

# Achieving Robot Autonomy

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# 1 Definition of Autonomy

The notion of autonomy in robotics is open to interpretation. A paraphrased dictionary definition of autonomy includes the following:

- a) a condition or quality of being self-governing;
- b) self-determination; and
- c) independence.

Since robots are designed to work for humans, they should never, by definition, be completely autonomous. We are led then to the notion of relative autonomy in robotics, where greater autonomy implies lower supervision requirements. Autonomy can then be thought of, and is herein defined as, a measure of supervision.

The field of Supervisory Control can be viewed as a continuum which has fully supervised control at one end (i.e. teleoperated) and fully autonomous control on the other end. The amount of autonomy/supervision can be directly related to the amount of human interaction required for the robot to perform a given task. The amount of interaction can be quantified by the information quantity, in bits, and the information transfer bandwidth, in bits per second, of the messages that must be sent between the operator and the robot.

By making a system more autonomous, we can decrease the amount of work required by humans. The level of autonomy of a system can be measured by the level of supervision required to operate it: given two supervised systems working in environments of equal complexity and performing tasks at the same speed, the system that requires less supervision (which can be measured in bandwidth) is more autonomous than the other. Therefore, by saying that a system is autonomous, we do not mean that it is not controllable by humans, but that it can operate with some known level of capability in the absence of supervision for a defined period of time. It is still over-ridable by humans, and it is also reconfigurable by humans.

## **2 Driving and Opposing Factors**

### **2.1 Reasons for Autonomy**

Two fundamental reasons for making robotic systems more autonomous are:

- to assist humans in managing complexity and
- to achieve critical time responses in a changing environment.

Automation is very desirable for assisting humans in complex applications such as may be encountered in operations planning and management and in health monitoring. However, in these situations the information processing bandwidth required is a function of both the task complexity and the time available to process the data. Therefore, time response is the more fundamental driver for increasing robot autonomy.

### **2.2 Limitations on Direct Manual Control (Teleoperation)**

Given that the issue of autonomy is intimately linked with time response, the level of supervision achievable in a man/machine system can be seen to be limited by the communications system and by the time response capability of the operator. The communication system places constraints on bandwidth, time delay, and availability, thereby establishing an upper bound on the bandwidth with which the operator can interact with the system and on the amount of time available for interaction, and a lower bound on the time delays in communicating between the operator and the remote system. The operator is limited in his/her physical and mental reaction times, which places an upper bound on the amount of supervision that the operator can provide. A supervised robotic system must be designed to operate within the constraints of the communications system and the operator's response time.

Operator response time is relatively slow compared to modern robot mechanisms. Therefore it is reasonable to design a supervised robotic system such that the robot implements low-level, fast responses autonomously, while the operator supplies new setpoints and parameter values at a lower speed. The operator therefore provides "higher-level" commands.

### **2.3 Optimising the Use of a Communications Channel**

We can optimise our usage of a constrained communications channel through the use of communications systems engineering techniques. We can use modulation, data encoding, and error control techniques to achieve more efficient usage of the communications channel. Furthermore, we can design the overall control system such that the information transmission requirements over the communications channel are reduced. In order to reduce the information transmission requirements, we must put more intelligence into the remote system, thereby making it more autonomous.

### **2.4 Required Level of Autonomy**

As the operational capability requirements for a given robot are increased or the communications capability is decreased, the required level of robot autonomy must increase. Consequently our work as engineers is made more difficult. We can examine a specified operational capability of a telerobotic system and attempt to quantify the time response requirements. We can then determine the relationship between the level of autonomy required by the system and the performance of available communications channels.

### **2.5 Factors Determining Time Response Requirements**

The main factors that determine the time response requirements for a supervised robotic system are safety concerns, mission concerns, and the magnitude and probability of disturbances. All of these factors will combine to establish a required time response capability that must be met either through autonomous control or operator supervision. If neither of these control methods can be used to meet the time response requirements, then the requirements must be relaxed.

#### **2.5.1 Safety Concerns**

Safety concerns are primarily due to faults, i.e. their expected criticality or potential of criticality, and to perceived danger to the robot and its environment. Faults may shorten the life of the robot or decrease the capability of the robot. Therefore they must be detected, diagnosed, and dealt with quickly. The same is true of dangerous situations.

### **2.5.2 Mission Concerns**

Robot missions are concerned with obtaining data and/or performing some action on the environment (i.e. on an object). Mission concerns that drive the time response requirements are the importance of obtaining the data and/or performing the action in a timely manner. The following questions must be asked:

- When is the data/action needed?
- When is the data/object available? Will the same data/object be available later?
- How important is the mission, i.e. what is an acceptable cost to obtain the data or perform the action on the object in a timely manner?

As the importance of the mission increases, the probability of failure must be decreased. To decrease the probability of failure, onboard systems must be provided to detect, diagnose, and recover from faults in the absence of operator supervision.

### **2.5.3 Disturbances**

The third factor driving the time response requirement is environmental disturbances. These will vary greatly between application domains. They can include, for example:

- currents and turbulence in air and water;
- equipment shutdown in integrated industrial robot applications;
- surface irregularities in deburring applications;
- unmodelled robot self-dynamics;
- hostile behaviour; and
- equipment faults.

These disturbances should be analyzed as to their time response characteristics and the resulting interaction responses with the robotic system.

## **2.6 Factors Opposing Autonomy**

While time response is the prime driver for autonomy in robotic systems, other factors may oppose it. The main factors opposing autonomy are the various costs involved in developing and installing processing capacity onboard the robotic systems. Also, a lack of faith in the reliability and capabilities of autonomous systems by users unfamiliar with the technology has historically caused the delay of increased automation. Scepticism by observers/users is anticipated in developing embedded systems for higher level cognitive aspects of problem handling in autonomous control.

### **3 Fundamental Communications Bandwidth Requirements**

In a fully supervised (or completely teleoperated) system, the operator must control each movable function or degree of freedom of the robot in real time. The required bandwidths for the control channel (i.e. the communication channel from the operator to the robot) and the data channel (i.e. from the robot to the operator) are described in this section.

#### **3.1 Control Channel Bandwidth**

The required bandwidth of the control channel is equal to the sum of the products of the required tracking frequency response of each degree of freedom of the robot with its required resolution, measured in bits. The tracking frequency response is the ratio of actual robot motion to commanded robot motion as a function of frequency of command changes. (The faster the motion commands change the less the robot will be able to keep up). As we specify more degrees of freedom, greater resolution, and faster operator commands to the robot, the required command channel bandwidth increases.

#### **3.2 Data Channel Bandwidth**

The data channel bandwidth (from the robot to the operator) is determined by two factors: data-gathering tasks and the uncertainty of the robot and the environment.

##### **3.2.1 Data Gathering Tasks**

In data gathering tasks, bandwidths are determined by the quantity of data gathered divided by the amount of time available to send it to the operator. Therefore, as the quantity of data is increased, and the time available to send it is decreased, the required channel bandwidth is increased. The highest bandwidth requirement is in real-time data-gathering, i.e. where data gathered by the robot is required by the operator immediately. The required channel bandwidth is then determined by the quantity of information and the speed in which it is gathered.

##### **3.2.2 Uncertainties**

The uncertainty of the robot and the environment can be quantified by the products of the environmental entropy and frequency content, and by the mutual impedance between the robot and environment. Entropy is a direct measure of uncertainty and is defined in statistics as the negative expected value of the logarithm of the likelihood of the observed system being in a particular state [SCHARF]. The frequency content determines how fast the environment is likely to change. For a given environmental entropy level, the faster the environment is changing, the more difficult it is to make an accurate estimate of its state. The mutual impedances determine how the robot and environment interact and change each other's state.

#### **3.3 Increase Autonomy by Reducing Bandwidth**

Reductions in supervision requirements are quantified by the corresponding reductions in bandwidth requirements of the command and data channels. Therefore, to increase autonomy, we can look at methods of reducing bandwidth requirements.

## 4 Reduction of Command Channel Bandwidth

Reduction of command channel bandwidth can be achieved by decreasing the performance requirements of the task, i.e. degrees of freedom, tracking frequency response, and resolution, or by off-loading the control of some of these parameters to the robot. This thereby allows the operator to specify behaviour at higher levels. For a task of a given complexity, we should therefore look at means of allowing the operator to specify tasks using less degrees of freedom, lower frequency response, and less resolution than the robot would see. In the limit, we should be able to specify a complete mission plan and not send any more commands until the robot has either completed the mission or has requested assistance.

### 4.1 Reducing Task Performance Requirements

The first method of reducing the command channel bandwidth is to reduce the performance requirements of the task. If we can make the task simpler by requiring less resolution, speed, and degrees of freedom, we will significantly reduce the amount of supervision required by the operator. In order to make tasks simple, we must first understand them through a process of testing and verification.

#### 4.1.1 Reducing Degrees of Freedom

In order for the operator to be able to specify a task with fewer degrees of freedom than the robot must utilize in performing it, the robot must be able to use constraints either from its knowledge base or from the environment to control its unspecified degrees of freedom. Some examples of robot knowledge in performing tasks are:

- point the camera at the end of the manipulator;
- maximize the determinant of the manipulator Jacobian matrix;
- slide the endpoint of manipulator along the wall; or
- align the manipulator endpoint with the target.
- mate the robot's tool with the fastener before extracting it.

All of these constraints imply some knowledge or sensing information regarding the robot and/or its environment. Clearly, some onboard intelligence must be added to the manipulator in order to reduce bandwidth in this manner.

#### 4.1.2 Reducing Frequency Content

Similarly, we can allow the operator to specify a task in such a way that the specification has a lower frequency content than what the manipulator will require to perform it. This implies that the manipulator must perform local sensing and must adapt to the environment at the required rate. This requirement is applicable in target tracking, for example. The robot must sense the target and track it as it moves, while the operator gives it higher level commands, e.g. approach the target, grasp the target, move behind the target. Again, robot sensing and knowledge is required.

#### 4.1.3 Reducing Resolution

Resolution command requirements can be reduced by transmitting symbolic commands to the robot. This in turn requires that the robot has a model of itself and the environment, and that it can sense the environment.

## 4.2 High Level Task Specification

If we wish to develop a controller that will allow us to specify missions at a sufficiently high level that the robot can perform without constantly requesting assistance, we must specify the mission in terms of its goals and constraints. In the example of an autonomous submersible, its goals might be to find an object in the water column and to return to its base before its energy is depleted. Its constraints might be the bottom depth and the amount of stored energy. To allow the robot to resolve conflicting goals, e.g. completing the mission vs. returning before the energy is depleted, we must also define their relative importance and the method to be used in resolving them.

### 4.2.1 Resolving Conflicting Goals

Two methods are available for resolving conflicting goals: subsumption and cooperation. Subsumption is where one goal overrides another goal, e.g. the battery is almost depleted so abort the mission. Cooperation is where both goals are valid and a priority weighting scheme is used to combine the activities that result from the conflicting goals. An example is obstacle avoidance, where a robot will combine its desired course with an obstacle avoidance maneuver to go around an obstacle.

#### 4.2.2 Sharing Knowledge

In high level control systems, the operator and the robot must share some "knowledge" of the activities that the robot can perform and of the environment. New commands from the operator to the robot will then consist of :

- addition and deletion of goals;
- modifications to the importance of goals;
- modifications to the method of resolution;
- modifications to constraints; and
- modifications to the world model.

The minimum information necessary to transmit these messages, assuming a noise-free channel, consists of a message type identifier, whose length depends on the number of message types, and parameters to express the new information.

## 5 Reduction of Data Channel Bandwidth

### 5.1 *Need for Real-Time Data Transmission*

As described earlier, robot missions are concerned with obtaining data and/or performing some action on the environment. Data channel bandwidth requirements are generated by the requirement for timely data gathering and by the need for monitoring and verification of the robot's mission. Data channel bandwidth reduction can thus be achieved by:

1. reducing the bandwidth of real-time sensing tasks and
2. reducing the uncertainty in the robot and environment.

### 5.2 *Real-Time Sensing Data*

#### 5.2.1 Requirements for Real-Time Sensing Data

In any robotic system, if an operator needs data from the robot in real time, it is because the robot is:

- not capable of processing the data;
- not capable of performing the required actions on the environment based on the data;
- that the actions required are too complex for the robot to perform autonomously; or
- that the risk of the robot acting on the data is too high to allow autonomous decision-making and action.

Otherwise, it would be sufficient that the robot gather the data, perform appropriate actions, and inform the operator of the results. Bandwidth reduction for real-time sensing tasks can therefore be achieved by adding appropriate data processing capabilities, by adding actuators or effectors to allow the robot to act on the data, by increasing the capability of the robot to perform complex tasks, or by reducing the risk of the robot acting on the data.

#### 5.2.2 Adding Data Processing

Once we add data processing capabilities to the robot, the robot is generally able to transmit information back to the operator at a higher level of abstraction than with raw data. For example, the robot could send the operator the relative location of a recognized object rather than sending a complete video image. This capability thereby reduces the bandwidth of the data to be transmitted.

#### 5.2.3 Adding Actuators

To allow the robot to act on the data, the robot must be supplied with the necessary effectors to act on the environment. The sensor data must be processed to extract the desired information for the robot to make planning decisions, then the robot's effectors guided by the control system to achieve the desired results.

#### 5.2.4 Increasing Robot Capability

Providing sensors and effectors to the robot is not enough to allow it to perform complex tasks. The control system must be able to perform sequences of activities based on the detection of specified external and internal events. It must also have enough intelligence to recognize anomalous circumstances and to decide upon appropriate responses. It must be able to act toward the fulfilment of various goals (e.g. complete mission, preserve health) and to resolve these goals when they conflict.

### 5.3 *Reducing the Risk of Action - Reducing Uncertainty*

The risk entailed in the robot acting autonomously on the data that it gathers can be quantified as the product of some loss function with the uncertainty of the state of the robot and environment. The loss function quantifies the danger of acting (or not acting) on incorrect interpretation of the state of the robot and the environment (e.g. the loss entailed in not noticing a certain event vs. the loss entailed in acting on a false alarm). Risk can therefore be reduced by reducing the uncertainty of the state of the robot and its environment. This uncertainty can be quantified by the products of their entropy and their frequency content and by their mutual impedances. We can therefore reduce uncertainty by reducing entropy, by reducing the frequency content of the robot and its interaction with the environment, or by modifying the impedance of the robot. It is assumed that we cannot affect the frequency content or impedance of the environment.

#### 5.3.1 Reducing Entropy

Likelihood is increased and entropy therefore reduced by adding sensors to observe the states, by increasing sensor quality (accuracy, signal-to-noise ratio) to get better measures of the states, and by using a priori information as to the probabilities of states and state transitions. On the

other hand, entropy is increased through poor reliability. We can therefore decrease entropy by increasing the cost of the system through more and better sensors, through more extensive a priori modelling, and through increased reliability.

### **5.3.2 Reducing Frequency Content**

The frequency content of the robot determines how fast it is likely to change state due to operator commands or its own volition. As designers, we can specify this frequency content. We can lower uncertainty by making the frequency content arbitrarily slow at the cost of increased mission times. This invariably dictates increased energy consumption. It is, however, unreasonable to look at the frequency content of the robot without looking at the frequency content of the environment (which we cannot change) and the mutual impedances of the robot and environment. These two factors determine how fast the robot is likely to change state due to environmental disturbances regardless of the frequency content of the command signals.

The mutual impedances of the robot and environment, usually specified as the robot impedance and the environmental admittance, [HOGAN] determine how they interact. The impedance of the robot with respect to the environment specifies the dynamic response of the robot to environmental disturbances, and vice versa. The robot's impedance, therefore, is a measure of its goal-seeking behaviour in the presence of disturbances. As designers, we can control (to a certain degree) the impedance of the robot. Firstly, we can implement goal-seeking behaviour in a robot through a myriad of techniques - for the example of a submersible robot, we can control its attitude by arranging the centre of mass relative to the centre of buoyancy; we can cause it to hold a certain heading by measuring heading with a compass and by actuating thrusters or control planes as a function of deviations from a heading setpoint. Furthermore, we can enable it to avoid hitting an obstacle by adding an obstacle detection sonar and commanding it to alter its path to go around the obstacle. Through application of control system design techniques, we can alter the frequency response of the robot to environmental disturbances. In general, we can specify how much energy should be consumed to offset the effect of environmental disturbances.

## **5.4 Relation to Data Channel Bandwidth**

In the preceding discussion, the uncertainty of the robot and the environment is linked to the data channel bandwidth in two ways: through the direct bandwidth required for environmental data acquisition purposes and through the process of allowing the robot to take actions that would normally be guided by the operator. The former is driven by the operator's need to know the state of the robot and mission and increases the data channel bandwidth requirement. In the latter, we attempt to decrease the data channel bandwidth by allowing the robot to perform actions autonomously. As the robot is allowed to perform more functions autonomously, the operator's need to know the state of the robot decreases. In either case, we need to reduce the uncertainty of the states of the robot and environment.

As the robot is allowed to perform more functions autonomously, the operator's need to monitor the state of the robot decreases. Since the robot is programmed in terms of goals and constraints, the operator and the robot share some "knowledge" of the activities which the robot can perform and of the environment. The operator and the robot must each have a model of the robot (the operator's model of the robot may simply be his understanding of the description given in the instruction manual) and of the environment. All data channel messages can therefore be generated purely from deviations between sensor readings and the models. For example, the robot can send data to the operator such as "voltage level n 1% low" or "obstacle verified at position x,y,z". In the limit, if no deviations from the models occur, no messages need to be sent to the operator.

## **5.5 Deviations between Modelled and Observed Behaviour**

Deviations from the robot and environmental models can occur due to unmodelled disturbances and due to modelling errors. With a "thoroughly tested" robot, the only unmodelled disturbances in the robot itself will correspond to device failures, which must be handled through redundancy. Unmodelled disturbances in the environment, however, will also manifest themselves in the robot (through the robot's impedance as described previously). Modelling errors can occur in both the robot and the environment.

### **5.5.1 Unmodelled Environmental Disturbances**

Unmodelled environmental disturbances are herein defined as unmodelled motions or forces in the environment. They can consist of random and regular (or predictable) components. If the disturbances include regular behaviour, the robot can theoretically learn these regularities and add them to its environmental model. Once they are incorporated in its model, the robot can replan its actions to achieve its goals in the presence of the disturbances. If the unmodelled disturbances are random, the robot has the option of modifying its impedance to the disturbances, thereby trading off power consumption and sluggish behaviour for reduced response to disturbances.

### 5.5.2 Modelling Errors

Modelling errors in the robot are herein defined as differences between the actual and expected behaviour of the robot with respect to actuator commands. These errors should not occur in a "thoroughly tested" robot, except due to wear or to device failure. Another cause of "apparent" modelling error is due to the behaviour of the robot when in unexpected contact with the environment. In this case, the interaction has modified the robot's behaviour and the error, if any, is due to the modelling of the environment.

Modelling errors in the robot can be managed in two ways - by reducing performance such that the error is outside the performance bounds or by adapting the model to correct the error. The former method is used commonly in control system design - the frequency response of the system is kept below any unmodelled frequencies (e.g. bending modes) in the system. The latter is a subject of adaptive control methods.

Modelling errors in the environment can include omissions as well as inaccuracies. Omissions include regular unmodelled disturbances (motions and forces) as well as unmodelled objects. Both types of modelling errors can be corrected by updating the world model with the new data derived from sensor readings. Both cases may generate the need for replanning.

## 6 Fundamental Requirements of an Autonomous Robot

From our summary of approaches to reduction of supervision, we can draw the following conclusions regarding control systems for autonomous robots :

- a) The robotic system inputs and outputs include:
  - an operator interface; there is a bidirectional communications link between the operator and the robot;
  - sensors as inputs; and
  - actuators as outputs.
- b) The controller will support hierarchical levels of goal-seeking behaviour. It must be able to resolve conflicting goals. Planning functions are required so that the robot can plan how to achieve its goals.
- c) Modelling of the robot and of the environment will be supported. Discrepancies between the model and the (processed) sensor readings will be recognized.
- d) The controller will allow control over the impedance of the robot to environmental factors.
- e) As designers we must understand the tasks that the robot is expected to perform autonomously. We must simulate the tasks with robotic hardware and understand the requirements.

## 7 Conclusion

Autonomy, having been defined as a measure of supervision, can be quantified in terms of communication bandwidth. Several factors drive the need for increased autonomy:

- the reduction of human management.
- the reduction of response time in a changing environment.
- bounds on the communication bandwidth.

Communications channels have two components: the control channel and the data channel. As robotic systems become more complex and we specify more degrees of freedom, greater resolution, and faster operator commands to the robot, the required command channel bandwidth increases. The data channel bandwidth is determined by data gathering requirements and uncertainty in the robots environment.

Reduction in supervision requirements and hence, increase in autonomy, are quantified by the corresponding reduction of the command and data channels. The command channel bandwidth can be reduced by decreasing the performance requirements in the work task and by offloading the high frequency, high resolution, and high degree-of-freedom tasks to the robot. Reduction of the data channel bandwidth may be achieved by adding the appropriate data processing capabilities to the robot, by adding actuators or effectors to allow the robot to act on thee data, by increasing the capability of the robot to handle complexity, and by reducing the risk of the robot acting on the data.

As robots are given more autonomy, they are given more responsibility to interpret their environment and act as desired. Differences in robot and environmental models can occur due to unmodelled disturbances and due to modelling errors.

Several requirements for autonomous robotic control systems were described. These are:

- The robotic system inputs and outputs include: a bidirectional communications link for operator interface; sensors; and actuators.
- The controller must be able to resolve conflicting goals and be able to plan to achieve its goals.
- Robot and environmental modelling must yield any significant discrepancies that exist.
- Impedance control is necessary if the robot is to interact with an uncertain environment.
- Designers must have an understanding of the tasks to be performed autonomously.

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1	2	3	4	5	6	7	8	9

### 2.2.1 Operator Interface

- The operators should be able to supervise the functioning of the robot at any level of the hierarchy
- has the ability to assume various levels of control

### 2.2.2 Inputs/Outputs

- Sensor values are input through various types of interfaces, e.g. binary, analog, serial
- Actuator commands are output through various types of interfaces, e.g. binary, analog, serial
- Control system software does not distinguish between different types of interfaces. These details are left to interface driver software

### 2.2.3 Hierarchical Goal-Seeking Behaviour and Planning

#### Goals, Costs, State Estimation

- Multiple independent goals will be valid at any time. Plans for attaining those goals may interact and conflict.
- Some goals will be valid for all time - others will be valid for the duration of an activity
- Uncertainty of sensor readings must be analyzed in the light of the potential costs of actions based on estimations
- Identify risky actions
- Costs of observations, time taken to generate adequate estimates. The quality of estimates can usually (often ?) be improved with time.
- How to generate costs
  - Types of cost functions
    - time
    - energy
    - accuracy
    - negative income vs. loss (Savage)

#### Planning

- online or offline
- libraries or tables of activities generated offline vs. plans generated online
- Jacobians to determine the potential contribution of various functions toward goals - can result in redundant (simultaneous) actions toward a goal.
- cost functions, evaluation functions (Albus) used in generating sub-plans
- can be generated using all goals (cost functions) to determine optimal plan
- Plan representations - Gantt, Critical Path, Petri, state graphs, finite state automata grammars

### 2.2.4 Modelling

### 2.2.5 Impedance Control

## 2.3 Transition to Autonomy

The previous section described a number of approaches to reduction of supervision requirements in a supervised control system. Reduction of supervision is defined to be equivalent to reduction of channel bandwidths. These approaches are summarized as follows :

Reduction of command channel bandwidth :

- reducing task complexity,
- decreasing performance requirements, or
- specifying behaviour at higher levels of abstraction.

Reduction of data channel bandwidth :

- reducing the bandwidth of real-time sensing tasks
  - adding appropriate data processing capabilities,
  - adding actuators or effectors to allow the robot to act on the data, or
  - reducing the risk of the robot acting on the data.
- reducing the uncertainty in the robot and environment.
  - reducing entropy through more and better sensors, more extensive apriori modelling, and increased reliability,
  - reducing the frequency content of the robot, or
  - modifying the impedance of the robot through structural modifications or through the addition of sensors, actuators, and control algorithms.

As with any new robotic application, the implementation of autonomy in the MSS will be progressive in nature. Certain tasks will become automated before others. Factors which drive this progression are:

«IP0,10» - "Bang for buck" - which features provide the best increase in performance per unit development cost? Performance measures include safety, speed, quality, and cost of operations, and operating costs.

- Strategic considerations  
- Development path - just as it is not generally practical to design and build an autonomous robotic system without first going through a supervisory control phase for debugging, it is unlikely that NASA management will allow large increases in automation of Space Station functions without long "shakeout" periods of supervised operation.

«IP»

- Levels of Autonomy
- desirable to have teleoperation of SPDMs from Earth
- ability to switch between levels

Considerable reluctance can be expected for the use of embedded systems for higher level cognitive aspects of problem handling. To illustrate, terrestrial expert systems for diagnosis will include an Explanation function, so that the operator can check the computer's results against his own judgement. This scenario is not practical here. A compromise solution available to the autonomous system designer is to implement a system that performs fault detection and partial diagnosis autonomously, and then implements a predetermined, conservative response. This may leave the spacecraft partially operable until the data is sent to the ground for processing by ground personnel and computers, analyzed, and a recovery plan is uploaded.

### Robots/Teleoperators

- definition of robots
- action/information at a distance
- hazardous areas
- greater strength
- automation of mundane tasks

Fault detection and response is an obvious area where automation is desirable in order to achieve critical time responses. This is especially true when communications is infrequent and of short duration. In general, automation to assist humans in handling complexity can be a ground-based function, and automation to achieve critical time responses should be space-based.

- The communications delays are considered to be negligible.
- channel noise