

AUTONOMOUS CONTROL SYSTEMS: ARCHITECTURE AND FUNDAMENTAL ISSUES

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ABSTRACT

Autonomous control systems must perform well under significant uncertainties in the plant and the environment for extended periods of time and they must be able to compensate for system failures without external intervention. Such control systems evolve from conventional control systems and their development requires interdisciplinary research. A hierarchical functional autonomous control architecture is introduced here and its functions are described in detail. The fundamental issues in autonomous control system modelling and analysis are discussed.

1.0 INTRODUCTION

Autonomous control systems must perform well under significant uncertainties in the plant and the environment for extended periods of time and they must be able to compensate for system failures without external intervention. Such *autonomous* behavior is a very desirable characteristic of advanced systems. An autonomous controller provides high level adaptation to changes in the plant and environment. To achieve autonomy the methods used for control system design should utilize both (i) algorithmic-numeric methods, based on the state of the art conventional control, identification, and estimation theory, and (ii) decision making-symbolic methods, such as the ones developed in computer science and specifically in the field of Artificial Intelligence (AI). In addition to supervising and tuning the control algorithms, the autonomous controller must also provide a high degree of tolerance to failures. To ensure system reliability, failures must first be detected, isolated, and identified, and subsequently a new control law must be designed if it is deemed necessary. The autonomous controller must be capable of planning the necessary sequence of control actions to be taken to accomplish a complicated task. It must be able to interface to other systems as well as with the operator, and it may need learning capabilities to enhance its performance while in operation. The development of autonomous controllers requires significant interdisciplinary research effort as it integrates concepts and methods from areas such as Control, Identification, and Estimation Theory, Computer Science, especially Artificial Intelligence, and Operations Research.

In this paper, an autonomous controller architecture is introduced and discussed in detail. For such controllers to become a reality, certain fundamental questions should be studied and resolved first. These fundamental problems are identified, formulated and discussed, and future research directions are outlined.

Autonomous controllers can of course be used in a variety of systems from manufacturing to unmanned space, atmospheric and underwater exploratory vehicles. In this paper, we develop an autonomous controller architecture for future space vehicles. Referring to a particular class of control problems has the advantage that the development addresses relatively well defined control needs rather than abstract requirements. Furthermore, the autonomous control of space vehicles is highly demanding; consequently the developed architecture is general enough to encompass all related autonomy issues. It should be stressed that all the results presented here apply to any autonomous control system. In other classes of applications, the architecture, or parts of it, can be used directly and the same fundamental concepts and characteristics identified here are valid.

Future space vehicles must be capable of autonomous operation to accomplish their missions. Emerging aeromaneuvering vehicles such as the Aeroassisted Orbital Transfer Vehicle and the Aerospace Plane will be required to maneuver at high altitudes and hypersonic velocities in a flight regime characterized by significant uncertainty in atmospheric density and aerodynamic characteristics. Uncertainty in these parameters may cause significant deviation from the nominal trajectory, conceivably leading to the loss of the vehicle. Significant time and communication constraints during the atmospheric flight dictate that the vehicles should perform autonomously for extended periods of time since pilot or ground support intervention may not be possible. Future space systems, such as manned space platforms, contain significant flexible structural components. Model uncertainties and system parameter variations require advanced adaptive control techniques to meet stability and performance specifications. An

autonomous adaptive control system is needed to deal with gross fundamental and environmental changes in the system. For space systems these include hardware failures, docking disturbances, payload articulation, and man-motion disturbances.

In this paper, the architecture of autonomous controllers necessary for the operation of advanced planetary and aeromaneuvering space vehicles is developed. The concepts and methods needed to successfully design such an autonomous controller are introduced and discussed. A hierarchical functional autonomous controller architecture is described in detail; it is designed to ensure the autonomous operation of the control system and it allows interaction with the pilot / ground station and the systems on board the autonomous vehicle.

Section 2 gives a brief history of the development of control systems to motivate the necessity for autonomous controllers. The functions, characteristics, and benefits of autonomous control are outlined. Next it explained that plant complexity and design requirements dictate how sophisticated a controller must be. From this it can be seen that in some cases it is appropriate to use methods from operations research or AI to achieve autonomy. Such methods are studied in *intelligent control theory*. An overview of some relevant research literature in the field of intelligent autonomous control is given.

In Section 3, an autonomous control functional architecture for future space vehicles is introduced. The controller is hierarchical, with three levels, the Execution Level (lowest level), the Coordination Level (middle level), and the Management and Organization Level (highest level). The general characteristics of the overall architecture, including those of the three levels are explained, and an example to illustrate their functions is given.

In Section 4, fundamental issues and attributes of intelligent autonomous system architectures are described. An approach to the quantitative, systematic modelling, analysis, and design of autonomous controllers is discussed. It is a "hybrid" approach since it is proposed to use both conventional analysis techniques based on difference and differential equations, together with new techniques for the analysis of systems described with a symbolic formalism such as finite automata. The more global, macroscopic view of dynamical systems, taken in the development of autonomous controllers, suggests the use of a model with a hybrid or nonuniform structure, which in turn requires the use of a hybrid analysis. It is pointed out that in the process of developing "intelligent" systems one often derives a conventional solution. Finally, some concluding remarks are given in Section 5.

2.0 CONVENTIONAL AND AUTONOMOUS CONTROL SYSTEMS

Autonomous means having the power for self government. *Autonomous controllers* have the power and ability for self governance in the performance of control functions. They are composed of a collection of hardware and software, which can perform the necessary control functions, without external intervention, over extended time periods. To achieve autonomy, the controller must be able to perform a number of functions in addition to the conventional control functions such as tracking and regulation. These additional functions, which include the ability to tolerate failures, are discussed later in this section.

There are several *degrees of autonomy*. A fully autonomous controller should perhaps have the ability to even perform hardware repair, if one of its components fails. Note that 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. The autonomous controller architecture given in the next section provides the functions to attain a high level of autonomy. It can interface with both the crew, ground station and the on-board systems of the space vehicle. A command by the pilot or the ground station is executed by dividing it into appropriate subtasks which are then performed by the controller. The controller can deal with unexpected situations, new control tasks, and failures within limits. To achieve this, high level decision making techniques for reasoning under uncertainty and taking actions must be utilized. These techniques, if used by humans, are attributed to *intelligent* behavior. Hence, one way to achieve autonomy is to utilize high level decision making

techniques, "intelligent" methods, in the autonomous controller. Autonomy is the objective, and "intelligent" controllers are one way to achieve it. The field of Artificial Intelligence [6] and operations research offer some of the tools to add the higher level decision making abilities.

Autonomous controllers are evolutionary and not revolutionary. They evolve from existing controllers in a natural way fueled by actual needs, as it is now discussed.

2.1 Design Methodology - History

Conventional control systems are designed using mathematical models of physical systems. A mathematical model which captures the dynamical behavior of interest is chosen and then control design techniques are applied, aided by CAD packages, to design the mathematical model of an appropriate controller. The controller is then realized via hardware or software and it is used to control the physical system. The procedure may take several iterations. The mathematical model of the system must be "simple enough" so that it can be analyzed with available mathematical techniques, and "accurate enough" to describe the important aspects of the relevant dynamical behavior. It approximates the behavior of a plant in the neighborhood of an operating point.

The first mathematical model to describe plant behavior for control purposes is attributed to J.C. Maxwell who in 1868 used differential equations to explain instability problems encountered with James Watt's flyball governor; the governor was introduced in 1769 to regulate the speed of steam engine vehicles. Control theory made significant strides in the past 120 years, with the use of frequency domain methods and Laplace transforms in the 30's and 40's and the introduction of the state space in the 60's. Optimal control in the 50's and 60's, stochastic, robust and adaptive control methods in the 60's to today, have made it possible to control more accurately significantly more complex dynamical systems than the original flyball governor.

The control methods and the underlying mathematical theory were developed to meet the ever increasing control needs of our technology. The evolution in the control area was fueled by three major needs:

- (i) The need to deal with increasingly complex dynamical systems.
- (ii) The need to accomplish increasingly demanding design requirements.
- (iii) The need to attain these design requirements with less precise advanced knowledge of the plant and its environment, that is, the need to control under increased uncertainty.

The need to achieve the demanding control specifications for increasingly complex dynamical systems has been addressed by using more complex mathematical models such as nonlinear and stochastic, and by developing more sophisticated design algorithms for, say, optimal control. The use of highly complex mathematical models however, can seriously inhibit our ability to develop control algorithms. Fortunately, simpler plant models, for example linear models, can be used in the control design. This is possible because of the feedback used in control. Controllers are designed to meet the specifications around an operating point, where the linear model is valid and then via a scheduler a controller emerges which can accomplish the control objectives over the whole operating range. In autonomous control we are also proposing to increase the operating range of the plant. This will involve the use of decision making processes to generate control actions so that a performance level is maintained even though there are drastic changes in the operating conditions.

There are needs today that cannot be successfully addressed with the existing conventional control theory. They mainly pertain to the area of uncertainty. Heuristic methods may be needed to tune the parameters of an adaptive control law. New control laws to perform novel control functions should be designed while the system is in operation. Learning from past experience and planning control actions may be necessary. Failure detection and identification is needed. These functions have been performed in the past by human operators. To increase the speed of response, to relieve the pilot from mundane tasks, to protect operators from hazards, autonomy is desired. It should be pointed out that several functions proposed in later sections, to be part of the autonomous controller, have been performed in the past by separate systems; examples include fault trees in chemical process control for failure diagnosis and hazard analysis, and control system design via expert systems.

2.2 Functions of an Autonomous Controller

There are certain functions, characteristics, and behaviors that autonomous systems should possess [35,14]. These are outlined below. Some of the important characteristics of autonomous controllers are that they relieve humans from time consuming mundane tasks thus increasing efficiency, enhance reliability since they monitor health of the system, enhance performance, protect the system from internally induced faults, and they have consistent performance in accomplishing complex tasks.

There are autonomy guidelines and goals that should be followed and sought after in the development of an autonomous system. Autonomy should reduce pilot/crew/ground station work load requirements for the performance of routine functions. The gains due to autonomy would be superficial if the maintenance and operation of the autonomous controller taxed the operators. Autonomy should enhance the functional capability of the future space vehicle. Since the autonomous controller will be performing the simpler routine tasks, men will be able to dedicate themselves to even more complex tasks.

There are certain autonomous system architectural characteristics that should be sought after in the design process. The autonomous control architecture should be amenable to evolving future space vehicle needs and updates in the state of the art. The autonomous control architecture should be functionally hierarchical. Highest authority lies nearest the pilot, crew, or ground station; for lower level subsystems to take some actions, they have to clear it with a higher level authority. The system must, however, be able to have the lowest level subsystems, that are monitoring and reconfiguring for failures, act autonomously to enhance system safety.

There are also certain operational characteristics of autonomous controllers. Ground controllers and/or the pilot or crew should have ultimate supervisory override control of future space vehicle autonomy functions. Autonomous activities should be highly visible, "transparent", to the ground controllers and the flight crew to the maximum extent possible.

Finally, there must be certain features inherent in the autonomous system design. Autonomous design features should prevent failures that would jeopardize the overall space vehicle mission goals or safety. These features should enhance crew safety, and avoid false alarms and unnecessary hardware reconfiguration. This implies that the controller should have self-test capability. Autonomous design features should also be tolerant of transient errors, they should not degrade the reliability or operational lifetime of future space vehicle functional elements, they should include adjustable fault detection thresholds, avoid irreversible state changes, and provide protection from erroneous or invalid external commands.

2.3 Intelligent Autonomous Control

The necessity for a succession of increasingly complex control systems from classical to adaptive and intelligent control, to meet the ever increasing performance requirements on the current and future complex dynamical systems, is described. The basic elements of intelligent controllers are highlighted and an outline of the relevant research on intelligent control is given.

2.3.1 Motivation: Sophistication and Complexity in Control

The complexity of a dynamical system model in terms of determinism, nonlinearities, etc., and the increasingly demanding closed loop system performance requirements, necessitate the use of more complex and sophisticated controllers. For example, highly nonlinear systems normally require the use of more complex controllers than low order linear ones when goals beyond stability are to be met. The increase in uncertainty, which corresponds to the decrease in how well the problem is structured or how well the control problem is formulated, and the necessity to allow human intervention in control, also necessitate the use of increasingly sophisticated controllers. Controller complexity and sophistication is then directly proportional to both the complexity of the plant model and the control design requirements.

Based on these ideas, [29,16] suggest a hierarchical ranking of increasing controller sophistication on the path to *intelligent* controls. At the lowest level, deterministic feedback control based on conventional control theory is utilized for simple, linear plants. As plant complexity increases, such controllers will need for instance, state estimators. When process noise is significant, Kalman filters may be needed. Also, if it is required to complete a control task in minimum time or with minimum energy, optimal control techniques are utilized. When there are many quantifiable, stochastic characteristics in the plant,

stochastic control theory is used. If there are significant variations of plant parameters, to the extent that linear robust control theory is inappropriate, adaptive control techniques are employed. For still more complex plants, self-organizing or learning control may be necessary.

At the highest level in their hierarchical ranking, plant complexity is so high, and performance specifications so demanding, that intelligent control techniques are used. The plant is so complex that it is either inappropriate or impossible to describe it with conventional system models such as differential equations. For instance, even though it might be possible to accurately describe some system with very complex nonlinear differential equations, it may be inappropriate if this description makes subsequent analysis too difficult.

The complexity of the plant model necessary for design depends on both the complexity of the physical system and on how demanding the design specifications are. There is a tradeoff between model complexity and our ability to perform analysis on the system via the model. However, if the performance specifications are not too demanding, a more abstract model can be utilized, which will make subsequent analysis simpler. This model intentionally ignores some of the system characteristics, specifically those that need not be considered in attempting to meet the particular performance specifications. Often, to obtain an abstract model, high level symbolic representations are utilized [28]. The choice of the modelling technique affects most aspects of analysis and design of a controller for the system; consequently, special control methodologies must be used with the abstract models. Such methodologies include advanced decision making techniques from the field of AI, which are used to reason over these representations and decide what control actions are appropriate to take. Since the AI techniques generally model the human decision making processes, about what actions to take next, they can easily provide for human interface.

It is perhaps of interest to notice that all controllers in the hierarchy described above can be considered to be a type of *problem solving system*. This is because there is a desirable goal behavior and the problem solver generates actions to change an initial undesirable behavior to the goal. It is our view that problem solving systems can be classified into two categories, conventional and AI. Several characteristics distinguish these two classes of problem solving systems. The conventional problem solving system is numeric-algorithmic, it is somewhat inflexible, it is based on the well developed theory of algorithms or differential equations, and it can thus be studied using a variety of methodical modelling, analysis, and design techniques. Classical control systems are an example of a conventional problem solving system. An AI problem solving system is a symbolic-decision maker, it is flexible with graceful performance degradation, and it is based on formalisms which are not well developed; actually there are very few systematic modelling, analysis, and design techniques for these systems. AI expert and planning systems are examples of AI problem solving systems [6]. When comparing the characteristics of AI and non-AI systems, one can make the following observations: The decision rate in conventional systems is typically higher than that of AI systems. The abstractness and generality of the models used in AI systems is high compared with the fine granularity of models used in conventional systems. Symbolic representations, rather than numeric, are used in AI systems. High level decision making capabilities similar to those of humans exist in AI systems to a much greater extent than in conventional systems. The result is that a higher degree of autonomy exists in AI systems than in conventional ones.

In the hierarchical ranking of increasingly sophisticated controllers described above, the decision to choose more sophisticated control techniques is made by studying the control problem using a controller of a certain complexity belonging to a certain class. When it is determined that the class of controllers being studied (e.g., adaptive controllers) is inadequate to meet the required objectives, a more sophisticated class of controllers (e.g. intelligent controllers) is chosen. That is, if it is found that certain higher level decision making processes are needed for the adaptive controller to meet the performance requirements, then these processes can be incorporated via the study of intelligent control theory. These intelligent autonomous controllers are the next level up in sophistication. They are enhanced adaptive controllers, in the sense that they can adapt to more significant global changes in the vehicle and its environment than conventional adaptive controllers, while meeting more stringent performance requirements.

One switches to more sophisticated controllers only if simpler ones cannot meet the required objectives. Below we list some of the reasons why it is necessary to use intelligent autonomous control for future space vehicles:

- (i) Future space vehicles will be increasingly complex. Some characteristics that are needed in the model used to design their controller can only be described by symbolic representation techniques.
- (ii) Control functions normally performed by the pilot, crew, or ground station must be incorporated into the controller for autonomous operation. Therefore, expert personnel's control decisions will have to be automated.
- (iii) Human intervention in the control process should be allowed. A facility to interrupt the autonomous operation of the controller in case of objective changes or the controller is failing should be included.

The need to use intelligent autonomous control stems from the need for an increased level of autonomy in achieving complex control tasks. The research results in intelligent autonomous control are highlighted in the next section.

2.3.2 Intelligent Autonomous Control: A Literature Overview

The field of intelligent control is new. Some of the recent research efforts have been reported in Proceedings of the 1985 Workshop on Intelligent Control and the Proceedings of the 1987 Symposium on Intelligent Control, and a wealth of useful references can be found there. Research that had a direct influence on our work is outlined below.

Intelligent controllers are hierarchical and the theory of hierarchical systems is relevant [22]. This work sets some of the fundamental concepts in intelligent control such as the need for varying degrees of abstractness in models used at the different levels in the controller. It also presents a theory of coordination for all subsystems of the intelligent controller. Coordination issues are also examined in [8]. The work in [12] extends Mesarovic's work. Fundamentals of intelligent systems such as the principle of increasing intelligence with decreasing precision, granularity, time scale density, model abstractness are discussed in [32], [33], and [23]; the need for the integration of techniques from AI, Operations Research and Conventional Control Theory to perform intelligent control tasks is also discussed there. The integration of AI and control theoretic methods is discussed in [9], [15], and [7].

In [14] the authors explain how a wide variety of AI techniques will be useful in enhancing space station autonomy, capability, safety, etc. This project oriented book points to relevant AI techniques, research areas, and progress in solving the posed problems. In [35] a detailed study of characteristics of autonomous space systems is given and an architecture for the complete autonomous operation of the space station is presented; examples are used to illustrate the behavior of the autonomous system.

There has been much work on developing intelligent controllers for robots. A good overview is given in [31]. The work in [3] describes an initial effort towards a hierarchical intelligent controller based on AI planning methods. Balaram developed an architecture for the planning system that incorporates intelligent control fundamentals and that is accurately structured for his control task. Other intelligent controllers that use planning techniques are given in [18], [17], [4], [10]. The vision problem for intelligent controllers is examined in [11].

The work by Saridis and Valvanis in [30-33], and [36,37] probably represents the most complete mathematical approach to the analysis of intelligent machines. They stress a three level hierarchy for intelligent systems with execution, coordination, and management levels, and the principle of "increasing intelligence with decreasing precision". They use entropy as a unified quantification of disorder in each of the three levels in their intelligent system. In an intelligent controller, they choose the control action that will decrease the entropy in their system.

Other important work in the field of intelligent control is given in [1], [24], [20], [13], [38]; a nested hierarchical controller is described in [39]; some similarities between planning and intelligent control are given in [19]; and an interesting blackboard architecture is studied in [5]. The intelligent restructurable controls problem for aircraft was studied in [25]. The fault detection and identification problem in an intelligent controller was examined in [26,27].

A detailed functional architecture for autonomous controllers is the essential first step in their development. Such an architecture is introduced in the next section. It will show how to combine intelligent functions in a controller to achieve autonomy. Based on this architecture, the fundamental concepts and methods that need to be developed are identified.

3.0 AN AUTONOMOUS CONTROL ARCHITECTURE FOR FUTURE SPACE VEHICLES

In this section, a functional architecture of an autonomous controller for future space vehicles is introduced and discussed. This hierarchical architecture has three levels, the Execution Level, the Coordination Level, and the Management and Organization Level. The functions of each level are described in detail. The architecture exhibits certain characteristics, as discussed below, which have been shown in the literature to be necessary and desirable in autonomous systems. Based on this architecture we identify the important fundamental issues and concepts that are needed for an autonomous control theory.

3.1 Architecture Overview: Structure and Characteristics

The overall functional architecture for an autonomous controller is given by the architectural schematic of Figure 3.1. This is a functional architecture rather than a hardware processing one, therefore it does not specify the arrangement and duties of the hardware used to implement the functions described. Note that the processing architecture also depends on the characteristics of the current processing technology; centralized or distributed processing may be chosen for function implementation depending on available computer technology.

The architecture in Figure 3.1 has three levels. At the lowest level, the Execution Level, there is the interface to the vehicle and its environment via the sensors and actuators. At the highest level, the Management and Organization Level, there is the interface to the pilot and crew, ground station, or onboard systems. The middle level, called the Coordination Level, provides the link between the Execution Level and the Management Level. The sensors and actuators are implemented mainly with hardware. They are the connection between the physical system and the controller. Software and perhaps hardware are used to implement the Execution Level. Software is used for both the Coordination and Management Levels. Note that the multiple copies of the different levels reflect the distinct character of the various control functions necessary to achieve autonomy. For example, there may be one control manager which directs a number of different adaptive control algorithms to control the flexible modes of the vehicle via appropriate sensors and actuators. Another control manager is responsible for the control functions of a robot arm for satellite repair. The control executive issues commands to the managers and coordinates their actions.

Note that the autonomous controller is only one of the autonomous systems on the vehicle. It is responsible for all the functions related to the control of the physical system and allows for continuous online development of the autonomous controller and to provide for various phases of mission operations. The tier structure of the architecture allows us to build on existing advanced control theory. Development progresses, creating each time, higher level adaptation and a new system which can be operated and tested independently. The autonomous controller performs many of the functions currently performed by the pilot, crew, or ground station. The pilot and crew are thus relieved from mundane tasks and some of the ground station functions are brought aboard the vehicle. In this way the vehicle becomes more autonomous.

3.2 Functional Operation

Commands are issued by higher levels to lower levels and response data flows from lower levels upwards. Parameters of subsystems can be altered by systems one level above them 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, e.g., for display. All subsystems provide status and health information to higher levels. Human intervention is allowed even at the control implementation supervisor level (IIb).

The specific functions at each level are described in detail in later sections. Here we present a simple illustrative example to clarify the overall operation of the autonomous controller. Suppose that the pilot desires to repair a satellite. After dialogue with the control executive via the interface, the task is refined to "repair satellite using robot A". This arrived at using the capability assessing, performance monitoring, and planning functions of the control executive. The control executive decides if the repair is possible, under the current performance level of the system, and in view of near term planned functions. The control executive, using its planning capabilities, sends a sequence of subtasks sufficient to achieve the repair to the control manager. This sequence could be to order robot A to: "go to satellite at coordinates xyz", "open repair hatch", "repair". The control

manager, using its planner, divides say the first subtask, "go to satellite at coordinates xyz", into smaller subtasks: "go from start to $x_1y_1z_1$ ", then "maneuver around obstacle", "move to $x_2y_2z_2$ ", ..., "arrive at the repair site and wait". The other subtasks are divided in a similar manner. This information is passed to the control implementation supervisor, which recognizes the task, and uses stored control laws to accomplish the objective. The subtask "go from start to $x_1y_1z_1$ ", can for example, be implemented using stored control algorithms to first, proceed forward 10 meters, to the right 15 degrees, etc. These control algorithms are executed in the controller at the Execution Level utilizing sensor information; the control actions are implemented via the actuators.

It is important at this point to discuss the *dexterity* of the controller. The Execution Level of a highly dexterous controller is very sophisticated and it can accomplish complex control tasks. The implementation supervisor can issue commands to the controller such as "move 15 centimeters to the right", and "grip standard, fixed dimension cylinder", in a dexterous controller, or it can completely dictate each mode of each joint (in a manipulator) "move joint 1 15 degrees", then "move joint 5 3 degrees", etc. in a less dexterous one. The simplicity, and level of abstractness of macro commands in an autonomous controller depends on its dexterity. The more sophisticated the Execution Level is, the simpler are the commands that the control implementation supervisor needs to issue.

3.3 Execution, Coordination, and Management/ Organization Levels

In this section only a few of the details of the functional operation of each of the three levels is given. For a more complete discussion see [2,40].

The functional architecture for the Execution Level of the autonomous controller is shown in Figure 3.2. Its main function is to generate, via the use of numeric algorithms, low level control actions as dictated by the higher levels of the controller, and apply them to the vehicle. It senses the responses of the vehicle and environment, processes it to identify parameters, estimates states, or detects vehicle failures, and passes this information to the higher levels.

The functional architecture for Coordination Level IIb is shown in Figure 3.3. Coordination Level IIb receives commands to perform predetermined specific control tasks from the control manager in the level above. It provides the appropriate sequence of control and identification algorithms to the Execution Level below. Its ability to deal with extensive uncertainties is limited.

The functional architecture for Coordination Level IIa is shown in Figure 3.4. Coordination Level IIa receives commands from the management level which it must determine how to perform using the designer and planner and considering information from FDI IIa and the control implementation supervisor. It generates a sequence of control actions that the control implementation supervisor can recognize and passes them to it. This coordination level has abilities to deal with significant uncertainties.

The functional architecture for the Management and Organization Level (I) is shown in Figure 3.5. It interfaces to the pilot, crew, ground station, and other onboard systems 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.

4.0 FUNDAMENTAL ISSUES

Based on this architecture we identify the important fundamental concepts and characteristics that are needed for an autonomous control theory. There is a successive delegation of duties from the higher to lower levels; consequently the number of distinct tasks increases as we go down the hierarchy. Higher levels are concerned with slower aspects of the system's behavior and with its larger portions, or broader aspects. There is then a smaller contextual horizon at lower levels. Also notice that higher levels are concerned longer time horizons than lower levels.

Due to the fact that there is the need for high level decision making abilities at the higher levels in the hierarchy, there is increasing intelligence as one moves from the lower to the higher levels. This is reflected in the use of fewer conventional numeric-algorithmic methods at higher levels as well as the use of more symbolic-decision making methods. This is the "principle of increasing intelligence with decreasing precision" by [29-33]. The decreasing precision is reflected by a decrease in time scale density, decrease in bandwidth or system rate, and a decrease in the decision

(control action) rate. All these characteristics lead to a decrease in granularity of models used, or equivalently, to an increase in model abstractness. Next we discuss our philosophy for an analytical study of intelligent autonomous systems.

The quantitative, systematic techniques for modelling, analysis, and design of control systems are of central and utmost practical importance in conventional control theory. Similar techniques for intelligent autonomous controllers do not exist. This is of course because of their novelty, but for the most part, it is due to the "hybrid" structure (nonuniform, nonhomogeneous nature) of the dynamical systems under consideration. The systems are hybrid since in order to examine autonomy issues, a more global, macroscopic view of a dynamical system must be taken than in conventional control theory. Modelling techniques for intelligent autonomous systems must be able to support this macroscopic view of the dynamical system, hence it is necessary to represent both numeric and symbolic information (See discussion in Section 2). We need modelling methods that can gather all information necessary for analysis and design. For example, we need to model the dynamical system to be controlled (e.g., a space platform), failures that might occur in the system, the conventional adaptive controller, and the high level decision making processes at the management and organization level of the intelligent autonomous controller (e.g., an AI planning system performing actions that were once the responsibility of the ground station). The nonuniform components of the intelligent controller all take part in the generation of the low level control inputs to the dynamical system, therefore they all must be considered in a complete analysis.

It is our viewpoint that conventional modelling, analysis, and design methods should be used whenever they are applicable. For instance, they should be used at the Execution Level of many autonomous controllers. We propose to augment and enhance existing theories rather than develop a completely new theory for the hybrid systems described above; we wish to build upon existing, well understood and proven conventional methods. The symbolic/numeric interface is a very important issue; consequently it should be included in any analysis. In this way conventional analysis can be used in conjunction with the developed analysis methods to obtain an overall quantitative, systematic analysis paradigm for intelligent autonomous control systems. In short, we propose to use hybrid modelling, analysis, and design techniques for nonuniform systems. This approach is not unlike the approaches used in the study of any complex phenomena by the scientific and engineering communities.

It was pointed out in Section 2 that complex control problems required a controller sophistication that involved the use of AI methodologies. It is interesting to observe the following [21]: Although there are characteristics which separate intelligent from non-intelligent systems, as intelligent systems evolve, the distinction becomes less clear. Systems which were originally considered intelligent evolve to gain more character of what are considered to be non-intelligent, numeric-algorithmic systems. An example is a route planner. Although there are AI route planning systems, as problems like route planning become better understood, more conventional numeric-algorithmic solutions are developed. The AI methods which are used in intelligent systems, help us to understand complex problems so we can organize and synthesize new approaches to problem solving, in addition to being problem solving techniques themselves. AI techniques can be viewed as research vehicles for solving very complex problems. As the problem solution develops, purely algorithmic approaches, which have desirable implementation characteristics, substitute AI techniques and play a greater role in the solution of the problem. It is for this reason that we concentrate on achieving autonomy and not on whether the underlying system can be considered "intelligent".

5.0 CONCLUDING REMARKS

A hierarchical functional autonomous controller architecture was introduced. In particular, the architecture for the control of future space vehicles was described in detail; it was designed to ensure the autonomous operation of the control system and it allowed interaction with the pilot and crew/ground station, and the systems on board the autonomous vehicle. The fundamental issues in autonomous control system modelling and analysis were discussed. It was proposed to utilize a hybrid approach to modelling and analysis of autonomous systems. This will incorporate conventional control methods based on differential equations and new techniques for the analysis of systems described with a symbolic formalism. In this way, the well developed theory of conventional control can be fully utilized. It should be stressed that autonomy is the design requirement and intelligent control

methods appear, at present, to offer some of the necessary tools to achieve autonomy. A conventional approach may evolve and replace some or all of the "intelligent" functions. Note that this paper is based on the results presented in [2].

It was shown that in addition to conventional controllers, the autonomous control system incorporates planning, learning, and FDI. An initial study of the FDI problem incorporating both conventional and AI FDI techniques was reported in [27]. Furthermore, AI planning systems were modelled and analyzed in a Petri Net framework in [28].

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6.0 REFERENCES

- [1] Albus J., et al. "Theory and Practice of Intelligent Control", Proc. 23rd IEEE COMPCON, pp 19-39, 1981.
- [2] Antsaklis P.J., Passino K.M., "Autonomous Control Systems: Architecture and Concepts for Future Space Vehicles", Final Report, Jet Propulsion Laboratory Contract, Oct. 1987.
- [3] Balaram J., "Telerobot Run Time Controller Functional Requirements", JPL Draft Report, Feb. 1986.
- [4] Bhatt R., et al. "A Real Time Pilot for an Autonomous Robot", Proc. IEEE International Symposium on Intelligent Control, pp 135-139, 1987.
- [5] Blank G., "Responsive System Control Using Register Vector Grammar", Proc. IEEE International Symposium on Intelligent Control, pp 461-466, 1987.
- [6] Charniak E., McDermott D. *Introduction to Artificial Intelligence*. Addison Wesley, Reading Mass, 1985.
- [7] Wroscoppe J., Bonnell R., "An Integrated Intelligent Controller Employing Both Conceptual and Procedural Knowledge", Proc. IEEE International Symposium on Intelligent Control, pp 416-422, 1987.
- [8] Cruz J.B., Stubberud A.R., "Knowledge Based Approach to Multiple Control Coordination in Complex Systems", Proc. IEEE International Symposium on Intelligent Control, pp 50-53, 1987.
- [9] DeJong K., "Intelligent Control: Integrating AI and Control Theory", Proc. IEEE Trends and Applications 1983, pp 158-161, Gaithersburg MD, May 1983.
- [10] Dudziak M., et al. "IVC: An Intelligent Vehicle Controller with Real-Time Strategic Replanning", Proc. IEEE International Symposium on Intelligent Control, pp 145-152, 1987.
- [11] Farsaie A., et al. "Intelligent Controllers for an Autonomous System", Proc. IEEE International Symposium on Intelligent Control, pp 154-158, 1987.
- [12] Findeisen W., et al. *Control and Coordination in Hierarchical Systems*. Wiley, New York, 1980.
- [13] Fiorio G., "Integration of Multi-Hierarchy Control Architectures for Complex Systems", Proc. IEEE International Symposium on Intelligent Control, pp 71-79, 1987.
- [14] Firschein O., et al. *Artificial Intelligence for Space Station Automation*. Noyes, New Jersey, 1986.
- [15] Fu K.S., "Learning Control Systems and Intelligent Control Systems: An Intersection of Artificial Intelligence and Automatic Control", IEEE Trans. on Automatic Control, pp 70-72, Feb. 1971.
- [16] Gevarter W.B., *Artificial Intelligence*. Noyes, NJ, 1984.
- [17] Traglia P., Meystel A., "Planning Minimum Time Trajectory in the Traversability Space of a Robot", Proc. IEEE International Symposium on Intelligent Control, pp 82-87, 1987.
- [18] Guha A., Dudziak M., "Knowledge Based Controllers For Autonomous System", Proc. IEEE Workshop on Intelligent Control, pp 134-138, 1985.
- [19] Hawker J., Nagel R., "World Models in Intelligent Control Systems", Proc. IEEE International Symposium on Intelligent Control, pp 482-488, 1987.
- [20] Hodgson J., "Structures for Intelligent Systems", Proc. IEEE International Symposium on Intelligent Control, pp 348-353, 1987.
- [21] Mendel J., Zapalac J., "The Application of Techniques of Artificial Intelligence to Control System Design", in *Advances in Control Systems*. C.T. Leondes, ed., Academic Press, NY, 1968.
- [22] Mesarovic M., Macko D., Takahara Y., *Theory of Hierarchical, Multilevel, Systems*. Academic Press, 1970.
- [23] Meystel A., "Intelligent Control: Issues and Perspectives", Proc. IEEE Workshop on Intelligent Control, pp 1-15, 1985.
- [24] Meystel A., "Planning / Control Architectures For Master Dependent Autonomous Systems with Nonhomogeneous Knowledge Representation", Proc. IEEE International Symposium on Intelligent Control, pp 31-41 1987.
- [25] Passino K.M., "Restructurable Controls and Artificial Intelligence", McDonnell Aircraft Internal Report, IR-0392, April 1986.
- [26] Passino K., Antsaklis P., "Restructurable Controls Study: An Artificial Intelligence Approach to the Fault Detection and Identification Problem", Final Report McDonnell Douglas Contract, Oct. 1986.
- [27] Passino K., Antsaklis P., "Fault Detection and Identification in an Intelligent Restructurable Controller", *Journal of Intelligent and Robotic Systems*, Vol. 1 June 1988.
- [28] Passino K.M., Antsaklis P.J., "Artificial Intelligence Planning Problems in a Petri Net Framework", Proc. of the American Control Conference, June 1988.

[29] Saridis G.N., "Toward the Realization of Intelligent Controls", Proc. of the IEEE, Vol. 67, No. 8, August 1979.

[30] Saridis G., "Intelligent Controls for Advanced Automated Processes", Proc. of the Automated Decision Making and Problem Solving Conf., NASA CP-2180, May 1980.

[31] Saridis G.N., "Intelligent Robot Control", IEEE Trans. on Automatic Control, Vol. AC-28, No. 5, May 1983.

[32] Saridis G.N., "Foundations of the Theory of Intelligent Controls", Proc. IEEE Workshop on Intelligent Control, pp 23-28, 1985.

[33] Saridis G.N., "Knowledge Implementation: Structures of Intelligent Control Systems", Proc. IEEE International Symposium on Intelligent Control, pp 9-17, 1987.

[34] Stephanou H.E., "An Evidential Framework for Intelligent Control", Proc. IEEE Workshop on Intelligent Control, pp 118-123, 1985.

[35] Turner P.R., et al., "Autonomous Systems: Architecture and Implementation", Jet Propulsion Laboratories, Report No. JPL D-1656, August 1984.

[36] Valavanis K.P., *A Mathematical Formulation For The Analytical Design Of Intelligent Machines*, PhD Dissertation, Electrical and Computer Engineering Dept., Rensselaer Polytechnic Institute, Troy NY, Nov. 1986.

[37] Valavanis K.P., Saridis G.N., "Architectural Models For Intelligent Machines", Proc. 25th Conf. on Decision and Control, Athens Greece, Dec. 1986.

[38] Villa A., "Hybrid Knowledge Based / Analytical Control of Uncertain Systems", Proc. IEEE International Symposium on Intelligent Control, pp 59-70, 1987.

[39] Waldon S., et al., "Updating and Organizing World Knowledge for an Autonomous Control System", Proc. IEEE International Symposium on Intelligent Control, pp 423-430, 1987.

[40] Antsaklis P.J., Passino K.M., Wang S.J., "Autonomous Control Systems: Architecture and Fundamental Issues", Dept. of Electrical and Computer Eng. Control Systems Technical Report #57, Feb. 1988.

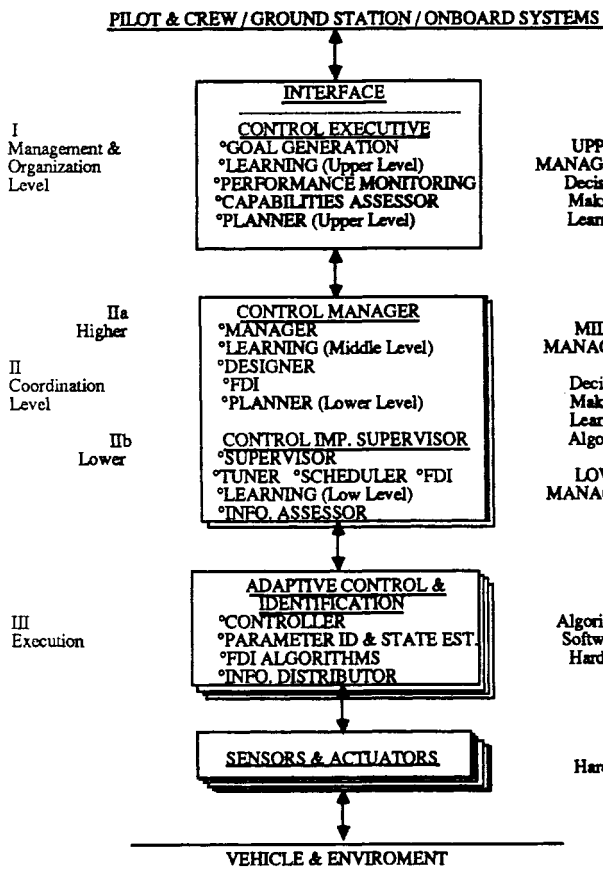


Figure 3.1 Autonomous Controller Architectural Schematic

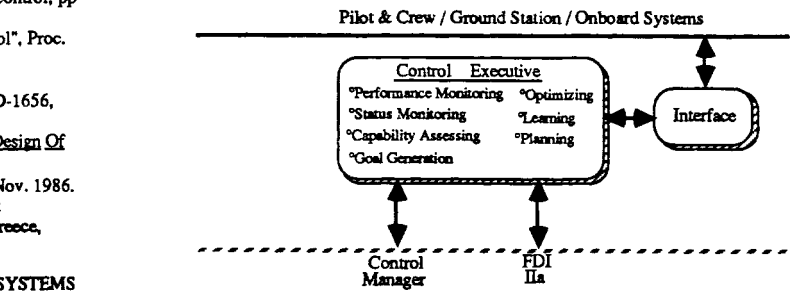


Figure 3.3 Coordination Level IIb

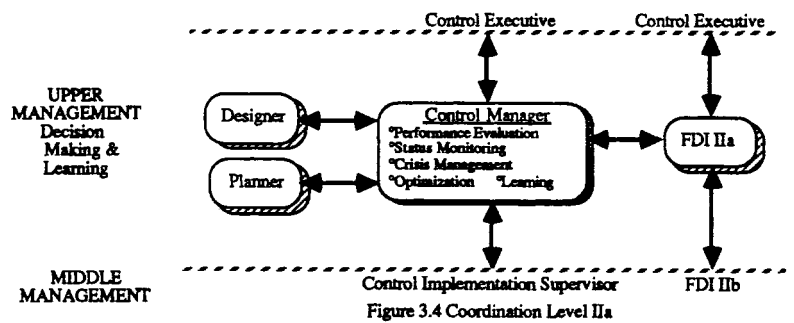


Figure 3.4 Coordination Level IIa

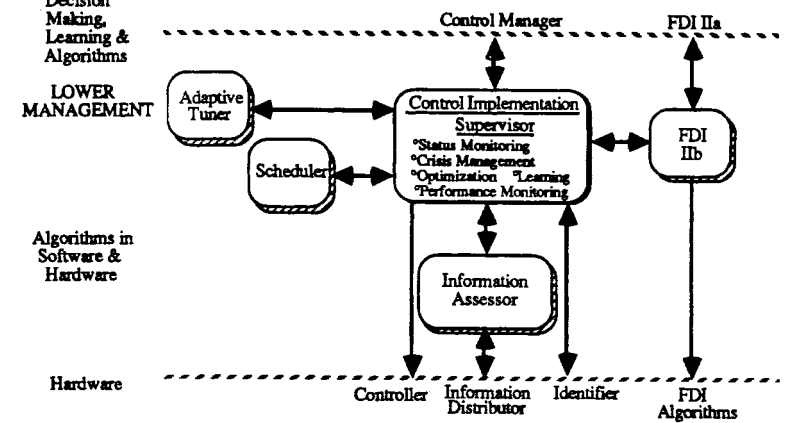


Figure 3.2 Execution Level

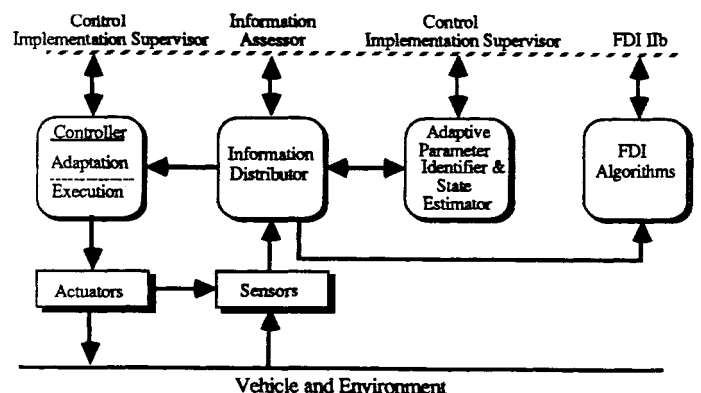


Figure 3.5 Management and Organization Level