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INTELLIGENT AGENT BASED POWER MANAGEMENT FOR UAV SYSTEMS

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Abstract

An intelligent agents based platform is presented which offers an instantaneous, automatic decision-making capability, enabling the execution of complex system level power management and mission planning/re-planning tasks on board a UAV. The agents platform is integrated with a 100 kW, aircraft power systems experimental test facility to demonstrate the response of the entire system to vignette-based mission events which are triggered both by the test hardware, such as electrical drive faults, and emulated events, such as a fuel shortage.

1 Introduction

Increasing levels of complex, dynamic power electronic source/sink systems will be found in future electrical systems for UAVs, due to the uptake of more-electric-aircraft technologies, resulting in platforms becoming critically dependent on their finite power and propulsion resource. Effective, efficient, adaptive power management techniques are therefore required to enable a platform to fulfil the flight objectives. Such flight objectives are becoming more onerous, which is driving a need for a larger degree of autonomy and contingency mechanisms to enable an appropriate response to unplanned events. Adaptive power management techniques will manage uncertainty, caused by changing flight objectives or unplanned events, such as faults, by dynamically allocating power in real-time according to subsystem priority and estimated future needs. Additionally, the power management will offer increased range, availability and survivability of the platform, together with the ability to operate in challenging environments [1] and make instantaneous decisions to events which normally necessitate manual pilot/operator intervention. Power management systems proposed for current UAVs enable subsystems to be operated independently and simultaneously but with an over-provision of power source/sink capability [2].

An intelligent agents' platform has been designed for platform level power/resource management to monitor the entire system and appropriately respond to platform level events. The agents enable the execution of complex system level power management and mission planning/re-planning tasks whilst also offering the instantaneous, automatic decision-making capability to manage unplanned events. The agents platform

has been totally integrated in a 100 kW aircraft electrical system test facility [3] to demonstrate the proof-of-concept by controlling multiple complex power electronic systems during a flight profile. The aircraft electrical system test facility [3] was developed during the Systems for Autonomous Systems Defence Technology Centre (SEAS DTC) Phase 1 programme to enable future advanced electrical networks for UAVs to be examined. SEAS DTC Phase 2 developed an intelligent agents platform, to demonstrate platform level resource/power management to extend the range and autonomy of the platform, which was totally integrated into the test facility for proof-of-concept.

The architecture of the demonstrator system is a three-layer, mixed hardware and software system, as shown in Fig. 1 [4]. The agent platform in Fig. 1 is a multi-agent blackboard architecture, designed to respond to multiple stimuli from mission goals and system level data via the status monitoring and data aggregation (SMDA) block. The SMDA performs several tasks including system-level data exchange, translation of higher-level planned tasks from the agents to low-level rig instructions and UAV health monitoring. The experimental test rig in Fig. 1 is a 100 kW aircraft electrical system demonstrator facility [3] comprising multiple, engine embedded generators, power electronic motor drive loads and supercapacitor based energy storage.

Figure 1. Overall topology of the experimental test facility, UAV platform (SMDA) and intelligent agent platform

In the following sections the experimental test facility, SMDA and agent platform will be described, followed by experimental results to vignette-based mission events.

2 Experimental Test Facility

The Intelligent Electrical Power Networks Evaluation Facility (IEPNEF) at the University of Manchester has been designed to emulate the electrical power network of a more-electric UAV.

IEPNEF, shown in Fig. 2, uses two variable speed drives, controlled by a real-time platform running a gas turbine model,

to emulate the high-pressure (HP) and low-pressure (LP) shafts of the engine. Coupled to the LP shaft drive is a 3,000 rpm, 70 kW five-phase fault-tolerant PM generator, whilst a 30 kW, 15,000 rpm three-phase SR starter-generator is coupled to the HP drive. The phases of the PM generator can be short-circuited and the generators can be physically disconnected from the bus to emulate generator or bus faults, which reduce the total generating capacity.

Figure 2. Experimental test facility diagram

The electrical loads of the aircraft are emulated using 60 kW of resistive load and a pair of 30 kW, bidirectional active loads. The active loads are controlled by a real-time platform, which runs a MATLAB simulation of real-world systems, enabling emulation of equipment such as fuel pumps, actuators and auxiliary power units.

The generators, resistors and active loads are connected together via a power distribution network (PDN), shown in Fig. 2, which allows the bus to be reconfigured and systems to be isolated from the 540 V DC bus.

All of the loads and generators connected to the PDN are commanded by the flight control system (FCS). The FCS is a real-time platform, which contains a generic gas turbine model and controls the activation of the other systems. The resistors, active loads and engine parameters are defined by the status monitoring and data aggregation (SMDA) system based on the agents' mission plan. The loads and engine parameters are therefore dependent on the phase of the mission and action of the agents to external inputs.

3 Status Monitoring and Data Aggregation

A key consideration of the design of an intelligent agents based power management system is to ensure a distributed and inherently scalable architecture to enable future system expansion.

A software application layer, the autonomous agent platform, forms the upper tier in the system. The essential premise is that by successive software abstractions, the hardware layer is presented to the upper application layer as components of a UAV with plausible and realistic power characteristics [5]. To

enable this abstraction, the layers are implemented as a distributed, real-time system that interacts over custom-designed data interfaces that exchange messages over an ethernet network using a combination of UDP and JSON/HTTP protocols. In addition to the UAV's onboard processing, additionally complex and computationally intensive processes can potentially be distributed over-the-air to ground-based, high-performance decision support systems that are capable of supplying finer-grain results on demand [6].

System coordination and integration is carried out by a multi-threaded status monitoring and data aggregation (SMDA) software layer, shown in Fig. 3, that:

- Interprets higher-level mission tasks from the agent platform to low-level platform instructions that can be executed on the test facility
- Continuously analyses and responds to real-time data from the test facility, informing the agent platform if any abnormal event occurs that requires significant modification to the mission plan
- Performs platform management functions of the UAV such as navigation/route-traversal, fuel management, health/condition monitoring and supervisory control

Figure 3. Overview of multi-threaded status monitoring and data aggregation (SMDA) software layer

The SMDA has been designed to replicate the required flight and navigation functions of a UAV platform in terms of simulating real-time flight parameters and route traversal. A mission sequencer is implemented within the SMDA to translate mission tasks – e.g. climb, cruise-out, ingress, attack, egress etc - including speed, altitude and geographical points – into electrical demands that can be understood and executed by the test facility. The agent platform takes high level mission goals and generates a suitable plan. It communicates mission tasks to the SMDA; the SMDA interprets these tasks into low level platform commands by enabling/disabling specific electrical loads that represent various electrical devices typically employed on a UAV such as actuators, landing gear and communications equipment, and also mission-specific devices like radars and jammers.

This design approach inherently provides the necessary framework to monitor, detect and action any anomalies in the system. Demonstration-wise, it also provides the capability to inject simulated 'events' into the system through manipulation

of data. For example, system-level events such as ‘generator failure’ and external events such as ‘fuel shortage’ or ‘incoming threats’ provide the ability to exercise the agents’ decision-making processes to mitigate such unexpected circumstances through task prioritisation and mission re-planning.

The SMDA allows the agents to be allocated supervisory or even full authority to enable or disable any electrical load, as and when required, based on the mission plan. The SMDA is capable of executing agent requests to reconfigure the power distribution system – for example, to reconfigure the load share between the two generators should a fault condition arise.

4 Agents Platform

The IEPNEF planning functionality was implemented in Ruby using the Roke AgentsInRuby framework. Briefly, AgentsInRuby is a framework for implementing systems comprising loosely coupled software components referred to as multi agent systems [7]. AgentsInRuby provides support for agent colony hosting across platforms, agent scheduling and an inter-agent communications protocol. AgentsInRuby employs a URI-based referencing scheme for inter-agent communication, supporting a TCP-based message transport. With this communications scheme, individual agents can be distributed between physical platforms and indeed can be easily relocated between those platforms.

In the IEPNEF agent implementation, the planning agent colony comprised a locator service by which means other agents can get in contact with one another, a timing scheduling service, a blackboard for sharing world model information between agents, and a planning agent.

Extra-colony communications was achieved using JSON representation of the derived task sequences delivered to the Java-based SMDA using the HTTP protocol; thus allowing robust physical separation of the planner and the SMDA. The agent-based platform supports easy extension to incorporate additional subsystem planners as the IEPNEF implementation develops.

The approach taken allowed the SEAS DTC PP015 project [4] to leverage work undertaken in the related PP017 Intelligent Power Management project; this had focused on power-aware route planning for uninhabited ground vehicles and had made use of a number of planning technologies including a task-oriented [8] goal/sub-goal rewriter for mapping mission goals onto subsystem tasks, and an operator-based (STRIPS-like [9]) sub-goal scheduler; together with support for dynamic plan monitoring and constraint-based plan-repair/re-planning. An overview of the mission planning and power management systems is shown in Fig. 4.

The IEPNEF planning agent ensured that the currently active task sequence, generated from its internal plan representation was both feasible and applicable in the light of events occurring within the IEPNEF rig, for example subsystem failures and recoveries. From time to time, the planner would generate a

new detailed task sequence for the SMDA component to evaluate and implement.

Figure 4. Interaction between planning and power management

4.1 Benefits of a multi-agent approach

Taken in isolation, the processes present in the IEPNEF planning functionality are the input of mission goals, real-time acquisition of status from the SMDA, data storage and retrieval, reasoning over data to generate feasible plans and continual plan monitoring to determine if the current plan is still feasible. None of these processes themselves directly mandate a multi-agent solution, however, there are numerous benefits to such an approach including, each agent encapsulating domain knowledge and the agents architecture encouraging modularity and re-use, together with rapid prototyping and reconfiguration.

Two considerations which are particularly germane to power management were encountered during development. Firstly, algorithmic reasoning for power management cannot treat subsystems (such as communications radios, sensors, electronic support) and their components as though they were forever independent of each other, and independent of the prevailing missions or tasks given to the system to perform. This is reasonable since the overall power demands on a system will at some level be treated holistically in the context of the mission. Secondly, time criticality is an important consideration in power planning. Conceptually, we start from a high-level description of a mission to be fulfilled which may contain temporal (and spatial) constraints. In any case, temporal constraints can be derived, such as by considering route traversal times, component duty cycles, and so forth. As plans are expanded and details filled in, the temporal granularity becomes finer. Whereas at the highest level, it is sufficient to say ‘survey point x’, a more detailed plan for achieving this might ultimately consider sensor power demands at the sub-second level. Similarly, when re-planning

occurs, solution updates must be calculable in a short enough time window such that they can be applied in time. In this case, the ability to re-home an agent onto fast dedicated hardware is advantageous.

5 Experimental Results

A single vignette ‘air attack’ combining an extended 55 minute mission profile [10] with five power management events (scenarios) has been developed to demonstrate the ability of the agents platform using a 100 kW experimental test facility. The mission contains both primary tasks (action phases, highest priority), secondary tasks (loiter phases, second highest priority) and multiple background tasks of varying priority levels.

5.1 Loss of Fuel Scenario

A UAV will have a finite payload of fuel, sufficient for the mission, with a small overhead to enable the agents to extend the mission if events determine this to be necessary. As the test facility in Fig. 2 has an emulated gas-engine, the loss of fuel must be a simulated event to enable the intelligent agents to demonstrate their ability to manage a limited resource (fuel in this instance) for optimising mission availability.

Figs. 5 and 6 illustrate a loss of fuel scenario, which is an event triggered by the SMDA. Fig. 5 shows the SMDA interface which is used to reduce the fuel available to a level insufficient for completion of the full mission which results in the SMDA creating a new event. The agents respond by evaluating each segment of the remaining mission ‘mid-flight’, while the test facility is under the control of the agents’ platform, to determine which phases can be truncated or eliminated, and which are high-priority and must be maintained if possible.

Figure 5. SMDA interface showing detection of fuel shortage

Fig. 6.a shows the altitude profile for the 55 minute mission with full fuel available and Fig. 6.b. demonstrates the agents re-planned mission in response to the fuel shortage. The mission re-plan has truncated the secondary task (loiter phase) in Fig. 6.b, highlighted in dashed outline, compared to Fig. 6.a

in order to enable the primary task, the high-priority action phase, highlighted in dotted outline, to be completed.

Figure 6. Altitude profiles highlighting the secondary (dashed outline) and primary tasks (dotted outline)

5.2 Evasive Manoeuvre Scenario

The UAV can be deployed on missions containing multiple objectives. Throughout any mission the UAV must be able to survive unexpected, critical events by having emergency mission planning capability. This agent capability was demonstrated by triggering a ‘threat’ event. The agents have a dual response to this event; firstly, the SR generator on the engine HP shaft is unloaded to maximise engine performance, secondly the mission profile is immediately modified to enable evasive manoeuvres to be undertaken.

Unloading the SR generator enables a better engine response and handling in order to achieve optimum flight performance that is needed to evade the ‘threat’. The system fully unloads the SR generator, while the electrical load is within the available capacity of the PM generator, at which point an increase in load results in the SR generator picking up the excess load.

Modifying the mission profile causes a series of autonomous evasive manoeuvres, including acceleration and steep climbs, to be performed until the threat is over, whereupon the original mission profile goals are resumed.

5.3 Reduced Generation Capacity Scenario

The UAV is highly dependent on electrical systems to enable the mission goals to be successfully completed. As a result, any electrical power shortage must be appropriately handled to potentially prevent the mission objectives being jeopardised.

The agents’ response to a power shortage was tested by short circuiting a phase of the PM generator in the test facility. The event is early in the mission so that a significant portion of the mission must be evaluated by the agents before a response is made to the event. This event results in the available PM generator power output being reduced.

The SMDA is informed by the PM generator control that a phase has been short-circuited, this enables the PM generator to safely continue operating on the remaining four phases. Fig. 7 shows the SMDA screenshot where the power loss is highlighted on the middle right of the figure and the available total electrical power, circled in the centre of Fig. 7, is updated to 85 kW to reflect the loss of power generation.

Figure 7. SMDA interface showing reduction in generation capacity

The SMDA fires the event to the agents' platform which evaluates the remainder of the mission. The first evaluation of the mission seeks to complete the original mission without any re-planning by re-configuring low priority loads during mission phases when the total load power exceeds the power available. The agents perform several iterations to minimise the loads which are re-configured to maximise the mission which can be completed. If a solution cannot be achieved where the high-priority tasks are preserved then the agents will re-plan the mission.

No mission re-planning is required by the agents in this scenario as the power shortage is addressed by briefly re-configuring lower-priority electrical loads to reduce the total peak load during any mission segment where over 85 kW of load was required. This enables the loads associated with the higher-priority tasks to remain online to enable the mission goals to be completed successfully during a scenario which, without the agents, would have resulted in failure of the mission goals.

5.4 Generator Fault Scenario

This test is similar to the previous scenario, however, the power shortage in this scenario is more severe. In this case the SR generator is faulted by being electrically disconnected from the bus, this results in the total generation power being reduced by 30 kW to 70 kW. As in the previous scenario, the event is early in the mission so that a significant period of the mission remains that must be evaluated. The agents' decision in this scenario is that the mission goals are unachievable due to multiple mission tasks, including the high-priority tasks, being

'infeasible', due to the lack of power, and so the UAV is commanded to return to base using a low-power cruise mode.

5.5 Load Fault Scenario

The UAV may be deployed on missions with tasks which are dependent on multiple electrical systems. If any of the electrical systems is offline then the mission must be evaluated to decide whether the mission objectives can still be fulfilled.

The loss of loads is an event triggered by the flight control system in the test facility. Here the 'jammer' load is disabled, as secondary tasks in the mission profile are dependent on this load.

The electrical loads are highlighted in the bottom right of Fig. 8, where blue text represents a load is online, grey text is an offline load, which is available for use, and red text is a faulted load, which is not currently available. The SMDA monitors the status of all electrical loads and detects that the 'jammer' is faulted. In Fig. 8, this results in the 'LSTATUS', highlighted in the centre of Fig. 8 containing a '0' which represents the offline 'jammer' load. The SMDA then performs two tasks in response to the faulted load, first an event is sent to the agents' platform, then the SMDA checks all known mission segments within its mission sequencer, further down the timeline (future outlook), to identify those particular segments that would be affected by the device failure. Once affected segments have been identified, a verification report is sent to the agents by the SMDA and the confirmation window is highlighted mid-left in Fig. 8. The agents then re-evaluate the original mission and issue a re-planned mission in which all secondary tasks have been removed as these cannot be successfully completed without the 'jammer'. The primary tasks of the mission are unchanged as they are independent of the 'jammer'.

Figure 8. SMDA interface showing loss of electrical load

The status of the loads are continuously monitored by the SMDA and so if faulted loads subsequently become available again mid-flight (perhaps a system error has been resolved, e.g. through sub-system reset or re-configuration), another mission re-plan is automatically triggered in the agents platform by the SMDA. The re-plan aims to re-instate the secondary goals in

the remaining mission so that the UAV can complete all remaining tasks given its restored capacity/status.

6 Conclusions

Intelligent agents have been demonstrated controlling a 100 kW laboratory facility to address five electrical and non-electrical power management scenarios that are representative of those expected in more-electric-aircraft or UAV systems. Each scenario results in the agents evaluating the mission with respect to the change in circumstances and making one of four types of decision; allow the mission to continue unchanged; re-configure low-priority loads; re-plan to truncate or remove mission tasks which cannot be successfully completed; request the platform returns to base. In each scenario the agents take appropriate action and command the experimental test facility, enabling the mission to be completed as fully as is possible.

Development of intelligent agents and their system integration inherently requires very close collaboration between diverse engineering functions. Software inter-operability across all levels of the system hierarchy is very important for effective interfacing, re-use and future scalability.

For any integrated UAV product applying agent technologies, there are inherently major inter-dependencies between agent decision-making and task execution, navigational/tactical systems and electrical power/propulsion that require new approaches to platform systems design and integration.

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