Coordination Challenges and Issues in Stability, Security, Transition and Reconstruction and Cooperative Unmanned Aerial Vehicle Scenarios

Myriam Abramson[1], **Ranjeev Mittu**[1], **Jean Berger**[2,]

Myriam.Abramson@nrl.navy.mil, Ranjeev.Mittu@nrl.navy.mil, Jean.Berger@drdc-rddc.gc.ca

[1]*US Naval Research Laboratory, Washington, DC USA*

[2]*Defense Research Development Canada, Quebec, CANADA*

Abstract—*Through the emergence of new doctrine, stability operations are becoming a core U.S. military mission that the Department of Defense (DoD) must be prepared to conduct and support. These operations are now given priority comparable to combat operations. The immediate goal often is to provide the local populace with security, restore essential services, and meet humanitarian needs. The long-term goal is to help develop indigenous capacity for securing and providing essential services. Many stability operations tasks are best performed by indigenous, foreign or U.S. civilian professionals. Large scale disasters are an example where Stability, Security, Transition and Reconstruction (SSTR) operations can provide value to foreign governments and non-governmental institutions which are under great stress to respond in a timely and effective manner. Without the means to properly coordinate these efforts, basic assistance and relief operations would be severely impeded.*

The use of Unmanned Aerial Vehicles (UAVs) to support Intelligence, Surveillance and Reconnaissance (ISR) is becoming increasingly important. These assets can enable the collection of needed information for the execution of a given set of tasks. In large scale operations, however, the ability for the UAVs to self-coordinate may be needed as it will be difficult for human operators to effectively control large teams of UAVs.

This paper will begin by introducing some of the key aspects of multiagent coordination, with a focus on the operational challenges with regard to SSTR such as disaster management response as well as UAV coordination. We will then discuss the coordination challenges and gaps in order to motivate an adaptive, multiagent based approach to coordination as well as additional opportunities for research. We will conclude with a brief summary.

1. INTRODUCTION

Coordination is the cornerstone of multi-agent systems, and various theoretical frameworks and limited views toward characterizing its very essence have been proposed. Models include interdependency management-based theory of coordination, organizational structuring, reference model, and multiagent frameworks. According to the theory of coordination proposed by Malone and Crowston [7], coordination is defined as the act of managing/mediating interdependencies between activities. A dependency is a relation among activities mediated by producing or consuming resources. They identify three types of dependencies: flow dependencies (e.g. goals), in which an activity produces a resource to be used by another activity; sharing dependencies, in which multiple activities can use the same resource, and fit dependencies, where multiple activities collectively produce/consume the same resource.

Organizational structuring [6] as a framework for activity interaction aims at modeling and capturing direct supervision, standardization skills, processes, outputs, mutual adjustment; authority structure, roles and responsibilities. The reference coordination model [9] is a meta-model multi-layered structure proposed to describe various coordination models. The model hierarchically composes object and activity levels, and an activity management level (described through a set of rules, specific mechanisms, programs or a selection of interaction patterns), ultimately leading to a meta-model defining an emergent coordination model, and then to a more abstract level (meta-meta model of coordination models) defining the so-called reference model. It contains terminologies and other concepts required to describe these coordination models. On the other hand, Tolksdorf recognizes the lack of consensus on the relations between coordination, communication and cooperation and outlines the need to work towards a standardized terminology which contains definitions and clarifications of basic notions including the term “coordination”. Agent framework [8] is also presented to form “the foundation for the development of a complete theory

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE
MAY 2007

2. REPORT TYPE

3. DATES COVERED
00-00-2007 to 00-00-2007

4. TITLE AND SUBTITLE
Coordination Challenges and Issues in Stability, Security, Transition and Reconstruction and Cooperative Unmanned Aerial Vehicle Scenarios

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory,4555 Overlook Avenue SW,Washington,DC,20375

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
2007 Knowledge Systems for Coalition Operations, 1-2 May, Waltham, MA.

14. ABSTRACT
Through the emergence of new doctrine stability operations are becoming a core U.S. military mission that the Department of Defense (DoD) must be prepared to conduct and support. These operations are now given priority comparable to combat operations. The immediate goal often is to provide the local populace with security, restore essential services, and meet humanitarian needs. The long-term goal is to help develop indigenous capacity for securing and providing essential services. Many stability operations tasks are best performed by indigenous, foreign or U.S. civilian professionals. Large scale disasters are an example where Stability, Security Transition and Reconstruction (SSTR) operations can provide value to foreign governments and nongovernmental institutions which are under great stress to respond in a timely and effective manner. Without the means to properly coordinate these efforts, basic assistance and relief operations would be severely impeded. The use of Unmanned Aerial Vehicles (UAVs) to support Intelligence, Surveillance and Reconnaissance (ISR) is becoming increasingly important. These assets can enable the collection of needed information for the execution of a given set of tasks. In large scale operations however, the ability for the UAVs to self-coordinate may be needed as it will be difficult for human operators to effectively control large teams of UAVs. This paper will begin by introducing some of the key aspects of multiagent coordination, with a focus on the operational challenges with regard to SSTR such as disaster management response as well as UAV coordination. We will then discuss the coordination challenges and gaps in order to motivate an adaptive multiagent based approach to coordination as well as additional opportunities for research. We will conclude with a brief summary.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

of coordination”. The authors suggest that future extensions to the proposed formalism should evolve toward providing formal proofs of the best coordination schemes associated with different scenarios, and develop formal methods to derive coordination mechanisms suitable for any given scenario based on the interdependencies among agents.

1.1 Coordination Taxonomy

Recently, Storms and Grant [10] proposed a simple taxonomy for coordination, capturing relevant, but basic properties relating to some popular metaphors

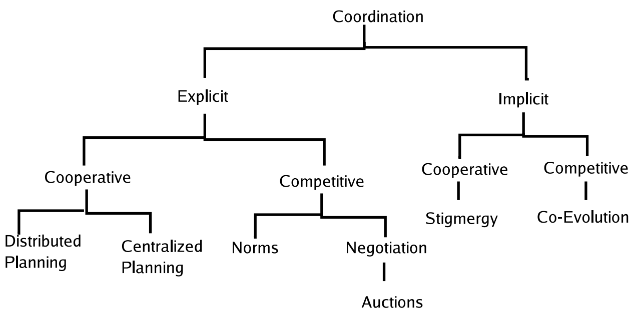

Figure 1: Coordination Taxonomy and Related Coordination Mechanism

to describe currently known approaches. Figure 1 shows a compact taxonomy highlighting these properties while exhibiting links to computational approaches based on those metaphors.

Coordination may first be explicit or implicit referring to communication. Implicit coordination is based on predefined or learned agreements shared by interacting agents as opposed to explicitly resorting to communication (explicit) means to mediate interactions. Agreements may derive from social laws or conventions (means of managing commitment in changing circumstances) in which agents operate under local sensing and control allowing information-sharing and interaction through multi-level pattern (intent, plan) recognition and local environment changes (markers). Coordination may be cooperative or competitive in terms of agent behaviours. Cooperative behaviours specify a common shared goal whereas competitive or self-interested attitudes emphasize individual goals. We contend that possible state-dependent behaviour/attitude may coexist at the same level as well, leading to a third mixed or semi-cooperative form. Coordination may be static or dynamic. In addition, coordination may be centralized or decentralized in which single (dedicated agent with specialized coordination capability) or multiple (e.g. all agents having coordination capabilities) entities are responsible to mediate interactions, defining the control property. Finally coordination strategies may be static or dynamic, that is, determined at design time or at run-time respectively.

1.2 Coordination Metaphors and Mechanisms

Based on that taxonomy, a variety of well-known metaphors for agent behaviour and communication toward coordination may be easily mapped, such as organizational (authority structure, role - cooperative), biological (living systems, colony/swarms, stigmergy – cooperative) and market (negotiation, auction, mechanism design – competitive). A real-world problem domain involving systems with specific organizational and problem decomposition structures and constraints may also expand complexity to multi-level and cross-level coordination issues, resulting in the composition or combination of coexisting metaphors exhibiting a variety of properties.

Widely used coordination mechanisms can be generally summarized in various classes and variants [11]. Such mechanisms include organizational structuring, defining social laws, agent responsibilities, capabilities, authority relationship, connectivity and control flow; market-based (negotiation, auction variants, mechanism design, argumentation); contract net, where a manager assumes the role of dividing a problem into sub-problems and searching for contractors to tackle them (bid), then evaluates bids, select and awards contracts; stigmergy (interaction between agents through their environment (markers recognition), emergent behaviour/intelligence - ant colony, swarms; as well as frameworks (distributed constraint satisfaction and/or optimization, decision theory and reinforcement learning, co-evolution, etc.). Any alternate interaction protocols/schemes may ultimately be derived or inspired from those variants.

Despite all proposed frameworks, a unified approach for coordination remains elusive as there is still no single best way to coordinate due to problem space properties, domain, system and state characteristic dependencies, required frequency of interaction and, respective intrinsic strengths and weaknesses of various approaches.

1.3 Coordination Metrics

Because coordination is an emergent property of interactive systems, it can only be measured indirectly through the performance of the agents in accomplishing a task where a task is decomposed in sub-goals. The more complex the task, the higher the number of sub-goals needed to be achieved. While performance is ultimately defined in domain-dependent terms, there are some common

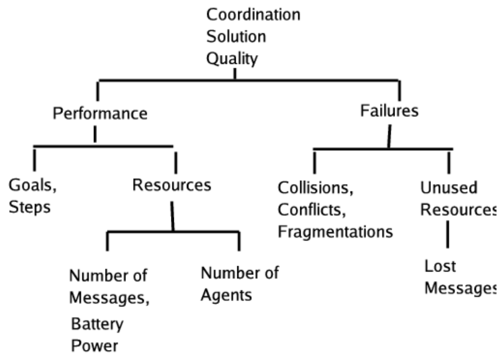

Figure 2: Coordination Quality Metric

characteristics. Performance in a task can be measured either as the number of steps taken to reach the goal, i.e. its time complexity, or as the amount of resources required, i.e. its space complexity. An alternative evaluation for coordination is the absence of failures or negative interactions such as collisions or lost messages. Figure 2 illustrates a simple taxonomy of coordination solution quality in pursuit games. A coordination metric can be obtained using multiple attribute decision-making methods such as a harmonic mean of appropriately weighted goals achieved, resource expanded, and conflicts [1] or a linear weighting combination of resource expanded and conflicts to evaluate coordination costs alone [4]. To show the scalability of a solution, the evaluation must linearly increase with the complexity of the task [2].

2. COORDINATION CHALLENGES AND ISSUES

We now briefly describe the SSTR and UAV problem domains, and then discuss coordination challenges and issues in these domains, in order to motivate an adaptive multi-agent based approach to coordination.

2.1 SSTR Example

Through the emergence of new doctrine, stability operations are becoming a core U.S. military mission that the Department of Defense (DoD) must be prepared to conduct and support. These operations are now given priority comparable to combat operations. The immediate goal often is to provide the local populace with security, restore essential services, and meet humanitarian needs. The long-term goal is to help develop indigenous capacity for securing and providing essential services. Many stability operations tasks are best performed by indigenous, foreign or U.S. civilian professionals [13]. Large scale disasters are an example where SSTR operations can provide value to foreign governments and non-governmental institutions which are under great stress to respond in a timely and effective manner. Without the means to properly coordinate these efforts, basic assistance and relief operations would be severely impeded.

By definition, SSTR operations are conducted outside the boundaries of US lands and territories. While there are similarities at the systems level for the employment of automated information systems regardless of whether the operations are conducted outside US boundaries or domestically for homeland defense (Defense Support to Civil Authorities), there are generally more legal restrictions that must be considered when DoD is responding domestically. This includes a distinction between National Guard forces that are acting in a State role on orders from their Governor (Title 32), and those that have been called-up in a Federal role (Title 10) on orders from the President. This also includes restrictions on the collection and sharing of law enforcement data and intelligence related information between other Federal Agencies and DoD. For these reasons we will limit our scope to examples of military operations outside of US borders.

The U.S. military may be tasked to lead and manage efforts involving non-DoD participating partners, which may include select military units of other nations and/or non-governmental organizations (NGO) such as the United Nations, Doctors Without Borders, International Red Cross/Red Crescent, and other international relief organizations.

Large scale natural disasters are one example where proper coordination could provide value. Notional examples include

> ***Disaster Relief:*** *Following a tsunami in the western Pacific, the U.S. Navy is appointed Combined/Joint Task Force Commander for disaster relief operations involving an island nation that experienced severe destruction from several 50-foot waves. Coalition partners include naval elements from various Pacific Rim nations, e.g., Australia, Thailand, Japan, China, South Korea, and India. Ground/air elements*

from these same countries are involved in delivering relief supplies and distribution of those supplies is being managed by a combination of efforts by the host nation, the World Bank, USAID, and international relief organizations such as the Red Cross.

Humanitarian Assistance: *Following a period of severe drought and dislocation of local peoples, the U.S. Army is appointed Combined/Joint Task Force Commander for humanitarian assistance operations in a region of sub-Saharan Africa. Coalition partners include the United Nations, Doctors Without Borders, and the International Red Cross.*

These examples demonstrate the range of SSTR operations. Finding a unified approach is a key problem that is particularly acute where a cooperative approach in the preparedness phase has to be complemented with a competitive approach in the response phase due to life-threatening situations.

The National Response Plan [12] is used by Federal agencies and departments domestically and not for SSTR operations, but it provides a national-level framework that could bridge other coordination gaps that exist for an international response. The NRP provides a unified framework with detailed protocols for a comprehensive approach to all phases of disaster management, namely preparedness, prevention, response, recovery and mitigation. Those guidelines seek to improve the coordination and integration of federal, state, local and private sectors and incorporate lessons learned and best practices. The coordination efforts are as follows:

Coordination of plans: *To execute mitigation efforts of future disasters.*

Coordination of public information: *To combat fear and the spread of misinformation.*

Multi-agency coordination system: *Between public health, housing and transportation agencies, etc.*

Computational research issues in this framework involve multiagent planning, replanning and scheduling between heterogeneous coordination entities. The context of a plan ensures that the desired results will be obtained with minimal costs. Distributed techniques such as automated plan merging and negotiation tools between responders may resolve local conflicts issues without an entire replanning effort. The degree of interdependence (coupling) in capabilities and resources is a factor in the complexity of the coordination task. While coordination tools have been directed towards assisting human-to-human collaboration, agents can be introduced to reduce interdependence by providing fast and robust solutions bypassing delays in human response such as information gathering tasks. Specifically, coordination support assistant agents can help incident commanders in directing large-scale teams and gather information for situational awareness. Human-computer interactions have also become critical in flexible robot-agent-person teams to smooth out the cognitive demands of such interactions.

2.2 UAV Example

Network centric automated decision support capabilities for operations and mission planning in tactical military domains and environments may involve a heterogeneous group of sensors and effector agents drawn from distinct classes. These assets are generally engaged over a variety of mission tasks including ISR and response/service tasks evolving in a potentially dynamic, uncertain, dense and congested environment with both known and unknown targets and threats (a mix of moving/static, evading/non-evading behaviors).

These “agents” must cooperatively and/or non-cooperatively search and act on the environment to carry out a collection of distributed continual planning ISR and response/service management tasks. These include information gathering, exploration, target search: detect, locate, track, identify, classify/confirm, assess outcome, monitor, track and move, engage, destroy, etc.

Tasks may be naturally determined or dynamically dictated as a result of agents’ actions, emerging goals or changes in current state estimation, requiring proper dynamic resource management and coordination. It should be noted that picture compilation and exploitation are not mutually exclusive or loosely coupled, and interdependencies due to resource contention or goal dependencies may generally be quite complex. For instance, a distributed information gathering task may explicitly serve the purpose of picture compilation. This would help in further refining the strategy used to collect additional information needed for continual refinement of the picture. A reconnaissance mission is such an example, in which shared cognitive maps translating probability of target/threat locations or identity declarations may be exploited to optimize heterogeneous resource allocation in gathering additional information while updating/improving state estimation (picture compilation quality) in dynamic uncertain environments. The same observation on resource sharing and goals interdependencies holds for inter- and intra-picture exploitation tasks.

In these problems, resources must be allocated and coordinated in a timely manner to dynamically schedule and visit targets/threats, determine suitable routes among obstacles and manage airspace utilization and resource sharing.

A key enabler of a sustainable military force is the notion of a tiered system. A tiered system is an integrated, multi-tier intelligence system encompassing space and air-based sensors linked to close-in and intrusive lower tiers. The lower tiers (e.g., UAVs) are not only the critical source of intelligence; they can also serve as a key cueing device for other sensors. There is active research and exploration within the US DoD to understand the technical challenges in building tiered systems.

Multiagent (human and computational, cooperative, self-interested, or a mixture of both) coordination to achieve coalition formation, task allocation, path planning and other activities represent key areas to be explored. In that respect, coordination through learned behaviors and through human interactions offers a major challenge.

3. CHALLENGES AND GAPS

There exist similar technical challenges with regard to coordination in both problem domains, such as cooperative information-sharing in partially observable dynamic environments. As an example, in SSTR operations the communications infrastructure may be severely degraded or completely destroyed, preventing the first responders to effectively communicate. Similarly in scenarios requiring multiple UAVs to coordinate, distance and environment factors may prevent reliable communication.

Recent technological advances in mobile ad-hoc networks (MANET) are key enablers in the deployment of net-centric cooperative multiagent systems on the battlefield and in natural disaster areas. The limited communication range in MANET provides only a partial knowledge of the global environment but is not necessarily restricted to the immediate neighbors. Those constraints make it advantageous for agents to self-organize within their communication range using multicast, while the absence of centralized control requires a distributed control policy to manage joint distributed beliefs. The uncertainty that a message will arrive at its destination in a finite amount of time violates one of the basic communication assumptions of distributed constraint satisfaction algorithms [5]. How to extend those algorithms to open and uncertain environments is still an active area of research [3]? Coordination strategies have to be robust against message loss and equipment failures. The concept of network-aware coordination, in which agent-based coordination algorithms can utilize network state information in order to communicate more effectively by understanding each others communications constraints, is an area that has not received much attention. Additionally, human-computer interactions have become critical in flexible robot-agent-person teams to smooth out the cognitive demands of such interactions and need to be explored further.

Some deficiencies in surveillance and reconnaissance persistence, penetration and identification, battle damage assessment, and data processing, exploitation, and dissemination are due to serious limits [assets] to penetrate foliage, track individuals, identify Weapons of Mass Destruction components, defeat camouflage, and identify decoys. Dealing with these surveillance and reconnaissance challenges will require lower tiers (UAVs) of close-in and intrusive sensors. However, even as the DoD becomes more dependent on networked C3ISR, no dedicated 'red team' effort exists which concerns itself with camouflage, concealment, and deception; vulnerabilities; and tactics which might be used by adversary against our emerging C3ISR system. This is an area where recent advances in game theory can play a significant role in understanding adversarial behaviors, which can be encoded in simulations to aid in the development of tiered systems, particularly from the perspective of how these assets will coordinate in response to such behaviors.

It should be noted that tiered-system components such as UAVs or space-based assets are not only useful for ISR activities supporting more traditional combat operations, but may also enable effective SSTR operations.

Given the diversity of the assets, and the fact that coordination must be achieved both in the horizontal and vertical planes, and the environments in which the components of a tiered system will operate; it is not likely that a single coordination approach or even a family of coordination approaches will work well from a static perspective. It is more reasonable to expect that systems should learn which approaches work well and under which circumstances, and adapt appropriately.

4. TOWARDS ADAPTIVE MULTI-AGENT SYSTEMS COORDINATION

A suitable framework (or multiple frameworks) is required to address current challenges and issues in agent-based coordination. The proposed multiagent coordination approach should be flexible enough to adequately address resource constraints imposed by limits in the communication, computational and temporal dimension (should exhibit adaptability in time-constrained environments); handle information constraints such as security and privacy in information exchange; permit run-time reasoning regarding the selection of particular coordination mechanism/protocol; tradeoff between the cost of reasoning versus value of coordination, and attempt to dynamically choose between centralized and decentralized mechanisms.

The framework should support the investigation of coordination concepts in net-centric problem settings/environments. It should provide flexibility for problem definition, and allow for studying different concepts, including models, algorithms, or agent-mediated decision support capabilities. The framework should permit basic simulation in order to validate advanced multi-agent coordination concepts in order to asses the value of coordination.

5. CONCLUSION

Coordination is a key requirement underlying distributed continual planning to satisfactorily improve net-centric decision support components characterizing dynamic planning and execution. In this paper we briefly overviewed the basic elements and aspects of coordination and focused on some of the issues, gaps and challenges lying ahead for the defense research community. As a result, research areas to be further investigated have been identified in relation to SSTR such as disaster management response and the cooperative UAV problem domains.

References

[1] M. Abramson, W. Chao, and R. Mittu, Design and Evaluation of Distributed Role Allocation Algorithms in Open Environments, International Conference on Artificial Intelligence, Las Vegas, NV, 2005.

[2] E. H. Durfee, Scaling up Agent Coordination Strategies, IEEE Computer, 2001.

[3] P. J. Modi, Distributed Constraint Optimization for Multiagent Systems, PhD thesis, USC, 2003.

[4] A. Rosenfeld, G. A. Kaminka, and S. Kraus, Adaptive Robotic Communication using Coordination Costs for Improved Trajectory Planning, in Proceedings of the American Association of Artificial Intelligence, 2006.

[5] M. Yokoo, Distributed Constraint Satisfaction, Springer-Verlag, 1998.

[6] Henry Mintzberg, "The Structuring of Organizations: A Synthesis of the Research, Prentice Hall, Englewood Cliffs, N. J., 1979.

[7] Thomas W. Malone and Kevin Crowston, "What is Coordination Theory and How Can it Help Design Cooperative Work Systems", In Readings in Groupware and Computer-Supported Cooperative Work, Assisting Human-Human Collaboration, Ed. Ronald M. Baecker, Morgan Kaufmann Publishers, Inc., SF, California, 1993.

[8] Riyaz Sikora and Michael J. Shaw, "A Multi-Agent Framework for the Coordination and Integration of Information Systems", In Management Science, Vol. 11, Issue 11, Part 2 of 2, November 1998.

[9] Robert Tolksdorf, "Models of Coordination", In Engineering Societies in the Agent' World, A. Omicini, R. Tolksdorf, and F. Zambonelli, Editors, ESAW 2000, LNAI 1972, Springer-Verlag, Berlin Heidelberg, 2000.

[10] P.P.A. Storms and T.J. Grant. Agent coordination mechanisms for multi-national network enabled capabilities. In Proceedings of the 11th International Command and Control Research and Technology Symposium (ICCRTS) on Coalition Command and Control in the Networked Era, Cambridge, UK, Sept 2006.

[11] Gerhard Weiss, "Multiagent Systems and Distributed Artificial Intelligence", In Multiagent Systems – A Modern Approach to Distributed Artificial Intelligence", Gerhard Weiss, Editor, the MIT Press, Cambridge, Massachusetts, 1999.

[12] US Department of Homeland Security, "National Response Plan", [Web Site] http://www.dhs.gov/xprepresp/publications, last accessed 01/23/2007.

[13] US Department of Defense, "DoD Directive 3000.05-Military Support for Stability, Security, Transition, and Reconstruction (SSTR) Operations", http://www.dtic.mil/whs/directives/corres/html/300005.htm, last accessed 02/07/2007.