts, 2007). Convergence is the ability for independent actors to achieve operational coherence in a deterministic manner. The emergence of platforms with multiple modalities (eg. sensing, SAR, strike, etc….) in the manned and unmanned arenas allows for additional flexibility in the allocation of resources at the added cost of an increasing complexity in the search space. The resource allocation problem for AC2 must be able to consider any platform for any task based upon the platform's capabilities. Optimizing across any modality (COMMS, strike, sensing, etc…) is an NP-hard problem. The AC2 resource allocation must consider all modalities simultaneously in assigning assets to objectives.

As stated above, the AC2 resource allocation problem is a combinatorial optimization problem that must consider the dynamic environment; a nonlinear, multi-modal objective function; nonlinear constraints; and binary decision variables. Algorithms which address resource allocation problems of this nature tend to be based on heuristic methods. The extreme team methods (Scerri et al., 2005) are effective in the presence of communications limitations where global decision support is not a viable option. Extreme teams have the following characteristic:

- Near real-time assignments
- Platforms may perform more than one task
- Inter-task constraints may be present

Extreme teams are largely based on distributed constraint optimization problems (DCOP) methods. These types of algorithms can be applied to either end of the C2 topology spectrum or can be used in a complementary fashion for a localized topology shown in Table 1.

Table 1: Recommended Resource Allocation Algorithms for C2 Topologies.



| Distributed | Localized | Centralized |
|---|---|---|
| DCOP | DCOP+Heuristic | Heuristic |

The AC2 resource allocation performance must be considered in light of scalability, satisficing behavior (GPO, 1982), robustness, and generality. It is important that the resource algorithm scale for large numbers of assets and mission objectives. If the solutions are near-optimal and generated in a reasonable timeframe, the performance can be considered to meet the satisficing criteria. In addition, the algorithm must be stable, converge rapidly, and insensitive to initial conditions. Finally, the algorithm must be able to accommodate the general nature of the objective described above.

The objective function under consideration by the optimization engine should consider the following components;

- Mission Effectiveness
- Mission Risk
- Mission Persistence
- Information Utility

The Mission Effectiveness considers all aspects sensing communications and weapons required to meet mission goals. The risk component considers items such as METOC enemy defenses, deconfliction and energy consumption. The Persistence parameter may be required to minimize global change in the solution set. For example, if a global optimizer is used, then the results could be dramatically varied at every solution step. Persistence will reduce this variability. Finally, the Information component is must be incorporated as a metric to ensure that the right data gets to the right place and platforms. For Autonomous C2 the ramifications of *automated* subtask generation should also be considered. Mission planners generate many subtasks to satisfy the overall mission objectives to achieve the desired effect(s). AC2 must also be able generate sub-goals in a parsimonious manner so that objectives can be accomplished and new constraints generated by these sub-goals are readily satisfied. The process of introducing sub-goals and their associated constraints introduces a complexity versus performance issue that should be bounded within the AC2 construct. This notion is analogous to Akaike's Information Criterion (AIC)

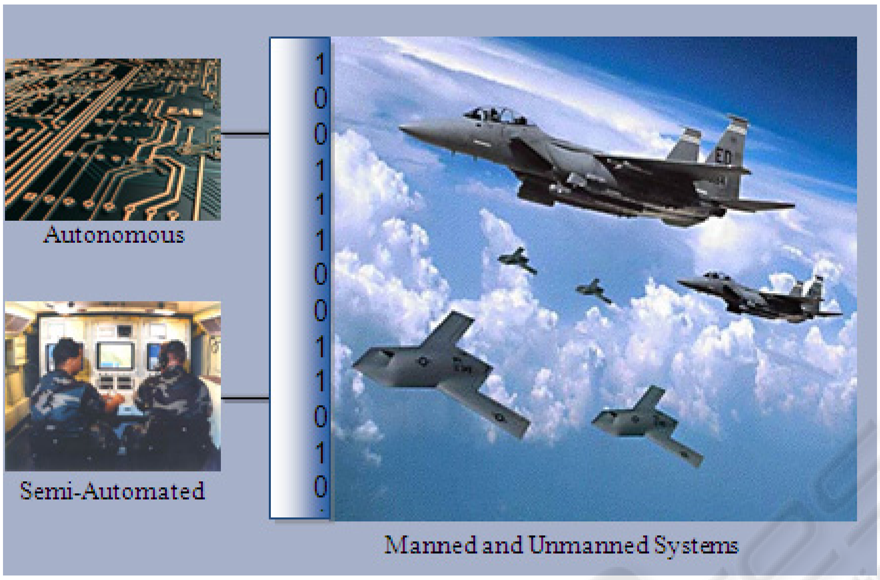


Figure 9: Notional depiction of an AC2 Turing test in a mixed manned/unmanned systems environment.

where the number of parameters and the log-likelihood of the error in the function being fitted are balanced.

## 5 CONCLUSIONS

Command and control *in the ether* represents a shift away from traditional C2 constructs. AC2 represents the ubiquitous nature of C2 in the distributed realm where emergent behaviors are manifested by large groups of platforms that are more complex than those emulating ants and birds in colony and flocking models, respectively. The potential collaborative behaviors that would emerge under different information management strategies should be addressed as part of an integrated investigation incorporating the C2 topology and resource allocation ideas described here.

While C2 of UxVs will be a driver in developing AC2, the evolutionary step of mixed manned and unmanned missions can be considered as an AC2 Turing Test. This notion is exemplified in Figure. 8 where the manned platforms under direction of the AC2 system do not know whether they are under direction of manned or unmanned systems.

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