Hierarchical Intelligent Attitude Controller for Spacecraft

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Abstract

The need for autonomous, intelligent attitude controller for spacecraft and the benefits of integrating artificial intelligence(AI)/Expert System and automatic control techniques are discussed. A hierarchical intelligent attitude controller which consists of a traditional model-based controller and a supervisory real-time knowledge-based system that provides the 'meta control' to the low-level controller is presented. It has the potential to yield higher levels of performance in terms of attitude accuracy and stability under uncertain environments, tolerate faults and to facilitate autonomous onboard operations. The challenges and considerations in the design of the system are discussed.

INTRODUCTION

As spacecraft are geared to provide many new and sophisticated services, higher levels of performance and new features are demanded from the on-board attitude control system of the spacecraft. Attitude Control System(ACS) is an important subsystem of a spacecraft and its proper functioning is vital for the success of the space mission. The main function of ACS is to orient and maintain the spacecraft and/or its payloads such as cameras, antennae and radiometers in the desired direction, despite disturbance forces acting on the spacecraft.

As traditional attitude control systems may not be able to adequately meet the demanding requirements of modern space missions, new approaches such as intelligent control that integrates artificial intelligence and automatic control techniques are gaining much interest.

An intelligent controller can provide improved performance in terms of attitude accuracy and stability, enhance the robustness of the controller by accommodating significant changes and uncertainties in the plant/subsystem parameters, enable uninterrupted proper functioning of the system despite failures in the system, and provide onboard autonomous operational capabilities. Though Fu[1] in 1971 proposed the idea ofintegrating the concept of artificial intelligence and automatic control and there were several research and developmental efforts[2-5] in the past, only recently with the availability of powerful embedded computers and advances in AI/Expert System techniques and tools, intelligent controls have begun to enter practical applications.

We discuss in this paper the motivation and need for integrating artificial intelligence and automatic control techniques for spacecraft attitude control, and present the framework of the proposed hierarchical intelligent attitude controller. We also highlight some of the challenges and considerations in the design of the system and techniques used by the system.

ATTITUDE CONTROL SYSTEM

Attitude control of spacecraft is the process of orienting and maintaining the spacecraft and/or its application payloads in a desired direction. The satellites axes inclination with respect to a reference is called its attitude, or orientation. As disturbance forces acting on the spacecraft tend to turn the spacecraft away from its nominal orientation, the attitude control system(ACS) counteracts the disturbance forces and maintains the spacecraft at the desired attitude. Attitude control is also required to orient solar panels towards the Sun for maximum power generation and for other purposes.

ACS, the heart of a spacecraft, consists of a controller (onboard computer) and various types of attitude sensors and actuators. The controller processes the attitude information from sensors according to given control strategies and generates control signals for actuators to correct attitude errors, if any. Actuators generate torque, or force, in the desired direction under command from the controller. The resulting spacecraft motion is influenced by the spacecraft dynamics and is measured by attitude sensors. Different types of attitude sensors, such as Earth sensors, gyros, star sensors and Sun sensors, and actuators, such as reaction control system, momentum wheels and reaction wheels are used for spacecraft control.

Proper functioning of the ACS is vital for spacecraft operation and for rendering services such as domestic and international telecommunication and broadcasting, weather forecasting (meteorology), remote sensing and reconnaissance(defense applications).

NEED FOR INTELLIGENT ATTITUDE CONTROL SYSTEM

The motivation for an intelligent attitude control system is driven by the need for:

- Coping with several kinds of uncertainties present in the overall system,
- Higher levels of autonomy, which makes spacecraft operations less dependent on human intervention from ground, and
- Capability to tolerate failures automatically to provide uninterrupted proper functioning and to achieve high degree of mission success.

Coping with uncertainty

Mathematical models and parameters of the components of ACS used for design and validation of the control system may not be accurate enough to reflect inherent nonlinearity and uncertainties in the actual system, resulting in lower levels of in-orbit performance than what has been observed during design verification and validation. Especially in large flexible spacecraft the frequency and the damping of flexible modes, which play crucial role, cannot be accurately predicted or measured on the ground. Further, performance of actuators and sensors may degrade during their over 10 years of continuous operation. Also disturbances from the space environment in which the spacecraft functions are, to some extent, uncertain and change randomly.

Though classical linear control theory provides some robustness, the robustness is functional over a relatively small range of uncertainties. However, ACS operate under large process and disturbance uncertainties and its proper functioning without human intervention is required. High performance required by most space missions under uncertain, unpredictable and randomly varying situations can be achieved through self-modification of control strategy and adjustment of control parameters based on active monitoring of performance of various subsystems and by applying artificial intelligence and expert system techniques.

Autonomy

As the spacecraft designs and missions become complex it is desirable that many of the operations be performed autonomously onboard with minimum human intervention from ground. Also, inherent delays in taking corrective actions from ground after analyzing telemetered data, limited visibility of low-earth orbiting satellites and impossibility of interactive control in deep-space missions (due to long communication delays) further reinforce the need for higher levels of onboard autonomy.

Automation vs Autonomy: Automation can be defined as self-operation of a process or subsystem without outside control under normal, usually repetitive or routine conditions. An automated machine reacts to feedback information and adjusts itself to a given norm. The feedback improves the dynamic characteristics of such machine. Most of the present ACSs are based on the measurement, processing and control of the parameters of interest through feedback of sensory signals. In a way, they are dumb, since they can perform only a predefined limited tasks based upon a prior knowledge of the operating environment. These systems are non-autonomous as they lack the capabilities of reasoning and decision making.

Automation with the added capability of self-governing which includes problem-solving, decision making and self maintenance under variable or abnormal conditions is known as autonomy. There are several levels of autonomy ranging from the simple closed-loop control to maximising mission performance and optimal utilisation of resources.

Autonomous onboard operations improve safety, maximize scientific return and efficiency of onboard instruments by minimizing outages and enable mission operation with less staff on ground by delegating tasks to the onboard system. AI techniques provide the autonomous systems the power of reasoning, planning and scheduling.

Fault Tolerance

Failure of attitude control system could lead to failure of the entire space mission. Onboard diagnosis of failures and timely proper remedial actions in case of failures can significantly improve the mission performance and reliability and enhance the mission success. Though earlier systems had some form of failure detection and safe shutdown operations, the detection was generally based on limit-checking. Knowledge-based approaches to failure diagnosis allow use of more sophisticated and powerful schemes[6].

Autonomous onboard failure diagnosis and management overcomes the problems of the ground-based approach and facilitates appropriate quick actions. This reduces the risk of serious failures, improves mission reliability, provides uninterrupted service, increases dependability of the mission and avoids the need for highly skilled ground control personnel.

Self-Learning

Onboard controllers can be made to *learn* and perform better, improving their performance and correcting their mistakes. *Learning* can be defined as any change in the system that allows it to perform better the second time on repetition of the same or similar task. Machine learning techniques can be used to enhance performance and react to situations that are similar to what the system had experienced earlier.

INTELLIGENT ATTITUDE CONTROLLER

Intelligent control system must infer, make decisions, cope with unexpected situations and uncertainties and optimize mission resources under critical time constraints.

In the intelligent attitude controller, shown in Fig.1, knowledge-based system(KBS) logically resides on the top of a traditional low-level controller. The controller provides the routine low-level closed-loop control, to keep the spacecraft in the desired state despite disturbance forces by generating opposing thrust/torque through the actuators.

The supervisory knowledge-based system reasons about high-level information about the system and provides 'meta-control ' to the low-level controller. It influences the controller only indirectly by supervising the performance of the control system and reconfiguring the controller, sensors and actuators and adjusting the control parameters, as and when necessary.

Knowledge-Based System

Knowledge-based system is a computer program that uses knowledge and inference procedures to solve problems that requires human expertise. It, also known as a expert system, is an unique arrangement of software components that permits knowledge about a specific area (domain) to be used for problem solving and decision making.

Knowledge base, a very important component of the system, contains detailed knowledge required to solve problems in a particular area of application. It is a collection of rules, facts, heuristics, rules of thumb, or other information. More knowledge about an area of application gives the KBS better ability to arrive at quality solutions to problems. The KBS uses different types of knowledge such as experts' knowledge, operators' experience, rules of thumb, designers' expertise, long term control system performance criteria and actual measured data from the process, to influence the control system behaviour.

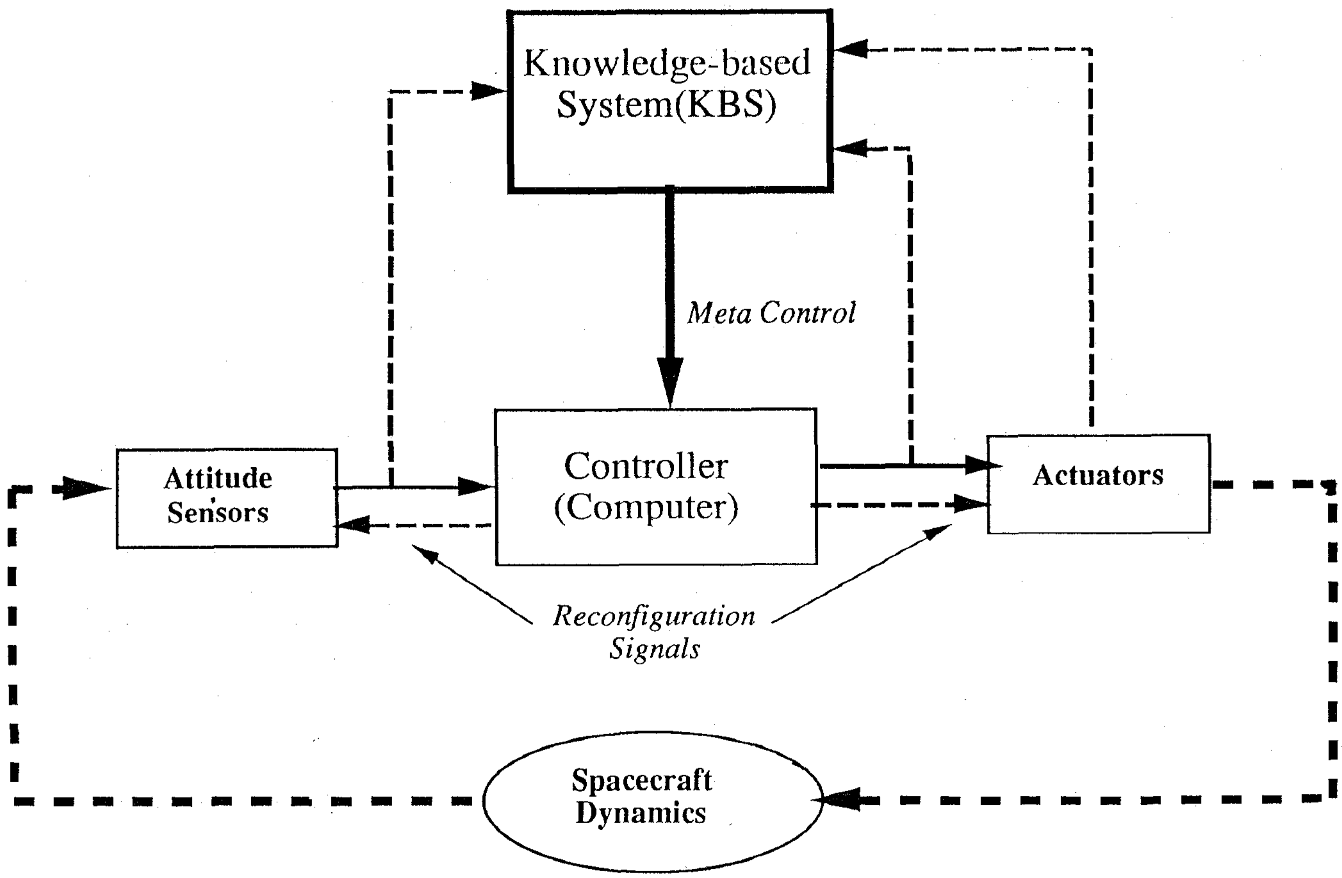

Fig. 1 Intelligent Attitude Controller for Spacecraft

Inference engine is a software that processes the knowledge in the knowledge base to arrive at solution for a given problem. It performs the reasoning function and implements search and pattern-matching operations. It analyses data and information in the knowledge base to arrive at decision or reach a conclusion.

Role of KBS

The KBS monitors and analyses the state of the system as measured by the sensors, evaluates the performance of the sensors, controller and actuators and does the following:

- Automatically arrives at appropriate control strategy (autonomous decision making) and controller gains and fine tunes the controller for improved performance,
- Diagnose and isolate failures, if any, in real-time and reconfigures the controller, sensors and actuators to enable continued operation, and
- Reacts to abnormal and unanticipated situations by making appropriate decisions to cope with the situation by modifying the actions of the controller and other systems.

Also the KBS has heuristics to handle extreme situations and to keep the spacecraft in a safe condition, until human intervention.

All anomalies, recovery attempts and autonomous actions is reported to the ground and the crew. It provides a status report detailing fault type and its location, corrective actions performed, and other pertinent information such as the degree of severity, etc. Autonomous actions, however, can be overrided through ground control, if desired.

The proposed architecture combines the advantages of the model-based control in which well-defined mathematical models of the process being controlled are known and the knowledge-based control which is based on expert-like (heuristic) knowledge, typically encoded in the form of a collection of reasoning rules.

Real-Time Operation

The knowledge-based system(KBS) in the intelligent controller must operate in real-time. It has significant differences compared to expert systems commonly used for medical diagnosis, design, financial analysis/ advice and other similar applications where data is static and time to arrive at a decision is not critical.

The real-time KBSs must have the ability to recognize external events and to respond to them within the prescribed time, which is determined by the criticality of the event. Also, it must have the ability to revise the decisions and conclusions arrived earlier when the previously believed facts are no longer held true. This is known as *nonmonotonic reasoning.* The real-time domains have the following special characteristics, posing a set of complex and challenging problems for design and development of real-time KBS[7,8].

Temporal reasoning: Time is an important variable in monitoring and control, and the KBS needs the ability to reason about the past, present and future (expected or anticipated) events, as well as the sequence in which the events had occurred.

Focus of attention: When a significant event occurs, a real-time system should be able to reprioritize its goals and focus on important goals first. Such systems are also known as *reactive systems.*

Continuous operation: It must be capable of continuous operation over a long time. It calls for efficient recycling of memory elements that are no longer needed (known as *garbage collection*) and archiving of sensor data as far back as they are required.

Dynamic data: Incoming sensor data, as well as facts that are deduced, do not remain static during the problem solving/decision making process. They may decay in validity with time or they may cease to be valid because external events have changed the state of the system.

Asynchronous inputs/interrupts: Real-time systems must be capable of accepting asynchronous inputs and interrupts from external events. Also, they must be capable of interrupting an ongoing decision making process and resuming it after higher priority tasks are processed.

Handling uncertain or missing data: The system must be capable of handling reasonably well uncertain, incomplete, vague or missing information.

Reasoning Strategies

To arrive at the best possible decision within the given time the concept of *progressive reasoning* could be used. In this approach knowledge is divided into several layers with increasing levels of sophistication. Reasoning starts with the bottom layer and the conclusion obtained in this layer is stored and the reasoning process continues in the upper layers. At the expiration of the prescribed time, the conclusion reached from the upper most layer is taken as the best possible decision for execution.

Some of the special techniques and methodologies used in real-time KBS are[5,8] satisfied problem solving to provide guaranteed response, temporal reasoning to consider time-dependent information and nonmonotonic reasoning to account for changing inputs.

CONCLUSION

The increasing complexity of spacecraft and space platforms, the greater sophistication and capabilities of the new missions and the need for more on-board autonomy and higher longevity of the missions(over 10 to 12 years) place several challenging requirements on the attitude control system(ACS) of a spacecraft.

Significant benefits can be gained by using artificial intelligence and expert system concepts for spacecraft attitude control. An intelligent, autonomous attitude control system can provide improved performance under uncertain and unexpected environments through adaptation and self-modification, facilitate higher levels of autonomous operations and tolerance to failures, significantly reducing dependence on ground support, minimize interruption in services rendered by the space missions and enhance the survivability of the mission.

The proposed configuration can be used in several other applications including, power plants, chemical processes, industrial controls and robotics.

Schemes for onboard evaluation of performance of several components of the ACS and for auto-tuning the controller, procedures for failure diagnosis, implementation of real-time KBS within the limited capabilities of space-qualified, embedded computer system and validation of intelligent controller are some of the areas that need further study.

Design and development of an onboard intelligent attitude controller for a spacecraft is a difficult and challenging task. However, considering the advances taking place in the area of onboard computers, KBS tools, failure diagnosis and validation of intelligent systems, it is expected that intelligent, autonomous attitude control system can be flown in the near future.

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