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A Unified Cooperative Control Architecture for UAV Missions

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ABSTRACT

In this paper, we propose a unified cooperative control architecture (UCCA) that supports effective cooperation of Unmanned Aerial Vehicles (UAVs) and learning capabilities for UAV missions. Main features of the proposed UCCA include: i) it has a modular structure; each function module focuses on a particular type of task and provide services to other function modules through well defined interfaces; ii) it allows the efficient sharing of UAV control and onboard resources by the function modules and is able to effectively handle simultaneously multiple objectives in the UAV operation; iii) it facilitates the cooperation among different function modules; iv) it supports effective cooperation among multiple UAVs on a mission's tasks, v) an objective driven learning approach is also supported, which allows UAVs to systematically explore uncertain mission environments to increase the level of situation awareness for the achievement of their mission/task objectives.

Keywords: UAV cooperative control architecture, information fusion, sensor management

1. INTRODUCTION

For future surveillance, remote, and hazardous missions, organizations will rely on unmanned aerial vehicles (UAVs) to collect social and environmental data of ground conditions. To enable a multitude of UAVs to operate in a single airspace, research in the 20th century focused on reactive collision avoidance, intelligent path planning, and sensor/resource scheduling. Learning methods (e.g. reinforcement) and Markov Decision Process (MDPs) were trained offline to optimize a UAV routes and tasks; however these solutions were subject to en-route challenges of re-planning do to mission changes and unforeseen, real-time mission alterations. Assuming individual UAVs could not achieve complete autonomy; efforts in the 21st century focused on swarms of UAVs working cooperatively. Cooperative UAV strategies partitioned the individual UAV tasks to the group using similar methods as for single UAVs, with significant efficiency benefits of "cooperative" identification of communication sharing. Key to future implementation and operational use of intelligent and cooperative control methods requires (1) *robust control* and optimization to changing physical sensor, target, and environmental conditions, (2) understanding of mission goals do to adversarial deceptions using functional *game-theoretical control*, and (3) *situational awareness control* to manage uncertainty, agent-based task requirements, and global/local performance objectives. To meet these challenges, in this paper, we propose an unified cooperative control architecture (UCCA) as a general framework to support effective cooperation of a group or groups of UAVs and learning capabilities in dynamic, uncertain mission environments. Key advantages of the proposed UCCA include

1) The proposed UCCA for UAV missions provides a unified framework for various function modules to effectively operate and cooperate. The UCCA has a concise three layer structure, which includes a *physical* layer, a *function* layer, and a *situation awareness* layer. The physical layer defines the basic control space of the UAV and onboard resources, and provides control interfaces to the function layer. The function layer consists of function modules that handle various tasks in UAV missions and a special Task Coordination Module (TCM) that allows other function modules to cooperate and share the control of the UAV and its onboard resources [1]. The situation awareness layer is in place to allow the effective sharing of information among different function modules. In the proposed UCCA, new function modules can be easily incorporated and cooperate with existing function modules.

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2) A novel Hierarchical Layered Decision Framework (HLDF) is adopted in the TCM of the function layer for the sharing of UAV control and onboard resources among function modules for multiple competing objectives. The HLDF suits perfectly the modular structure of the function layer. Unlike conventional combined objective approaches for handling multiple-objectives, the HLDF allows the specification of desired performance for individual objectives for different function modules, and is able to yield Pareto optimal control decisions with the desired overall performance. An objective with a higher importance will be protected from possible compromises from other less important ones. And depending on the nature of the objective, suitable control strategies, e.g., one-step or multi-step look-ahead control strategies, etc., can be used in different function modules [1].
3) The proposed UCCA provides excellent support for the cooperative control of a team of UAVs for complex missions. For UAV cooperation, a *networking module* will be implemented in the function, which is dedicated to maintaining a communication network among the group of UAVs and provide communication services to other function modules. The proposed UAV UCCA also facilitates the integration of higher-level function modules, such as coordinate mission planning, and allows them to cooperate effectively with existing lower-level function modules. The above supports enable function modules at multiple UAVs to efficiently cooperate on all levels of UAV mission/tasks.
4) An objective driven learning (ODL) framework is supported to allow UAVs to systematically increase the level of situation awareness for the achievement of their mission/task objectives. In the proposed UCCA, uncertainties of the environment and adversaries are taken into account by the uncertainties of the states and environmental parameters in the situation awareness layer. Algorithms will be developed for various function modules to allow the evaluation of the impact of uncertainties to the achievement of their objectives. Based on the evaluation, function modules are able to collect necessary information through on board sensors, other function modules, and the networking module from other UAVs to maximize the system performance.

The paper is organized as follows. Section 2 introduces the proposed UCCA, its three-layer structures, and basic components. Section 3 and 4 discuss the UCCA's supports for cooperative control of a group of UAVs and the objective driven learning framework. Section 5 summarizes the paper with concluding remarks.

2. THE PROPOSED UCCA FOR UAV MISSIONS

The proposed UCCA for UAV missions provides a unified framework for various function modules to effectively operate and cooperate. It is designed to provide efficient support for UAV multi-tasking, cooperation, and responsiveness of a network of UAVs to mission uncertainties. Fig. 1 shows the structure of the UCCA. It consists of three interconnected layers which are a physical layer, a function layer, and a situation awareness layers.

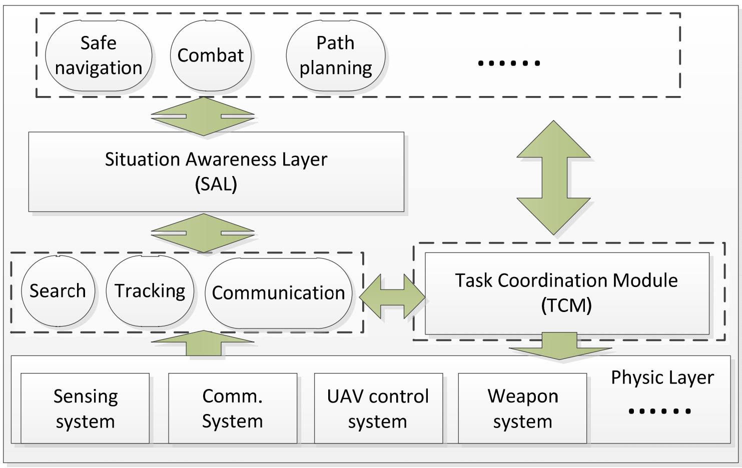

Figure 1. Structure of the UAV system in the unified cooperative control architecture

The **physical layer** supports the basic operations of the UAV and the onboard hardware resources. It consists of the basic control systems for the UAV and other on board hardware resources, such as sensors, communication system, weapons, etc. In the proposed UCCA, the physical layer defines the control space of the UAV and onboard resources, and provides interfaces that allow the access from the function layer.
The **function layer** (indicated by the dashed line areas) consists of function modules that handle various tasks in UAV missions, e.g., safe navigation, collision avoidance, path planning, search, target identification, target tracking, etc. Each function module is specialized in a specific type of UAV task and has its own model of the problem using a distinct set of states and parameters, and a Task Coordination Module (TCM) that allows other function modules to coordinate and cooperate.

In the proposed UCCA, states/parameters of a function module can be shared with other function modules by registering them at the **situation awareness layer (SAL)**. The SAL summarizes the current knowledge of the UAV about the environment from different task perspectives. Structures of the SAL and the function layer will be further discussed next.

2.1 The situation awareness layer

In the proposed UCCA, the **SAL** is in place to facilitate information sharing among different function modules. It consists of states registered by the function modules which summarize the current knowledge of the UAV about the environment from different tasks' perspectives. Fig. 2 shows an illustrative example of states/parameters registered in the SAL and their relationships with function modules in the function layer. As shown in Fig. 2, registered states from a function module can be accessed by other function modules as their inputs. Together states registered states at the SAL form a directed graph, which can be analyzed using statistic models such as Bayesian networks and inference diagrams [2] to evaluate the impact of the performance of one function module on that of other function modules and on the overall system performance. The structure also facilitates the introduction of new function modules and allows them to effectively share information and cooperate with existing function modules.

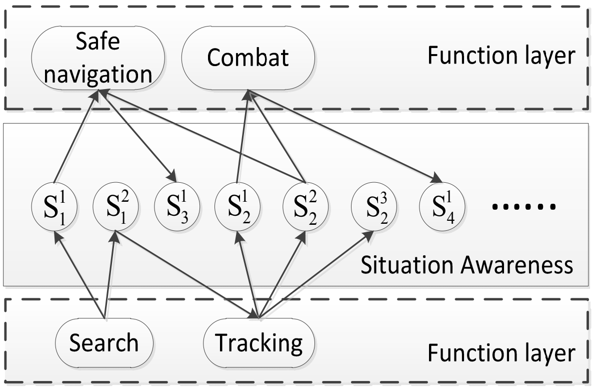

Figure 2. An example of function modules and their states registered in the situation awareness layer

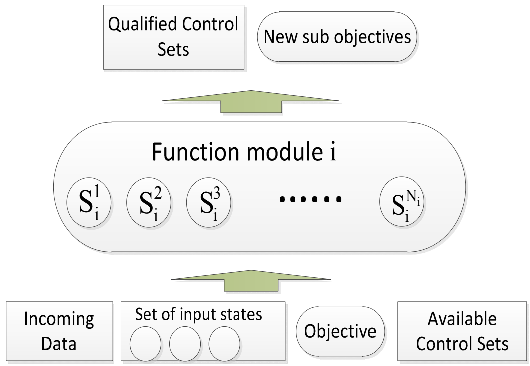

Figure 3. Basic structure of a function module

2.2 The function layer

Function modules
In the proposed UCCA, function modules are specialized in various types of tasks in UAV missions. The capabilities of a function model are two-fold. First it acts as an information processor that uses incoming data to update its states. Second it acts as a controller guiding the UAV, utilizing its onboard resources and cooperating with other function modules to accomplish its objectives.

Fig. 3 shows the basic structure of a function module. Inside a function module, a set of states and parameters, denoted as $S_i^1, \ldots, S_i^{N_i}$, summarizes the current information and the state of the specific problem that the function module is to handle. Table 1 shows some examples of function modules and their states. In general, states and parameters of a function module are dynamic and stochastic in nature, whose levels of uncertainties reflect the level of situation awareness for the objective of interest.

To facilitate cooperation, function modules have well defined inputs and outputs. Inputs of a function module include i) data for processing and state updates, ii) states of other function modules from the SAL that are relevant to its task, iii) a targeting objective specified as a requirement on a utility function of the states, e.g., $J(S_i^1, \; S_i^2 \ldots) \geq \tau_i$, and iv) control sets available for the function module to control the UAV or other resources.

Table 1. Exemplar states in different function modules

Function module	Possible states and parameters
Target identification	target ID, target type, other target properties of interest, etc.
Search	spatio-temporal density of the target's occurrence, probability of target occurrence in different surveillance regions, target detection results, etc.
Tracking	number of targets, target spacing, tracks, road map information, etc.
UAV safe navigation	threat modeling parameters, UAV survival probabilities, etc.

Note that in the proposed UAV control architecture, instead of maximizing utility functions, objectives for function modules are set as *requiring utility functions to reach a desired performance threshold*. For example, it is more reasonable to require the tracking module to maintain the tracking accuracy of a target above desired threshold, rather than to track the target as accurate as possible with all the UAV's resources. This approach is a more appropriate for UAV missions that have multiple objectives competing for UAV resources. It is adopted in the hierarchical layered decision framework (HLDF, to be introduced later for the TCM) for making Pareto optimal control decisions with desirable performance tradeoffs among multiple UAV tasks.

Outputs of a function module consist of i) the qualified sets of control decisions, and ii) sub-objectives (requirements) for other function modules whose states are relevant (as the function module's inputs). The outputs allow a function module to directly control the UAV and its onboard resources, or indirectly through other function modules for the achievement its objective. Note that, because of the way in which objectives for function modules are specified, instead of producing a single unique control decision for the UAV or other resources, function modules yield the sets of qualified control decisions, which are subsets of the available control sets from the inputs.

The task coordination module (TCM)

A special component of the function layer is the task coordination module (TCM) which handles the coordination and cooperation of other function modules. Function modules need to share the control of the UAV and the onboard resources for their assigned objectives. For example, tracking and search function modules use the same set of sensors, and both need to control the flight path of the UAV for their respective objectives. Thus control decisions for the UAV and its onboard resources need to balance among multiple objectives and cannot be directly made by any single function module. As illustrated in Fig. 1, the physical layer of the UAV is directly controlled by the TCM rather than other function modules. One major function of the TCM is to cooperate with other function modules to make control decisions that yield desired overall system performance. For this purpose the TCM adopts a Hierarchical Layered Decision Framework (HLDF) proposed in [1].

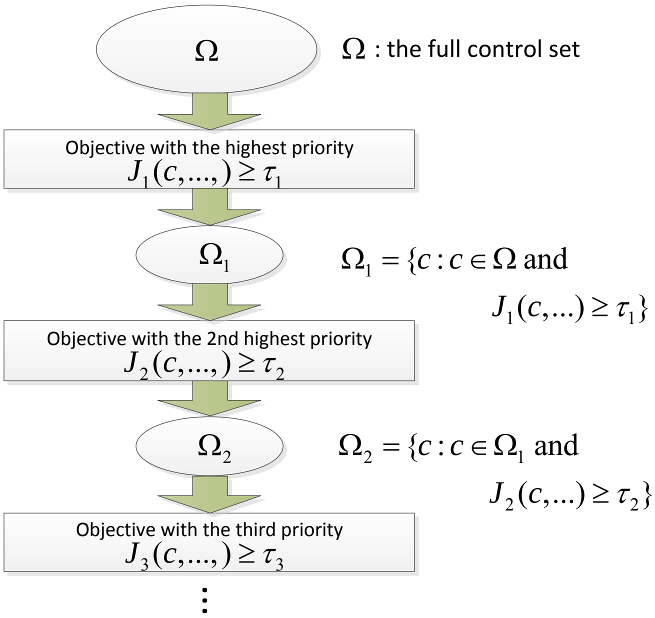

Figure 4. Decision making process in the HLDF

Fig. 4 illustrates the HLDF, where the control decisions are made based on a prioritized list of current objectives (including sub-objectives). It starts from the objective with the highest priority. The TCM first sends the objective (denoted as $J_1(c,...) \geq \tau_1$) and the full control set Ω, e.g., for the UAV, to the corresponding function module. The outputs from the function module include a reduced control set Ω_1 that qualified for the requirement on J_1. Then the TCM proceeds with the objective of highest priority in the remaining objective list, by sending the objective with the reduced control set, in this case Ω_1, to the corresponding function module. The process repeats and the control set will converge to the final control decision with the desired overall performance. Note that the control set can be discrete or continuous; the uniqueness of the final control decision can be guaranteed with minor modification to the objective with the lowest priority.

Major benefits of this approach include: i) it allows the specification of desired performance requirement to each individual function module, and yields Pareto optimal control decisions with desired overall system performance on multiple objectives; ii) an objective with a higher priority will be protected from possible compromises from other less important ones; iii) fully compatible with modular structure in the function layer; and iv) depending on the nature of the objective, suitable control strategies, e.g., one-step or multi-step look-ahead control policies, etc., can be used for different function modules.

In [1] the problem of the cooperative control of a group of UAVs for a surveillance mission in a hostile environment. The HLDF was proposed for the handling multiple objectives in UAV missions. Objectives in the surveillance mission include i) navigating the UAVs safely in the hostile environment with stationary and moving threats, ii) search for targets, iii) target identification, and iv) maintain adequate tracking accuracy on detected targets. Fig. 5(a) shows the scenario with a group of 4 UAVs, 5 moving targets, and three restricted regions (denoted by the red circles) that the UAVs should avoid. In this work to avoid making myopic control decisions, a multiple objective and a multi-step look-ahead control strategy was also proposed based on the Roll-out policy [3].

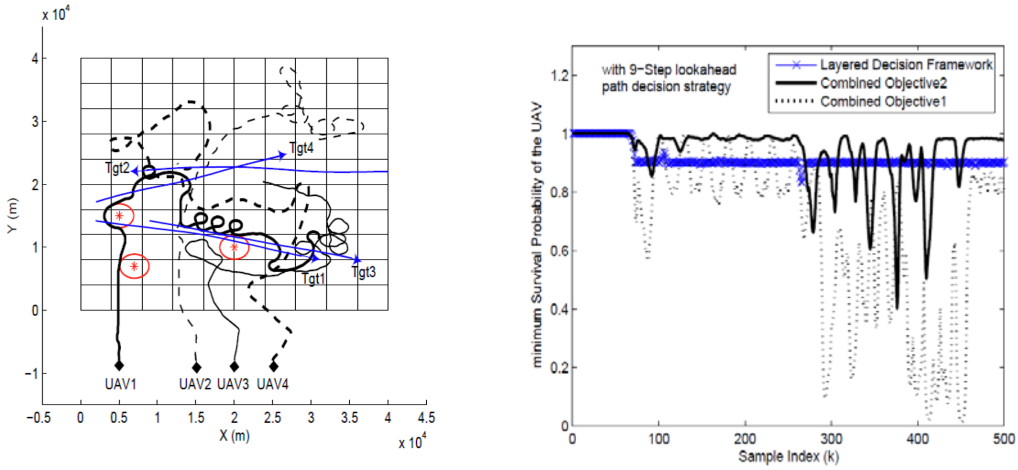

Figure 5 (a). UAV surveillance scenario **(b). Minimum survival probability of UAV 1**

To demonstrate the advantage of the layered decision framework over the conventional combined objective approach, Fig.5 (b) shows the minimum survival probabilities of UAV 1 over 100 Monte Carlo simulations with each simulation lasting 500 time intervals. It was shown that, for the objective of safe navigation, which is to keep the survival probability of the UAV close to the required threshold $\tau_{PS}=0.9$, the layered decision framework (HLDF) with a 9-step look-ahead path decision strategy yield significantly better performance than two conventional combined objective approaches. With HLDF, the rare drop of the UAV survival probability to 0.8 occurred only once in the 100 runs; while the combined objective approaches failed to meet the objective most of the time. See [1] for the details on the problem formulation, algorithms and simulation results.

Another function of the TCM is to allow the cooperation among different function modules. As shown in Fig. 2, function modules are interconnected with states of one (registered with the SAL) being the inputs of another. Fig. 3 shows that outputs of a function model may include new objectives for other function modules whose states are the function module's input. In the proposed UAV control architecture, a newly generated sub-objective will be added to the objective list of the TCM with a priority level inherited or assigned form its parent objective, and be appropriately dispatched by TCM to the corresponding function module. This mechanism allows multiple function modules in the function layer work as an integrated system for UAV missions/tasks.

3. SUPPORT FOR THE COOPERATION OF A TEAM OF UAVS

The proposed UCCA provides efficient and effective support for the cooperative control of a group or groups of UAVs for complex missions. For UAV cooperation, a dedicated *networking module* (NM) will be implemented in the function layer to allow UAVs to maintain cooperatively a communication network, and provide communication services for other function modules.

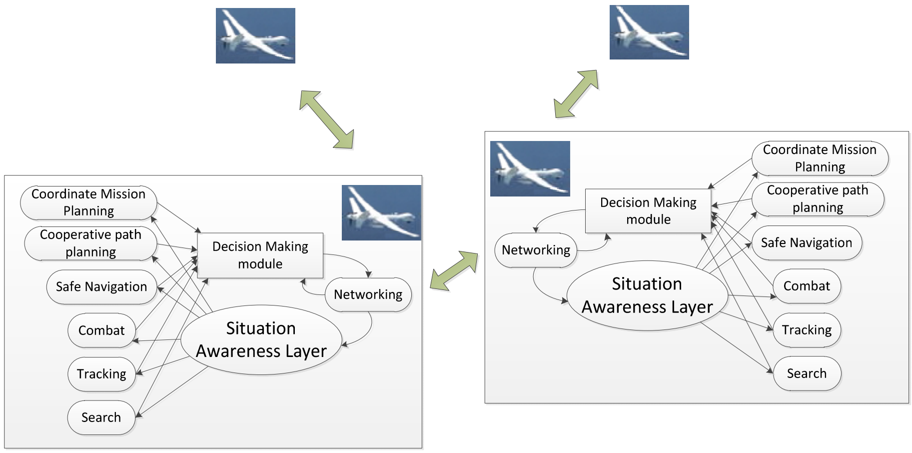

Figure 6. Cooperation of UAVs on various tasks

Fig. 6 illustrates how function modules on multiple UAVs are able to cooperate within the proposed UAV UCCA. For cooperation, communication requests are sent to the networking module through the TCM. The NM will take care of the transmission/reception of data to/from other UAVs. Received data will be forward by the NM to the data reception buffer of the corresponding function module in situation awareness layer, or be forwarded to the next UAV along the data package's routing path in the communication network.

Networking Modules on UAVs also have the function of maintaining cooperatively the connectivity and capacity of the communication network to meet dynamic communication needs of UAV mission. Like other function modules, the NM is able to send control requests to the TCM to control the UAV according to its networking objectives. Through the networking module, function modules such as coordinate mission planning, cooperative path planning, combat, tracking, search, of a UAV can communicate with their counterparts of other UAVs, which allows cooperation of UAVs for various tasks. In this proposed work, cooperative control algorithms that are able to adapt to network conditions will be developed for these function modules. In a game theoretical framework, cooperative control strategies will be developed to allow tradeoffs between cooperation performance and communication requirements [6--13].

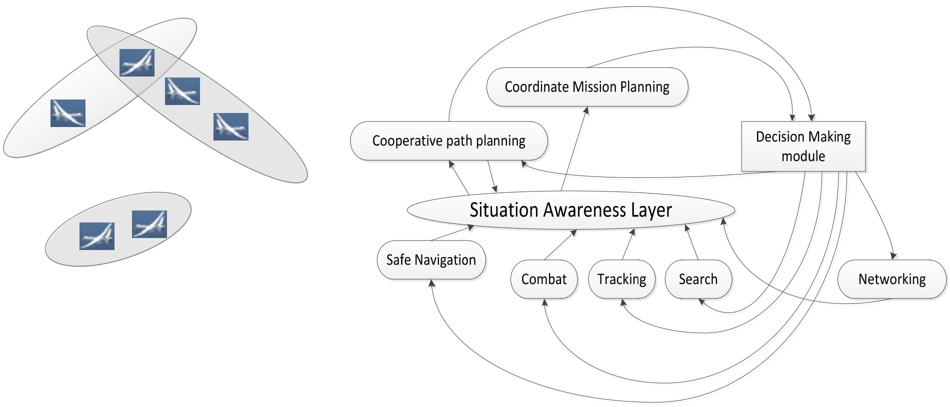

Figure 7. Coordinated mission planning under the proposed UAV control architecture

For UAV cooperation, the proposed UAV UCCA also facilitates the integration of high level function module for coordinate mission planning, and allows it to work effectively with existing lower level function modules. As illustrated in Fig. 7, the function module for coordinate mission planning allows a group of UAVs to cooperate over a complicated mission by assigning the mission's tasks to subsets of UAVs. For a UAV, tasks assigned from the *coordinate mission planning module* (CMPM) generate a dynamic list of objectives. The objectives are then dispatched through the TCM to the corresponding function modules for execution. By monitoring relevant states in the situation awareness layer, the CMPM gets feedback on the degrees of achievement of the tasks, based on which new objectives will be generated towards the achievement of the assigned tasks. In addition, the CMPM will support dynamic mission planning which allows the reassignment tasks to UAVs according to information feedback from field level operations.

4. LEARNING UNDER THE PROPOSED UAV UCCA

The capability of learning is crucial for UAVs to operate and accomplish their missions in dynamic uncertain environments and in the presence of intelligent adversaries. In this proposed work, learning functions for UAV missions are categorized into two types. The proposed UAV control architecture supports an *objective driven learning* (ODL) framework to effectively guide the UAVs to increase the level of situation awareness. It involves not only learning algorithms for processing data and reducing mission/environmental uncertainties but also algorithms that are able to evaluate impact of uncertainties on various tasks and actively guide the learning process.

In the proposed UCCA, uncertainties of the environment and adversaries are reflected by the uncertainties of states and parameters in various function modules. In the proposed ODL framework, in addition to learning algorithms that reduce uncertainties in UAV missions, algorithms will be developed for function modules to evaluate the impact of uncertainties to the achievement of their objectives and set appropriate objectives for learning and information gathering processes. Fig. 8 shows an illustrative example of the ODL process, where a high-level function module cooperates with several low-level function modules with learning capabilities and guides the learning process in service of its objective.

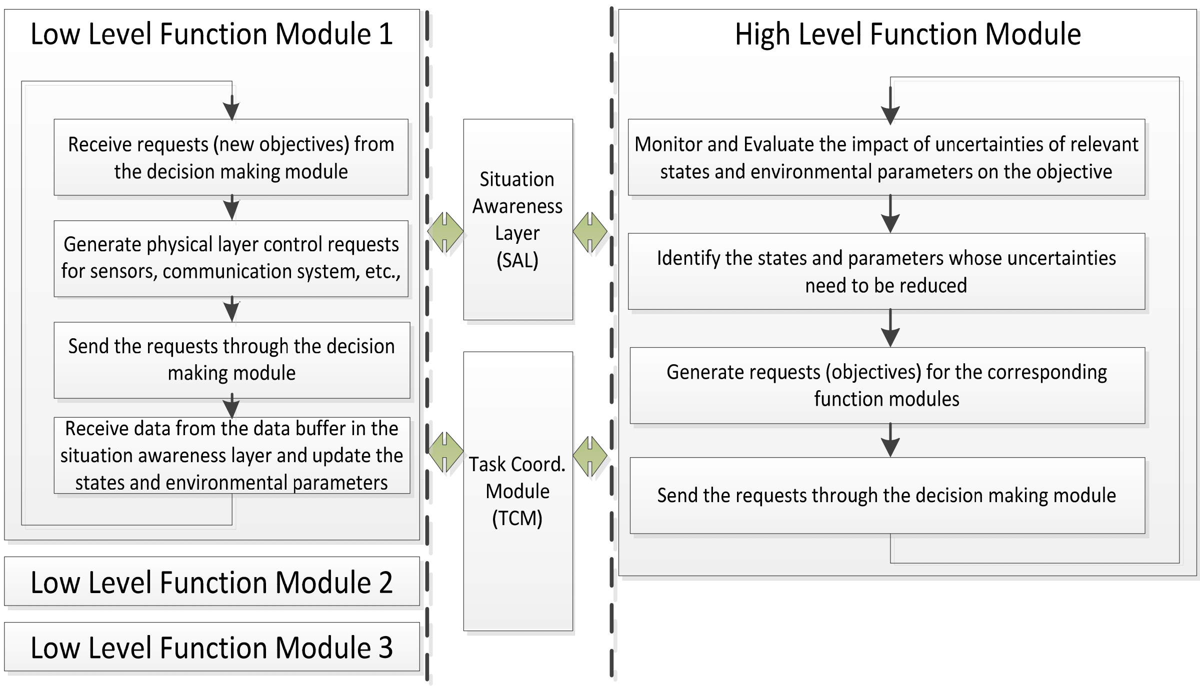

Figure 8. The objective driven learning process in the proposed UCCA

In general, algorithms for search, tracking, and target identification are learning algorithms, which process information from onboard sensors to reduce the uncertainty in targets' presence, kinematic states, and identities for the needs of high-level functions modules for combat identification, mission assignment, etc. Other learning algorithms involve the learning of environmental parameters which allow algorithms to adapt to environmental uncertainties and changes, such as the learning of spatio-temporal density parameters for event occurrence in a search mission [4,14]. Another example is the learning of state transition costs in the Markov decision process for UAV's mission plan [5]. These algorithms can be accommodated in the UCCA under the ODL framework.

5. CONCLUSIONS

In this paper, a unified cooperative control architecture (UCCA) is presented, which supports effective cooperation of a group of UAVs and learning capabilities in uncertain dynamic mission environments. It has a concise three layered structure, which consists of i) a *physical* layer that defines the basic control space of the UAV and provides interfaces for the control of the UAV and onboard resources, ii) a *function* layer that has various function modules specialized in different tasks in UAV missions and a special task coordination module (TCM) for the coordination and cooperation of the function modules, and iii) a *situation awareness* layer that contains states registered by the function modules to facilitate the sharing of information among the function modules. To allow function modules to efficiently share the controls of the UAV and the onboard resources, the TCM adopts a novel hierarchical layered decision framework (HLDF), which is able to yields Pareto optimal control decisions with desired overall system performance. To facilitate the effective cooperation among different function modules a *networking module* will be implemented in the function layer, which is dedicated to maintaining a communication network among the group of UAVs and provide communication services to other function modules. The proposed UCCA also facilitates the integration of higher-level function modules, such as coordinate mission planning, and allows them to cooperate effectively with existing lower-level function modules. Finally, an objective driven learning (ODL) approach is proposed under the UCCA. It allows UAVs to systematically explore uncertain mission environments to increase the level of situation awareness for the achievement of their mission/task objectives.

6. REFERENCES

[1] X. Tian, Y. Bar-Shalom and K. R. Pattipati, "Multi-step Look-Ahead Policy for Autonomous Cooperative Surveillance by UAVs in Hostile Environments," *Journal of Advances in Information Fusion*, 4(2), Dec. 2009

[2] R. D. Shachter, "Evaluating Influence Diagrams," *Operations Research*, Vol. 34, No. 6, 1986, pp. 871–882.

[3] D. P. Bertsekas, and D. A. Castanon, "Rollout algorithms for stochastic scheduling problems," *Journal of Heuristics*, 5(1):89-108, April 1999.

[4] H. Chen, D. Shen, G. Chen. E. Blasch, and K. Pham, "Tracking evasive objects via a search allocation game," IEEE American Control Conference (ACC), 2010.

[5] D. Shen, G. Chen, J. B. Cruz Jr., K. Pham, E. Blasch, and R. Lynch, "Cooperative controls with intermittent communication" in Proc. of SPIE, Vol. 7691, 2010

[6] G. Chen and J. B. Cruz, Jr., "Genetic Algorithm for Task Allocation in UAV Cooperative Control," *Proceedings, AIAA Guidance, Navigation, and Control Conference*, Austin, Texas, August 2003.

[7] J B. Cruz, Jr, G. Chen, D. Garagic, X. Tan, D. Li, D. Shen, M. Wei, X. Wang, "Team Dynamics and Tactics for Mission Planning," *Proc. of the 42nd IEEE Conf. on Decision and Control,* 2003.

[8] D. Shen, G. Chen, J. B. Cruz, Jr., and K. Pham, "An Adaptive Sequential Game Theoretic Approach to Coordinated Mission Planning For Aerial Platforms," in M. Hirsch, etc editor, *Advances in Cooperative Control and Optimization, PP323-338, Springer Verlag, Berlin Heildelburg,* 2007.

[9] D. Shen, G. Chen, J. B. Cruz, Jr., and E. Blasch, "Game Theoretic Data Fusion Aided Path Planning Approach for Cooperative UAVs ISR," *2008 IEEE Aerospace Conference,* 2008.

[10] D. Shen, J. B. Cruz, G. Chen, and C. Kwan, et al, "A Game Theoretic Approach to Mission Planning For Multiple Aerial Platforms", *In Proc. of AIAA infotech@aerospace*, Sept. 26-29, Arlington, VA., 2005.

[11] G. Chen, D. Shen, J. B. Cruz, C. Kwan, S. Cox, S. P. Riddle, and C. Matthews, "A novel cooperative path planning for multiple aerospace vehicles," *In Proc. of AIAA infotech@aerospace*, Sept. 26-29, Arlington, VA., 2005.

[12] G. Chen, C. Kwan, D. Shen, J. B. Cruz, and A. Vannevel, "Adaptive Cooperative Path Planning for Multiple Platforms," *Proc. of IEEE Robio 2005,* June 29-July 3, Hong Kong and Macau, 2005.

[13] Shen, D., Chen, G., Blasch, E., Pham, K., Douville, P., Yang, C., Kadar, I., "Game theoretic sensor management for target tracking" *Proc. of SPIE*, Vol. 7697, 2010.

[14] A. Arsie, K. Savla and E. Frazzoli, "Efficient routing algorithms for multiple vehicles with no explicit communications", *IEEE Transactions on Automatic Control*, vol. 54, no. 10, pages 2302-2317, 2009.