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A Survey of Autonomous Control for UAV

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Abstract—**This paper presents the autonomous control for UAV. The autonomous control concept and Autonomous Control Level (ACL) metrics that can measure autonomy of UAVs are introduced. Compared with manned aircraft control task in battlefield, the functions of autonomous UAV system are organized. According to the laws of Increasing Precision with Decreasing Intelligent (IPDI), the architecture of autonomous control for UAV is given. The architecture can be divided into three levels: Execution Level, Coordination Level and Organization Level. The constraint conditions and realizations of Coordination Level and Organization Level are studied comprehensively. The key hardware and software technologies for multi-tasks are modularized depending on the requirements of mission. The software technologies are distributed to stages of flying particularly.**

Keywords-UAV; Autonomous Control; Autonomous Control Level (ACL); Architecture of Autonomous Control; Key Technologies

I. INTRODUCTION

UAV (unmanned Aerial Vehicle) is defined as a powered aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry lethal or nonlethal payloads [1]. UAV is better suited for "dull, dirty, or dangerous" missions than manned aircraft. Today, there is a large interest worldwide in the development of UAV for a number of civil and military missions, such as surface reconnaissance, law enforcement, disaster assistance, telecommunications relay, borderline surveillance, agricultural surveying, power-line monitoring, archeological sites control and many others.

While UAV control technologies have progressed steadily in recent years, the main control methodologies are still radio remote and preprogrammed. If communication link is not expedited or reliable, radio remote control mode no longer has any effect. Although the later control mode can break away from restriction of communication link, UAV doesn't update mission when plans or treat situations are changed. Even the combination of the two methodologies can't solve the situation under uncertain environment.

It is shown that current technologies are adequate for automated UAV that operate in a relatively structured environment. For UAV in a rapidly changing uncertain environment the present techniques are inadequate [2]. Thus, the autonomous control of UAV is proposed.

Autonomous control systems are designed to perform well under significant uncertainties in the system and environment for extended periods of time, and they must be able to compensate for system failures without external intervention. Autonomous control systems use techniques from the field of Artificial Intelligence (AI) to achieve this autonomy. Such control systems evolve from conventional control systems by adding intelligent components, and their development requires interdisciplinary research [3].

There are not many references about autonomous control. Antsaklis et al. [4, 5] presented the architecture of autonomous controllers necessary for the operation of future advanced space vehicles. The concepts and methods needed to successfully design such an autonomous controller are introduced and discussed. Then they provided an introduction to the area of intelligent autonomous control. The fundamental issues in autonomous control modeling and analysis were discussed, with emphasis on mathematical modeling [3, 6]. Doraiswami et al. [7, 8] proposed an integrated approach for the design and implementation of autonomous control systems that unifies the design problems of failure detection, isolation and accommodation. Pachter et al. [9] gave the challenges of autonomous control including the concept of autonomy, challenges of optimization, dealing with uncertainty and so on. And they summarized the enabling technologies for an autonomous tactical UAV [2]. Clough, B [10, 11] discussed how far we've come, how far yet we have to go, and how we plan on getting the autonomous control for UAV. What types of decisions we allowed the UAV to make, their breadth and impact, related to how autonomous the UAV is on reference [12]. Other references cited automated decision aiding/decision making [13-15] as one of the most difficult problems leading to autonomy.

In this paper, the survey of autonomous control for UAV is investigated. This paper is organized as follows: Section 2 describes the concept of autonomous control and Autonomous Control Level (ACL) for UAV. In section 3, the architecture of autonomous control for UAV, which can be divided into three levels, is presented. Section 4 gives the key technologies for autonomous control of UAV. Finally, Section 5 is conclusion.

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II. AUTONOMOUS CONTROL OF UAV

A. The concept of autonomous control

Autonomous means having the power for self government. Autonomous controllers have the power and ability for self governance in the performance of control functions. In the autonomous control describe as "a high degree of automation is applied in a very unstructured environment". "Automation" here refers to the absence of human intervention, and "unstructured environment" is associated with uncertainty [9].

It is clear that the development of autonomous controllers requires significant interdisciplinary research effort as it integrates concepts and methods from areas such as Control, Identification, Estimation, and Communication Theory, Computer Science, especially Artificial Intelligence, and Operations Research (OR). AI in this case can be looked at as a knowledge base, expert system, learning, or simply heuristics. What is more noteworthy is the strong role of OR, specifically planning, which can be viewed as the essence of decision making. The synthesis of high performance controllers for the solution of difficult control problems is what autonomous control is really all about.

An autonomous controller can deal with unexpected situations, new control tasks, and failures within limits. The serious challenge of autonomous control is the real-time optimization in uncertain environment without human intervention. Autonomous control enables many functions, normally accomplished by humans, to be done by the vehicles instead. A fully-autonomous controller should perhaps have the ability to even perform hardware repair, if one of its components fails. Conventional fixed controllers can be considered to have a low degree of autonomy since they can only tolerate a restricted class of plant parameter variations and disturbances.

There are many differences between automatic control and autonomous control. Automatic control provides the necessary automation of normal operational control. However, the role of an autonomous control system is to do more than provide automatic control. In addition to automation, the control system must provide a level of autonomy that can detect and respond to anticipated events and conditions. In a sense, the role of the autonomous control system is to act as an extension of the human operators to assure reliable, continuous operation of UAV over an extended lifetime under adverse conditions. Autonomous control can be defined as a higher level of automatic control.

UAV is serious sophisticated system with high-order whose subsystems are interrelated and estimation objects are various. The main capability of autonomous control for UAV is making its own decisions. Design for autonomous control ability can include providing diverse control mechanisms, advanced measurement devices, and redundant communication links. These features contribute to the ability of the autonomous control system to incorporate fault avoidance by design and permit fault tolerance by adaptation given the prospect of component degradation or failure.

Compared with manned aircraft control task in battlefield, the functions of autonomous UAV system can be organized as follows:

- Combat and flight mission planning;
- Health conditions monitoring;
- Fault detection, diagnosis, isolation and toleration;
- Missions and trajectories replanning which is according to insufficient battle information from sensors and data link;
- Autonomous take-off and landing;
- Flight attitude control, track following, payloads management and so on;
- Communication with ground station and other UAVs;
- The ability of dealing with unexpected situations;
- The ability of learning.

B. Autonomous Control Level (ACL) of UAV

The Autonomous Control Level (ACL) is a metric that can measure our own research programs, plan new programs, and compare autonomous control technology efforts [16]. The ACL concept was pioneered by researchers in the Air Force Research Laboratory's Air Vehicles Directorate who are charged with developing autonomous air vehicles [17]. The Autonomous Control Level and trend of UAV autonomy

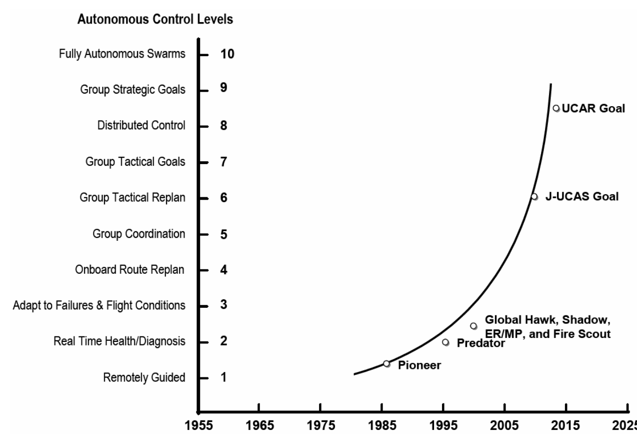

Figure 1. Autonomous Control Level (ACL) and trend of UAV autonomy

are shown in Fig.1. There are ten levels of UAV autonomy.

UAVs which are in operational use today do not rank very high on the scale of ACL, e.g. the Predator and the Global Hawk demonstrate an ACL in between level 2 and level 3. The DARPA-funded Joint Unmanned Combat Air Systems (J-UCAS) autonomy was planned to reach the level 6 of ACL. This goal was expected to be accomplished by 2015. However, this program was recently abandoned. By comparison, UCAR must achieve ACL from 7 to 9 to fly through a far more cluttered environment at low altitudes close to the threat. The concept of ACLs is widely accepted as a metric for describing autonomy in UAVs [18].

The detailed description of ACL is shown in [19].

III. THE ARCHITECTURE OF AUTONOMOUS CONTROL FOR UAV

It is important to design an appropriate and efficient architecture for autonomous control system. Since process of complicated architecture design is from low level to high level, from exact controller to decision-making unit, the hierarchical architecture is best suitable for sophisticated UAV system.

A basic multi-level (often three-level) hierarchy based on the laws of Increasing Precision with Decreasing Intelligence (IPDI) appears in many of the applications, such as power systems, autonomous mobile robots, underwater vehicles and so on. However, the hierarchical architecture varies with the different plants, multi-control methods and the complexity of applications.

The hierarchical architecture of autonomous UAV is shown in Fig. 2. This architecture has three levels: Execution Level, Coordination Level, and Organization Level.

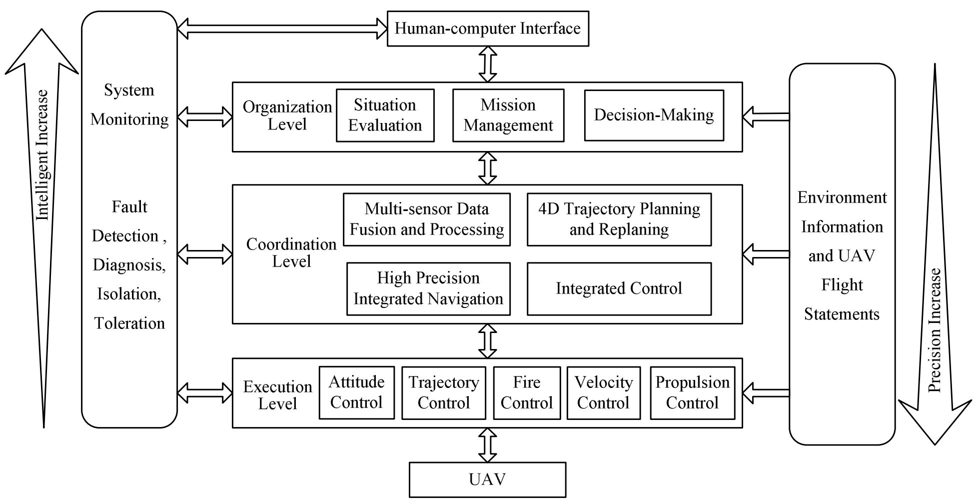

Figure 2. Hierarchical control architecture of autonomous control for UAV

The lowest level, called Execution Level with lowest intelligent, involves conventional control algorithms. There is the interface to UAV via the sensors and actuators. The highest level, called Organization Level with highest intelligent and lowest precision, involves intelligent, decision-making methods, situation evaluation and mission management. The middle level, Coordination Level, is the level which provides the interface between the actions of the other two levels and it uses a combination of conventional and intelligent decision making methods. The specific functions at each level are described in detail in later sections.

Commands are issued by higher levels to lower levels and response data flows from lower levels upwards. Parameters of subsystems can be altered by above level in the hierarchy. There is a delegation and distribution of tasks from higher to lower levels and a layered distribution of decision making authority. At each level, some preprocessing occurs before information is sent to higher levels. If requested, data can be passed from the lowest subsystem to the highest. All subsystems provide status and health information to higher levels. Human intervention is allowed even at the control implementation supervisor level, with the commands however passed down from the upper levels of the hierarchy [6].

The module of "system monitoring and fault detection, diagnosis, isolation, toleration" is used to get information, monitor the health and alter the operation parameters. When fault occurs, the module can detect and isolate fault to eliminate or reduce criticality.

The module of "environment information and UAV flight statements" gives the environment information to the three levels, and supervises the system statements.

This is a functional architecture rather than a hardware processing one. So it does not specify the arrangement and duties of the hardware used to implement the functions described. The idea of inner-loop and outer-loop is adopted to implement the hardware system. First, we take the Execution Level as an inner-loop to realize the conventional control function. The Coordination Level arranges in middle-loop to generate the trajectory, guidance and other signals. According to the decisions of outer-loop, the middle-loop coordinates the inner-loop and outer-loop operation and ensures the information flows and control flows are clear. Finally, the outer-loop is implemented by Organization Level.

A. *Execution Level*

The main function of Execution Level is to generate, via the use of conventional algorithms, low level control actions as dictated by the higher levels of the controller, and apply them to UAV. It senses the responses of the vehicle and environment, processes them to identify parameters, estimates states, or detects failures, and passes this information to the higher levels.

B. Coordination Level

Coordination Level receives decision-making from Organization Level to perform predetermined specific control tasks. It provides the appropriate sequence of control and identification algorithms to the Execution Level below. Its ability to deal with extensive uncertainties is limited. Main architecture and realization of Coordination Level are shown in Fig. 3.

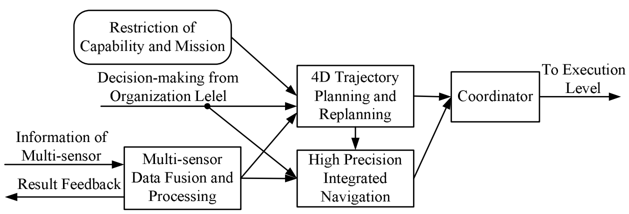

Figure 3. Main architecture and realization of Coordination Level

The other function of Coordination Level is to coordinate the subsystems and make the system more steady and efficient. The coordinator can integrate flight control, fire control and propulsion control to realize Integrated Flight and Fire Control (IFFC) system, Integrated Flight and Propulsion Control (IFPC) system and Integrated Flight/Fire/Propulsion Control (IFFPC) system [20].

C. Organization Level

Organization Level interfaces to the ground station and other UAVs and performs the highest level control functions. It oversees and directs all the activities at both the Coordination and Execution Levels. It is the most "intelligent" of the three levels. Main architecture and realization of Organization Level are shown in Fig. 4.

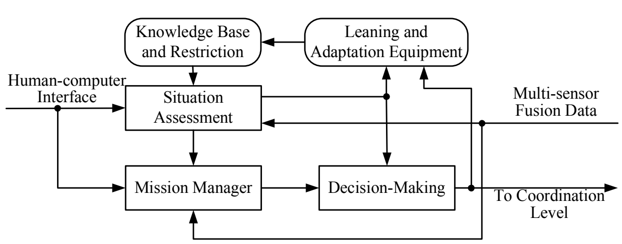

Figure 4. Main architecture and realization of Organization Level

IV. KEY TECHNOLOGIES FOR AUTONOMOUS CONTROL OF UAV

The autonomous control system is composed of key technologies which can be divided two parts: hardware and software.

Hardware technologies are shown in follows:

- High speed processor;
- High precision integrated navigation system;
- Air data system;
- Anti-disturbance and standard data link system;
- Take-off and landing system;
- Environment awareness system;
- Collision avoidance system;
- Payload technologies.

According to the intelligent level, software technologies are distributed to the three levels which are shown in Fig. 2. We must study these technologies from low level to high level. The software technologies, which are distributed to stages of flying mission, are listed in TABLE I.

V. CONCLUSION

Autonomous control, whose goal is to realize the autonomous flight and management, self-repairing, decision-making and so on, is the trend in the UAV control field. However, the fully-autonomous control has not yet been applied to an UAV system. It is a tremendous challenge from automatic flight to autonomous flight and still a very long way to go.

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TABLE I. SOFTWARE TECHNOLOGIES REQUIREMENT OF EACH UAV AUTONOMOUS FLYING STAGE

Flight Stage / Main Technologies	Taxing	Take-off	Climb	Cruise	Reconnaissance	Attack	Return	Glide	Landing
Robust reliable control	●	●	●	●	●	●	●	●	●
High precision integrated navigation	●	●		●	●		●	●	●
4D trajectory planning and replanning				●	●		●	●	
Multi-sensor data fusion and processing					●	●			
Integrated control			●	●	●	●		●	●
Situation assessment				●	●	●			
Mission manager	●	●	●	●	●	●	●	●	●
Autonomous decision-making					●	●			
System monitor and fault detection, diagnosis, isolation, toleration		●	●	●	●	●	●	●	●
UAV formation and cooperation control		●	●	●	●	●	●		