Role of Health Awareness in Systems of Multiple Autonomous Aerospace Vehicles

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Significant investment has been made in the development of off-line systems for monitoring and predicting the condition and capability of aerospace systems. These are most typically used to reduce the operational costs of a system. A recent trend in aerospace is to include these technologies on-line and to utilize the provided information for real-time autonomous or semi-autonomous decision making. While forms of health-based adaptation are used commonly in critical functions, such as redundant flight control systems, as the scope is expanded – for instance to the multiple vehicle level – new challenges and opportunities arise. Recent efforts have explored enhanced health-based adaptation at all levels of a heterogeneous, multi-vehicle system including the sub-system, system, and systems-of-systems layers. The enhanced health-awareness shows the potential to address two needs: i) enhanced safety, overall system performance, and reliability and ii) meeting the expectations of human operators that are inevitably present. In the context taken here, the latter refers to operator situational awareness, over-ride capability, and task or mission definition.

Motivated by the complexity of multi-vehicle systems, one approach to exploring the opportunities is to use a sub-scale indoor flight test facility where real faults are common and manifest in different forms. The facility enables large numbers of flight hours at low cost and supports a wide range of vehicle types and component technologies. The lessons learned and architecture are relevant for a broad range of aerospace systems. The paper begins with a brief review of background related to health awareness in aerospace vehicles and recent research highlights. The key challenges are then discussed followed by a description of the integrated, experiment based approach for exploring the technologies. The paper concludes with a summary of lessons from the approach and future opportunities.

BACKGROUND

Health management broadly refers to the use of measured data and supporting diagnostic and prognostic algorithms to understand the condition and to predict the expected capability of various subsystems and systems. The condition provides insight into the current state and primarily uses diagnostic algorithms while determining the capability requires more sophisticated prognostic algorithms. As a notional example, condition would consist of measuring the voltage of a battery (diagnosis) and assessing its state (fully charged, partially charged, discharged) while capability would estimate the amount of charge or remaining time at a selected load level (prognosis). An even more advanced capability would be estimating the number of remaining charge/discharge cycles. The use of diagnostic algorithms is now common in commercial and military aircraft and form the basis of many maintenance services. Tremendous value is provided through these technologies since they are able to minimize the time aircraft may be out of service for maintenance. These services often make use of extensive measurements suites that are available on existing aircraft and the analysis outputs are typically used for binary decision making: e.g. continue to use or replace. Although in some limited cases the information is down-linked near real-time, generally the analysis is performed off-line at regular intervals. There has also been limited application of on-line diagnostic algorithms in critical applications such as real-time sensor integrity algorithms for redundancy management in multi-channel fly-by-wire flight control systems. The successful applications to date of diagnostic and prognostic algorithms have, however, illustrated the potential for health-based algorithms and decision making.

Broader application of health-based diagnostic and longer viewing prognostic algorithms is an active area of research and offers significant potential for real-time decision making. Recent research has explored how these technologies may be used in real-time to augment the decision making of autonomous systems and systems-of-systems. The research is divided into several categories: i) sensors for providing the raw data for algorithms, ii) diagnostic and prognostic algorithms for mining the data and providing actionable condition and capability information, and iii) algorithms for utilizing the condition and capability data to make decisions. The resulting health-based adaptation can take place in various layers within a large scale system or system-of-systems. These layers range from subsystems such as primary flight control or power management, to systems such as individual vehicles, to systems-of-systems such as multi-vehicle mission management.

CHALLENGES

The research has identified and focused on addressing several key challenges. The first is the system complexity and techniques for addressing it. The large scale systems of interest include subtle interactions between the various sub-systems, systems, prototype algorithms, and the external environment. These interactions can lead to emergent behavior that makes it difficult to understand the contributions of various algorithms to the overall system performance. For instance consider the effect of a new algorithm for ensuring safe separation of aerial vehicles. How does this algorithm perform in the context of a large air traffic network in the presence of faults to various components and communication links? Further, how may these same technology elements be applicable to alternate missions such as search and rescue? Related to this is the development of suitable high level system missions and associated metrics to allow quantifiable evaluation of the performance. The second challenge is to develop a system architecture that provides a framework for guiding and maturing the technology components. Much of the existing algorithm development is performed in isolation and while based on excellent theoretical results may be limited in its consideration of peripheral effects within the complete system. A system architecture is required that allows the various elements to be placed in context to one another for development and evaluation. The third challenge is an evaluation environment that includes sufficient complexity, scope, and flexibility to address the first two challenges. While simulation provides some potential for evaluation, hands-on experiments with real hardware are essential to mature the technologies and address the challenges.

Recent advances in motion capture technology can be combined with continued developments in small scale electronics to enable rapid design and evaluation of flight vehicle concepts [1]. These evaluations can be extended to the mission level with additional vehicles and associated software. Boeing has been collaborating with other researchers since 2006 on the development of an indoor flight test capability for rapid evaluation of multi-vehicle flight control [2, 3, 4]. Several other researchers have also been developing multi-vehicle test environments including several outdoors [5, 6] and indoors [7, 8]. The effort at Boeing has focused on indoor, autonomous flight capability where the burden of enabling flight is placed on the system rather than on the vehicles themselves. This allows novel concepts to be flown quickly and with little or no modification. This also enables rapid expansion to large numbers of vehicles with minimal effort. Boeing has also focused on enhancing the health and situational awareness of the vehicles [4]. The expanded state knowledge of the vehicles now includes information related to power consumption and performance of various aspects of the vehicle. Automated behaviors are implemented to ensure safe, reliable flight with minimal oversight. The dynamics of these behaviors is considered in any mission software and the added information plays a key role in maximizing individual and system performance.

INTEGRATED SYSTEM EXPERIMENTAL ENVIRONMENT

The approach taken to address these challenges involves integrating component technologies into an open architecture with simplified sub-systems and systems that provide sufficient fidelity to explore critical, emergent issues. Simple systems consisting of small, commercially available vehicles are modified to include health awareness. These are combined under a modular architecture in an indoor flight environment which enables frequent integrated experiments under realistic fault conditions. The approach includes sufficient complexity to result in emergent behaviors and interactions between multiple vehicles, subsystems, the environment and operators. The approach avoids the inherent biases of simulation based design and evaluation and it is open to “real-world” unknown unknowns that can influence the overall system dynamics.

Boeing Research & Technology has been developing a facility, the Vehicle Swarm Technology Laboratory (VSTL), to provide an environment for testing a variety of vehicles and technologies in an indoor, controlled, safe environment [3, 4]. This type of facility provides a significant growth in the number of flight test hours available over traditional ranges and reduces the time required to first flight of a concept. The primary components of the VSTL include a position reference system, the vehicles and associated ground computers, and operator interface software. The architecture is very modular, supporting rapid integration of new elements and changes to existing ones. The position reference system consists of a motion capture system that emits coordinated pulses of light. This light is reflected from markers placed on the vehicles within viewing range of the cameras. Through coordinated identification by the multiple cameras, the position and the attitude of the marked vehicles is calculated and broadcast on a common network. The position reference system allows for modular addition and removal of vehicles, short calibration time, and sub-millimeter and sub-degree accuracy. The vehicles operated in the VSTL are modified commercially available remotely-controlled helicopters, aircraft, and ground vehicles whose onboard electronics are replaced with custom electronics. The electronics include a microprocessor loaded with common laboratory software, current sensors, voltage sensors and a common laboratory communication system. These electronics allow communication with the ground control computers and enable additional functionality. The ground computers execute the outer loop control, guidance, and mission management functions. A key component developed as part of the VSTL is enhanced vehicle self-awareness. A number of automated safety and health based behaviors have been implemented to support simple, reliable, safe access to flight testing. Several command and control applications are used to provide an interface between the operator and the vehicles. The level of interaction includes remotely piloted, low-level task control, and high level mission management. The mission management application was used to perform a range of missions to explore the opportunities associated with health-based adaptation and obtain some initial lessons.

LESSONS AND OPPORTUNITIES

To illustrate the flexibility of the architecture and of the indoor facility to test a variety of concepts rapidly, three distinct missions were evaluated. Each mission included a specific metric to quantify the performance. The first mission was non-collaborative and consisted of several vehicles repeatedly performing independent flight plans on conflicting trajectories. The metric was focused on evaluating flight safety and the performance of collision avoidance methodologies. The second mission consisted of an abstracted extended duration coordinated surveillance mission. The mission metric is associated with the level of surveillance provided in the presence of faults. The third mission exercised the full capability of the architecture. It highlighted the ability of the vehicles and architecture to support a diversity of possible tasks. The mission involves assessment of a hazardous area using multi-modal vehicles and tasking. Multiple human operators at different command levels were included. Success was measured as the completion of the various tasks included in the mission and robustness to faults.

The experiments revealed a number of lessons and opportunities for future research. The approach of integrating the various elements into a modular architecture and performing a range of simplified missions was validated. The interactions between the various components exhibited complex behaviors especially in the presence of faults. The peripheral effects of inserting new technologies or algorithms were revealed by the approach. Lower level functions, such as collision avoidance, especially need to be evaluated under a range of missions. The role of operators even in the essentially autonomous missions was also clear. In the case of faults, sufficient situational awareness is needed along with the ability to intervene if needed. While this capability existed, it was interesting that sometimes operators interacted with the system elements from the higher level command interface while at other times lower level interaction was used. These and other lessons indicate the need for several further avenues of research. First, a more formal framework for evaluating technologies and analyzing the experimental results is required. How tools be developed to guide decisions regarding which technologies to insert? What is the risk of disrupting other functions? Second, further research into the interactions between the systems and the human operators is needed. Human operators are inevitably present and as a result play a role in overall mission success. Can their influence also be included in terms of evaluating the overall potential benefit of a proposed technology? Hopefully these and other questions raised in the research can be addressed using the capability and architecture that is in place.

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