Self-Aware Vehicles: Mission and Performance Adaptation to System Health

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Advances in sensing (miniaturization, distributed sensor networks) combined with improvements in computational power leading to significant gains in perception, real-time decision making/reasoning and dynamic planning under uncertainty as well as big data predictive analysis have set the stage for realization of autonomous system capability. These advances open the design and operating space for self-aware vehicles that are able to assess their own capabilities and adjust their behavior to either complete the assigned mission or to modify the mission to reflect their current capabilities. This paper discusses the self-aware vehicle concept and associated technologies necessary for full exploitation of the concept. A self-aware aircraft, spacecraft or system is one that is aware of its internal state, has situational awareness of its environment, can assess its capabilities currently and project them into the future, understands its mission objectives, and can make decisions under uncertainty regarding its ability to achieve its mission objectives.

I. Introduction

In order to realize a future world where aviation has been transformed by autonomy and on-demand air transportation is a reality, new capability is needed beyond the current state of the art. Barriers to wide acceptance of autonomous aircraft include environmental noise concerns and the ability to safely "control" the operation of large numbers of vehicles of varying size in the national airspace. Perhaps more significantly, autonomous systems must display decision-making comparable or superior to a human.

These challenges can be met by self-aware aircraft. A self-aware vehicle knows its internal state and its external environment. Knowledge of the external environment can be gained through onboard sensors and/or airborne or ground-based assets. It can then take action based on this knowledge in conducting its assigned mission. The self-aware capabilities apply in varying degrees across the full spectrum of aircraft, from small UAVs to advanced vertical lift configurations to large transport aircraft.

As described, a self-aware aircraft requires integration of multiple individual technologies and development of integrated technologies. The concept leverages research in areas such as Digital Twin[1], Learn-To-Fly[2], and intelligent propulsion system[3], providing a practical application of the technologies and identifying gaps requiring further inquiry.

Central to the capability is autonomous decision making in the form of an adaptive mission manager. The adaptive mission manager autonomously flies the aircraft to complete the mission it has been assigned but it can adapt the way it flies based on the health of the vehicle, its external environment, and other desired characteristics such as minimizing noise or fuel burn. Thus, a vertical takeoff aircraft may safely limit climb performance in proximity to the ground to minimize noise but allow for increased noise and improved performance at altitude when the objectionable effects on the ground aren't a concern. The ability to modify how an aircraft flies based on its current health redefines nominal operations through graceful degradation of performance without compromising

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safety. Ultimately, increased understanding of the internal health and external environment could also lead to reduced design margins and increased vehicle performance.

II.   Self-Aware Vehicle Concept

A self-aware aircraft, spacecraft or system is one that is aware of its internal state, has situational awareness of its environment, can assess its capabilities currently and project them into the future, understands its mission objectives, and can make decisions under uncertainty regarding its ability to achieve its mission objectives (Figure 1). It is an intelligent system whose self-assessment and projection of its capability over a temporal range in real-time redefines its "nominal" operations.

Internal state awareness implies knowledge of platform health and capability. External situational awareness encompasses knowledge of external resources (airports, home base, supervisors, or collaborators) as well as threats that can affect system performance (weather, congestion, criticality of human operator status, uncooperative agents). Decision-making functionality in the adaptive mission management system must be able to translate mission objectives into actions and assess the impact of its internal and external state on its ability to execute the mission. If the combination of the internal and external state will not permit the system to achieve its mission objectives, the autonomous mission management system for the platform must revise the mission plan or otherwise alter the mission execution strategy to remain within current vehicle operational limits and safe operation.

These capabilities enable redefinition of "nominal" operations with potential impact on vehicle design and safety margins. Autonomous decision-making enables self-optimization of performance for mission execution. Real-time knowledge of the internal system states, including structural health, vehicle dynamics, etc. combined with assessment of vehicle/system current capability and projected capability over the duration of the mission have a potential to redefine design margins with inherent safety, reduce subsystem redundancy, increase reliability and decrease maintenance. Moreover, ability of the self-aware vehicle/system to adapt to its changing capability or to its environment or to adapt its mission enables graceful performance degradation.
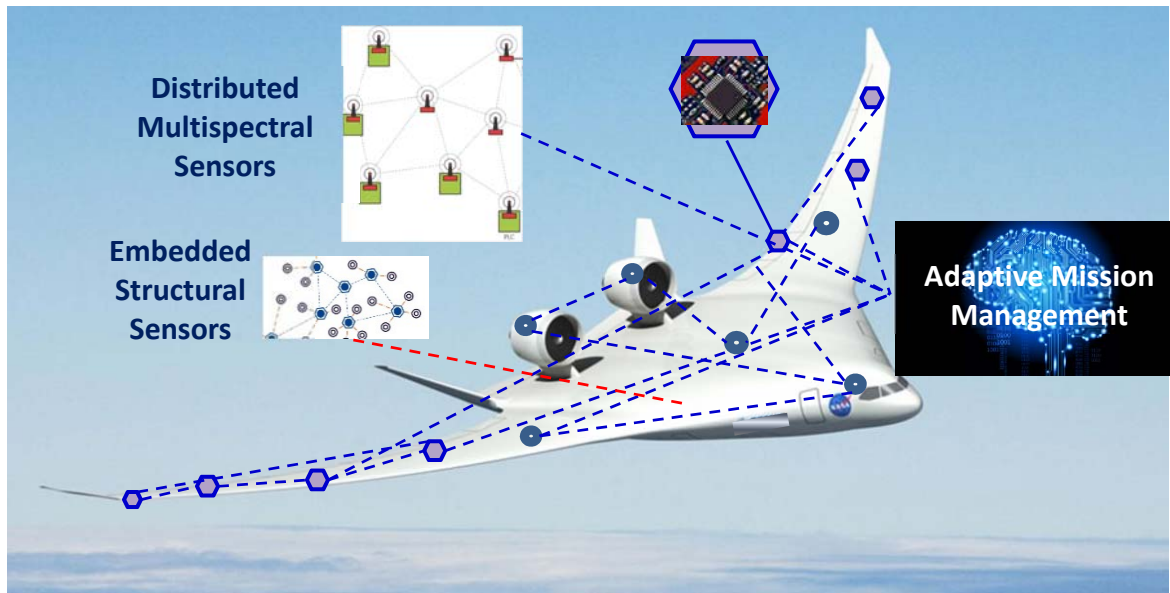
Figure 1. Self-Aware Vehicle/System example – aircraft with distributed networked multi-spectral wireless sensors and decision-making, intelligent adaptive mission management.

III.   Required Technologies

A number of constituent system and subsystem technologies are integrated into a system to enable a self-aware vehicle. Many of these constituent technologies have been developed over a number of years and in a different

context. For example, integrated vehicle health management system (IVHM) related technologies have been under development for well over 30 years with more notable recent instantiations on Boeing 787 and JSF. Similarly, L1 adaptive control has been applied to safety-critical aerospace systems to expand robust performance envelope and mitigate uncertainty and disturbance effects on stability and performance of aircraft and weapon systems[4]. For realization of the full benefits of self-aware vehicle concept, these types of constituent technologies must be further developed and combined into a highly integrated system.

A high-level diagram of major technologies and associated research areas for the self-aware vehicle concept is provided in Figure 2. One key point of emphasis is that *validation and verification* (V&V) for any aspect of self-aware vehicle technology should be done in parallel with the technology development. This parallel approach has two advantages – (a) focus the required fundamental V&V research to remove, or at the very least significantly reduce, the time gap between technology maturation and (b) ability to V&V the developed technology. This should allow for more rapid transition as well as potentially help advance V&V for adaptive, learning autonomous systems embodied by a self-aware vehicle.

The high-level overview of technical areas where either additional or new research is required to enable self-aware vehicles/systems includes:

Adaptive Mission Management[5] – This is the "brain" of the self-aware vehicle whose function includes such items as
- integrate internal vehicle/system state information with external situational awareness
- assess current and predict future capability over a variable time horizon and ability to complete current mission
- plan actions and predict actions of other vehicles/systems
- understanding mission objectives communicated at high level (so called commander's intent rather than detailed mission plan)

Decision-making under uncertainty – This is an integral part of adaptive mission management where decisions are made at multiple levels and these decisions include:
- the key aspect is making decisions under uncertainty that is introduced into the system by sensors and environmental disturbances
- predicting and understanding self-capability
- predicting of actions of other vehicles and objects
- certainty, trust and completeness of available information
- predicting, assessing, observing/understanding consequences of own actions
- demonstrate decision transparency to contribute to trust between machines and human and machine

Autonomous guidance, navigation and control (GNC) – Current capabilities need to be extended to incorporate
- operations in a full spectrum of data availability environments from data rich to data deprived (Multimodal autonomous navigation)
- autonomous guidance for safe mission execution building on time-critical coordination of heterogeneous vehicles with guaranteed collision avoidance that brings temporal aspect as a control variable that is lacking in most current methods [6]
- L1 Adaptive control for vehicles as a baseline to provide precise trajectory following and guarantee graceful degradation to performance under failure or unforeseen environmental disturbances

Networked distributed sensors – This includes geographically distributed, potentially wireless, multi-spectral sensors and sensor fusion, information extraction algorithms. These constitute fundamental building blocks for external situational awareness and internal state knowledge.

Vehicle state assessment – Digital Twin and Learn-To-Fly provide structural state and vehicle dynamics, respectively, that help determine vehicle capability and, hence, ability to execute the mission.

Human-machine interaction – The human is part of this system, onboard or off. High-level instruction on mission objectives, i.e. commander's intent, changes current operational paradigm. This is where we exploit the human to make the machine smarter and use the machine to make the human more effective. Furthermore, bi-directional effective communication of intent is one of key aspects of engendering calibrated trust in the system from the human perspective.

Intelligent Propulsion System – Driven by development of high temperature electronics and sensor miniaturization, next generation of Full Authority Digital Engine Controls (FADEC) will take advantage of

real-time component performance data and prognostics health monitoring to extract optimum propulsion performance while providing additional robustness and increased capability. This intelligent subsystem is a key element of the self-aware vehicle.

Validation & Verification, Test & Evaluation – It is well established that current state of the art V&V methods cannot assure that autonomous system will behave as designed under all circumstances. There are a number of different ideas and approaches on how to address this challenge that would be focused on self-aware vehicle/system and be developed in parallel with the technology. Test and evaluation (T&E) is expected to be an integral part of V&V.

Tools for determining autonomy impact on mission effectiveness – This is continuing the systems analysis tradition with focus on autonomy. Tools are required to properly assess impact of autonomy on all aspects of self-aware vehicle/systems to help develop appropriate safe, cost-effective, mission efficient architectures and concepts.

"Big Data" prognostics capability being developed should be utilized to assist in extracting information from large network of distributed multispectral sensors relevant to evaluating future vehicle capability. Self-aware vehicles present a good test case for applicability of algorithms developed for big data analysis to engineering databases (magnitudes differences in data volume).

Vehicle Flight Prediction[7] – This effort has a potential for significant synergies with self-aware vehicles, aircraft in the near-term. The synergies between these two concepts are currently under development.
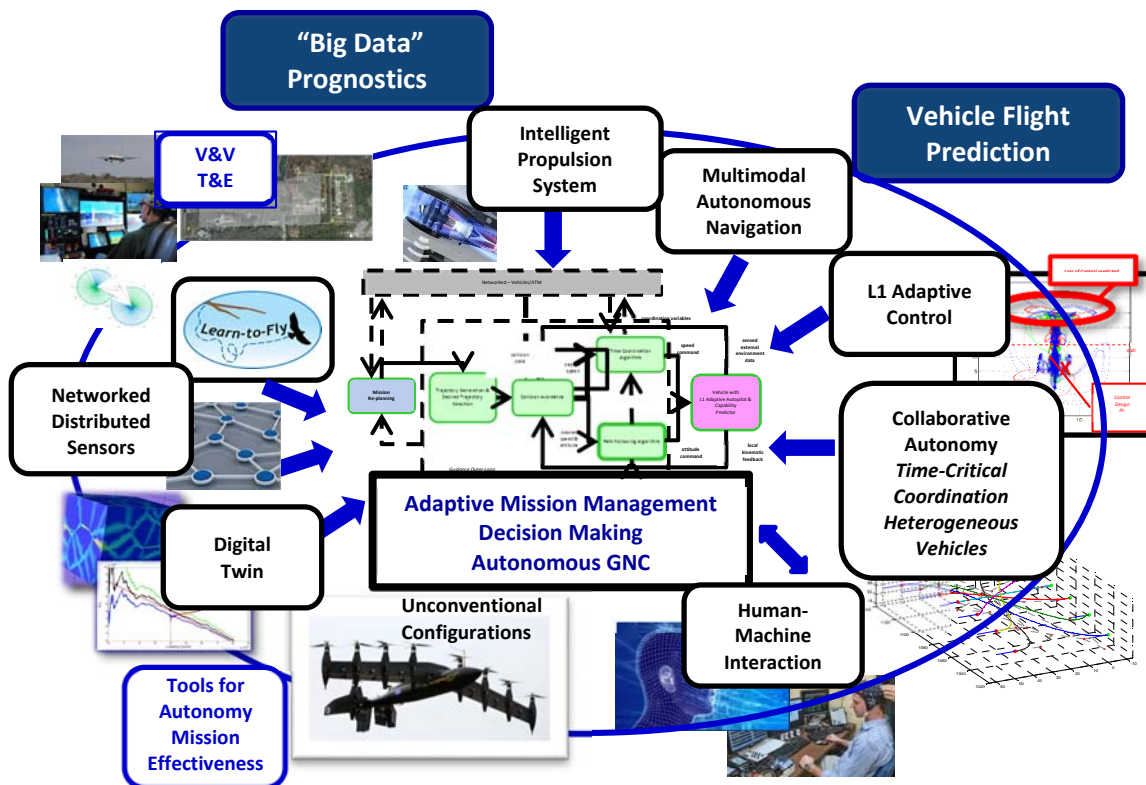
Figure 2 – Major technology areas at Langley for self-aware vehicles. [Boxes outlined in blue are complimentary areas of research].

Self-aware vehicle concept has several immediate applications. In the space domain, self-aware vehicle/system contributes to efforts in smart habitats that would operate for long periods of time, including periods of dormancy, away from low earth orbit. In earth science, it serves as a building block for teams of self-managed vehicles that enable UAV-based payload (sensor of interest) directed flight for atmospheric measurements and exploration. In aeronautics, self-aware vehicle technologies are applicable to all vehicle classes and missions with initial technology

infusion/proving ground into UAVs, innovative vertical lift concepts and performance self-optimization for transport aircraft. Moreover, self-aware capability provides truly autonomous flight including enabling cargo delivery and low-time or no-time pilot operations. In fact, autonomy is the enabling technology for an On-Demand Mobility vision[8]. Lastly, it allows aircraft to interact with cooperative and non-cooperative actors providing safety and increased capacity in the National Airspace System.

The required technologies can be grouped into several highly integrated areas – system health, vehicle dynamic capability and autonomous mission and performance adaptation.

A. System Health:

Internal state awareness requires additional capability to that available under the current state of the art in vehicle health management systems. In particular, self-aware vehicle incorporates Digital Twin concept for autonomous maintenance and real-time safety of structural system. Moreover, over a longer term Digital Twin autonomy constructs flow back to influence design, manufacturing and certification approaches.

The original concept of the Digital Twin was focused on maintenance and life-cycle sustainment[1]. Thus, the Digital Twin integrated ultra-high fidelity simulation with the vehicle's onboard integrated vehicle health management system, maintenance history and all available historical and fleet data to mirror the life of its flying twin and enable unprecedented levels of safety and reliability. The concept has evolved to include real-time health of the structural system. In the next 10 years, there will exist wide-spread vehicle structures sensor networks to monitor critical internal loads, and structural health/damage characteristics in real-time and during ground checks. Individual vehicle informatics will contain vehicle manufacturing, maintenance, and structural health sensor data. In flight, the vehicle will rely on onboard real-time, physics-informed models of structural response and structural margins as a function of actual and forecast flight maneuvers. On the ground, there are complementary high-fidelity, physics-based models to ascertain structural degradation and repair requirements during ground maintenance. In order to be truly effective, techniques to fuse data from all the disparate sources and models and then to extract information for both real-time and off-line structural health diagnosis and prognosis are a required capability.

Over the longer term, these initial capabilities will be extended to autonomous manufacturing. In particular, in-situ Non-Destructive Evaluation sensors will be monitoring the actual fabrication process. Fusion of sensor and model data from simulation of robotic fabrication will provide autonomous, in-process feedback to fabrication robots to ensure each individual vehicle meets a minimum guaranteed set of customer requirements.

There are numerous benefits to maintenance efficiency and sustainability associated with Digital Twin as a stand-alone system. However, there are additional significant benefits when Digital Twin is integrated into the self-aware vehicle concept. Specifically, real-time current and prognosis for the duration of the mission of vehicle structural health assessment provide a key component to assessing the vehicle's dynamic capability. For example, such a system could detect discrete damage and provide feedback to adaptive mission management/control system on what flight constraints would prevent overstressing the structure (e.g., avoid situations such as American Airlines Flight 587 accident). Moreover, each vehicle would have an allowable flight envelope certified to that particular vehicle with quantified reliability and minimum requirements guaranteed.

B. Vehicle Dynamic Capability:

Another major pillar of a self-aware vehicle is assessing and predicting vehicle dynamic capability. A key component for assessing vehicle dynamics is autonomous real-time nonlinear global aerodynamic model development based on flight data alone that has recently been demonstrated under the Learn-To-Fly project[9]. Since a complete 6 degree-of-freedom aerodynamic model is generated in real-time, current dynamic capabilities are known and future mission maneuvers can be simulated to assess vehicle ability to perform them.

In addition to provide more comprehensive assessment and prediction of vehicle's capabilities, the self-aware concept will take advantage of developments under Vehicle Flight Prediction. VFP is seeking to enable certification by analysis which would require, among other things, improved capability to conduct first principle modeling and simulation with quantified uncertainty to enable risk-based decisions. It is this capability that self-aware vehicle will leverage for decision making under adaptive mission management. Integration of structural health management with real-time vehicle dynamics fed into Virtual Flight Predictor provides vehicle capability self-assessment.

C. Autonomous Mission and Performance Adaptation

Self-aware vehicles seek to maximize autonomous capability and utilize a human as a collaborator for high level decision making. Under these circumstances, assuring safety of autonomous vehicles operating in an open environment requires reliable situational awareness (self-awareness/health management), and action planning and prediction of actions of other vehicles and objects. This must be accomplished while considering factors such as certainty and completeness of available information and trust in information sources and other entities. The system must be able to translate mission objectives, communicated at a high level of "commander's intent", into actions and assess the impact of its internal and external state on its ability to execute the mission. If the combination of the internal and external state will not permit the system to achieve its mission objectives, the autonomous control system for the platform must revise the mission plan or otherwise alter the mission execution strategy to remain within current system operational limits.

There have been significant advances at the component technologies, such as perception, planning, decision-making, necessary for autonomy. Also, a number of component technologies for safe operations have been considered and some developed under the NASA Aviation Safety Program[4,10,11]. Integrating these component technologies and applying them to a selected mission as part of the self-aware vehicle development will help assess technological readiness and expose the gaps that require further research.

For example, integrating dynamic flight envelope protection technologies with structural constraints generated by Digital Twin, real-time nonlinear aerodynamic model that generates dynamic flight envelope[11] with L1 adaptive control, utilizing look ahead sensors for proactive gust load alleviation, would allow for data-driven assessment of vehicle capability rather than heuristic rule-based. This in turn would allow for risk-based assessment of whether the vehicle can safely complete its original mission or whether mission or performance adaptation is necessary. The reliability of the prediction and associated confidence would immediately impact viability of replacing/reducing passive structural flutter margins with active control especially under off-nominal flight conditions for example.

IV.   Concluding Remarks

This paper presents a self-aware vehicle concept that integrates a number of component technologies into an onboard system that provides vehicle level internal state and external situational awareness, assessment of current and projected ability to perform a designated mission within specified performance bounds, mission performance optimization through vehicle reconfiguration or, if necessary, mission replanning and execution strategy to remain within current vehicle operational limits. These capabilities enable redefinition of "nominal" operations with potential impact on vehicle design and safety margins.

Self-aware vehicle capable of executing a complex mission in a harsh environment with high level of independence from external systems is a long term vision. Working to achieve this vision is a spiral approach that for a mission class integrates existing technologies with rapidly advancing ones in a systems approach embodied in the self-aware vehicle concept. A flexible system architecture capable of integrating increasingly more sophisticated and complex constituent components and frequent real-world mission application and testing are key to continuing advancement of the self-aware vehicle concept.

Self-aware vehicle is a complex highly integrated system, but if fully realized, it has a potential to revolutionize the way we design, build and operate aircraft of all mission classes.

V.   Acknowledgments

VI.   References:

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