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TR67-45
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GENERAL MOTORS CORPORATION

ROVING VEHICLE MOTION CONTROL

SECOND QUARTERLY REPORT
COVERING THE PERIOD
1 JUNE 1967 THROUGH 31 AUGUST 1967

Prepared by
B.P. Miller, T.M. Corry, D.E. Johnson,
R.J. Johnston and J.E. Lingerfelt

Prepared for
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
UNDER JPL CONTRACT NO. 951829

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Lunar & Planetary Programs

AC ELECTRONICS-DEFENSE RESEARCH LABORATORIES

SANTA BARBARA, CALIFORNIA

NOTICE

COPY NO. 24

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ABSTRACT

This report covers the second three months effort on a Roving Vehicle Motion Control Study conducted by AC Electronics - Defense Research Laboratories under a contract with the Jet Propulsion Laboratory of California Institute of Technology.

The report analyzes roving vehicle missions on the moon and Mars from the standpoints that affect motion control, and six baseline missions are evolved. These missions are then analyzed to determine their implications upon system requirements, and general system configurations are developed for each of the six cases.

The major problems of implementation are identified as data accumulation and data appraisal, and various approaches to these problems are discussed. An approach to the comparative evaluation of candidate systems is also described.

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1.0 INTRODUCTION

This report covers work accomplished during the second quarter on a contract with the Jet Propulsion Laboratory to study the problems of Roving Vehicle Motion Control (RVMC) of unmanned extra-terrestrial vehicles. The feasibility of using such vehicles hinges directly upon the availability of techniques for effectively and safely controlling their motion from the earth.

There have been a number of investigations of this problem as it relates to the lunar situation, but none which also considered the very different (and vastly more difficult) problem of control of Martian roving vehicles. The RVMC study has been initiated to consider the general constraints, techniques, methodologies, operational strategies, etc., applicable to both cases and to evolve approaches to the solutions of the RVMC problem.

During the first quarter, foundations were laid by defining the constraints and environmental factors affecting the RVMC problem, reviewing past work in the field, defining the bases for mission characterization and system requirements, and surveying the state-of-the-art in the major technologies involved.

In Section 2 of the present report, the mission elements presented in the previous report are analyzed to evolve a set of six generalized missions – three lunar and three Martian – which form the basis for subsequent effort. These six missions are described, not in terms of scientific or other objectives, but as traverses over various terrains under various modes of operation which differ mainly in the level of space-based automatic control and decision-making which is applied.

A basis for detailed characterization of the system requirements for each of the six missions is described in Section 3 and an example is carried out. The format of this characterization is such that the differences or similarities of any two sub-groups of the six missions can easily be extracted.

The implications of these system requirements upon the configurations of any system designed to meet them are discussed in Section 4, and configuration flow diagrams are developed for each of the six missions. Section 5 deals with the problems of implementation which seem to be most pressing, i.e., data gathering and data assimilation.

In Section 6, the question of how systems might be evaluated and/or compared rationally is taken up. An extensive list of useful measures of value is compiled and a method of combining them to make overall system comparisons is described. Finally, the approach to assigning quantitative values to some of the more important (at this stage) measures is discussed.

2.0 MISSION CHARACTERIZATION

As reported in the first quarterly report, it was decided that it would be preferable to characterize missions in terms of the operational or functional elements which tend to affect the control problem rather than to postulate an arbitrary set of missions. These elements were chosen so that the control problem for any specified roving vehicle mission could be defined in terms of appropriate combinations of the elements. Briefly these functional elements were listed as follows:

- Vehicle Functions

  F1) Safe transfer of a scientific payload to a specified point P

  F2) Orientation in a specified manner with respect to another object and possible physical connection with it.

- Manner of Choosing Destination

  M1) Preprogrammed

  M2) Decided by earth-control during the mission

  M3) Decided by preprogrammed decision processes.

- Manner of Specifying Destination

  C1) In terms of planar coordinates (e. g., range and bearing)

  C2) Range only - bearing unimportant

  C3) Bearing only - range unimportant

  C4) In terms of experimental requirements

  C5) Defined as a point previously occupied.

- Navigation Requirements

  N1) Commensurate with the specification of the destination

  N2) Significantly more stringent than the specification of the destination.

- Routine Control Decisions

  D1) Generated by earth command

  D2) Generated by on-board programs and/or equipment.

The first quarterly report also discussed the question of characterizing terrains in terms of the characteristics affecting the control problem. Three terrain models were postualted, each representing a somewhat different control problem. These may be described briefly as follows:

- <u>Terrains</u>

  T1) Gently rolling, bland, free of sharply defined features but having some hazardous slopes.

  T2) Moderately rough, occasional serious mobility obstacles, some sharply defined features. Safe path readily found.

  T3) Severely rough, frequent serious mobility hazards, continuous threat to safety. Safe path may not exist.

To complete the characterization of the control problem one needs an additional dimension, viz., the body being explored.

- <u>Body</u>

  B1) Moon

  B2) Mars

  B3) Other

If all possible combinations of these characteristics were to be considered independently possible, it is seen that there are 1080 separate cases. Individual consideration of each case would constitute an unmanageably large problem for the present RVMC study. Even a cursory examination, however, shows that not all cases need be considered, since some combinations are illogical and others are uninteresting. The characteristics were therefore analyzed as discussed below to identify combinations of interest and to reduce the list to a manageable subset while retaining the maximum amount of generality possible.

It is unlikely that any system would be of interest if it did not incorporate the capability to transfer the roving vehicle to a specified point (Function F1 above). Therefore, one can assume that whenever a system is required to have capability to orient the roving vehicle in a prescribed manner (F2), it will also have F1 capability. The reverse, unfortunately, is not necessarily true. Translational capability need not always be accompanied by the specialized orientation capability implied in F2.

In many cases, the requirement to orient the roving vehicle in a prescribed manner will entail capabilities not unlike those needed for translation over extremely rough terrain (F1 over terrain T3). In other cases, though, F2 might entail very specialized maneuvers and operations uniquely associated with the particular task at hand. The number of such possibilities seems virtually limitless. It does not seem to be very fruitful to pursue each of these possibilities in this study. Rather, each case should be considered when it arises as a requirement of a specific mission, and appropriate hardware and software added as needed. Thus, for this study Function F2 will not be covered as a separate case. Function F1 will be considered the basic function of the RVMC system, i.e., safe transfer of a payload to a specified point.

Of the three modes of choosing the destination, preprogramming (or M1) is appropriate when considerable detailed data are available prior to launch or when experimental requirements such as a specific geometrical array of destinations is imposed. It might also apply in some cases where previous traverses are to be repeated. In none of these cases does it appear that mode M1 would lead to system configurations which are sufficiently different from both M2 and M3 to warrant consideration of M1 as a separate case. It is true that, in some cases, the considerations which might make M1 appropriate, might also have a significant effect on operational strategy and even on hardware. For example, when repeated traverses are made over the same terrain, information gathered on early traverses might be used to great advantage on subsequent traverses, given the capability to store, analyze, and apply this information. Such possibilities can and should also be included under systems using methods M2 or M3. It appears then that method M1, if unique at all, is unique only in requiring the capability to store and retrieve the data needed to characterize the destination, and so need not be considered further. Therefore M1 will be dropped from further consideration. Systems having M2 and M3 will be considered.

Each of the five means of specifying the destination, C1 through C5, may entail distinct configurational features. To the extent that each is independently important, it should be considered. It was felt however, that systems capable only of achieving a given range (C2) or a given bearing (C3) are not of particular interest even if the corresponding system configurations might somehow be unique. For example, early missions might require the roving vehicle simply to move a given distance from the landing site to acquire an uncontaminated sample and return. There would be a clear desirability however, even on early missions, to have growth potential to handle bearing as well, thereby constraining the range capability to be compatible with the later combined range/bearing (C1) characterization. One can also argue that the kind of capabilities implied in C2 and C3 are available in any system capable of C1 (although it is also true that their combined presence might have some effect upon the manner in which the capabilities are achieved). These considerations lead to the elimination of C2 and C3 from further consideration except as degraded modes of operation under C1.

The specification of the destination in terms of experiment requirements (C4), as with F2, is virtually limitless in its possibilities. Many of these possibilities are subsumed under C1, but others are quite specialized, e.g., seek a high point or a low point, a hot spot or a cold spot, a hard region or a soft region. These specialized cases are not of major interest independently, but only in combination with broader capabilities. Each must be considered individually in the light of its own requirements and appropriate capabilities must be added. Since it is not basic to the roving vehicle control problem, C4 was eliminated from further consideration.

Return to a point previously occupied (C5) may be embodied in C1, but may sometimes require significantly better guidance and navigational capability. It may also make use of techniques and strategies generally not applicable to initial traverses to points. For example, in the case of return to the lander, terminal aids on the lander itself might be considered. In other cases it might require or benefit from the assimilation and use of data gathered on earlier traverses. Because of these unique features of C5 it cannot be dismissed from consideration. It is probably desirable that any system capable of transfer to a point previously occupied also have the capability to transfer to a point not previously occupied. Then C5 occurs only in combination with C1 and it seems appropriate to consider C1 as "standard" and C5 as an "optional extra." Each system will then be considered from the standpoint of providing C1 capability and then the implications of adding C5 capability considered separately.

The breakdown of navigation requirements is couched in terms of the required accuracy relative to that embodied in the description of the destination. Underlying this division was the supposition that one might frequently be content to arrive anywhere in a given area surrounding a point or at any feature having specified properties, but, once having arrived there, might want a rather precise value to locate the point. The real division here is thus not on the basis of navigational accuracy, per se, but on the basis of a priori and a posteriori requirements. Stated in another almost equivalent manner, this is the classical division between guidance and navigation. The former involves path planning and issuance of commands commensurate with the achievement of a specified goal, and the latter involves the determination of present position at some chosen point(s) on the traverse. The two navigational options N1 and N2 are thus seen as not mutually exclusive, but complementary functions, both of which will generally be present, even if in very rudimentary form. Therefore, rather than eliminate either one, we combine them into a single requirement.

The process of making routine control decisions and formulating detailed commands may be done either on earth or on the roving vehicle, as symbolized by D1 and D2. However, the considerations leading to a system having the sophistication to make its own choice of destination (M3) would hardly be consistent with earth-based routine detailed control (D1), except as an override or emergency mode. Since it must always be assumed that earth-based control can override at any time, this is included in D2.

The use of on-board routine control capability (D2) in conjunction with earth-based choice of the destination objectives is not inconsistent and must be retained as a rational and interesting possibility. Therefore, of the four possible combinations of M2 and M3 with D1 and D2 (M1 having been eliminated above), only three are worth further consideration.

It may reasonably be postulated that no system of interest would be limited to a single kind of terrain, even though the three terrains T1 through T3 constitute basically different problems from the control standpoint. The decision was made to impose the condition that all systems must have the dual capability of operating over either T1 or T2, and must be configured to be consistent with either or both. One might further include T3 in this combination, but it seems that this would impose sufficiently different requirements (which under some conditions may not even be feasible to meet) that it should be considered separately. One can reasonably suppose, however, that any system having T3 capability must also have T1 and T2 capability. Therefore, T3 capability will be handled as an "optional extra" and T1/T2 capability as "standard."

JPL ground rules have eliminated bodies to be explored other than the moon and Mars from present consideration. Therefore only B1 and B2 need be considered in any mission characterizations.

On the basis of these considerations, a family tree of functional elements may be derived as in Figure 2-1. The number of basic missions has been reduced to six. Each

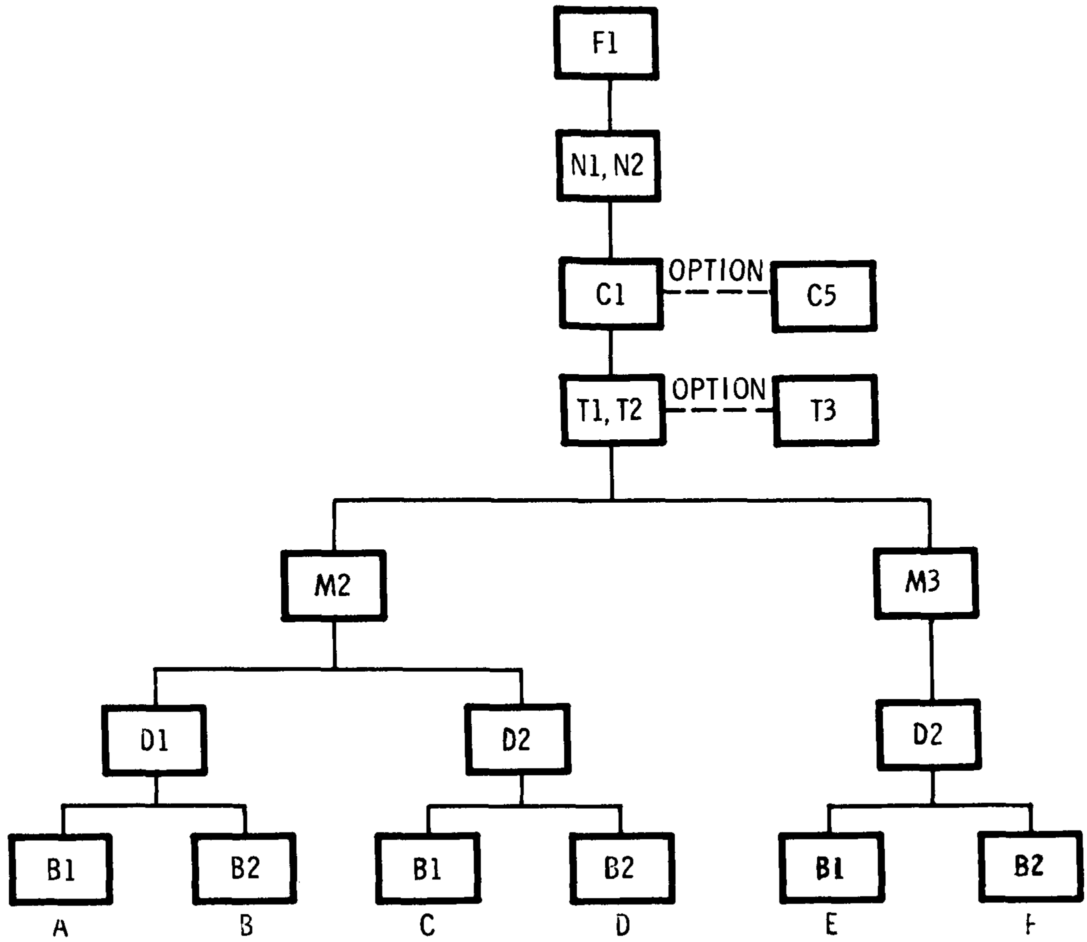


Figure 2-1 Mission Family Tree

of the six must be considered both with and without the "optional extras" which permit capability over terrain T3 and provide capability C5 to return to a point with greater efficiency than that achievable when traversing to a point for the first time.

The resulting six mission characterizations, A through F, are briefly described below. All are considered to be traverses to a prespecified destination over terrain which has some regions which are gentle rolling plains with occasional treacherous slopes and/or soft soil and other regions which are moderately rough and strewn with angular debris of varying sizes up to and sometimes exceeding the safe capability of the vehicle to negotiate, but where a safe path is readily available at all times. All involve the capability to provide guidance and navigation accuracy commensurate with mission scientific objectives.

A. On the moon, traverse to a given point, the location of which is specified by mission control in planar coordinates with a given permissible error. Provide mobility and steering as required to realize the specified accuracy and, from time to time, on command from earth, report present position in suitable coordinates to some specified accuracy. Respond to routine commands originating on earth for both detailed mobility functions and control sensor functions.

B. Same as A, except on Mars.

C. On the moon, traverse to a given point, the location of which is specified by mission control in planar coordinates with a given permissible error. Provide mobility and steering as required to realize the specified accuracy, and from time to time, according to preprogrammed instructions, report present position in suitable coordinates to some specified accuracy. Automatically generate and respond to all routine commands for both detailed mobility functions and control sensor functions. Provide capability for earth override of any on-board program or decision process and for reprogramming on-board logic as desired.

D. Same as C, except on Mars.

E. On the moon, traverse to a given point, the location of which is determined by on-board decision processes and specified in planar coordinates with a given permissible error. Provide automatic path planning and steering functions suitable to realize the specified accuracy, and from time to time, according to preprogrammed instructions, record present position in suitable coordinates to some specified accuracy. Automatically generate and respond to all routine commands for both detailed mobility functions and control sensor functions. Provide capability to store navigational and control sensor data and report out these data either on command or according to preprogrammed instructions. Provide capability for earth override of any on-board program or decision process and for reprogramming on-board logic as desired. Provide capability for complete earth control at possibly degraded performance levels.

F. Same as E, except on Mars.

For each of the above missions, the use of information acquired on previous traverses of the same terrain should be considered both from the standpoint of the manner of using such data and the associated equipment, software, personnel, and procedural requirements. Likewise, the additional requirements imposed by an extremely rough terrain which may in spots be only marginally negotiable or impassable should be enumerated.

The above mission descriptions tend to describe modes of operation as well as missions. There are three levels of control sophistication represented, corresponding to increasing degrees of roving vehicle autonomy. For purposes of identifying these three modes the following terminology has been adopted.

Fly-by-wire. This is the least sophisticated of the three. It requires all control decisions to be made on earth.

Semi-automatic. In this mode, routine start, stop, and steering commands are generated on-board the roving vehicle in accordance with a destination and general path plan formulated on earth.

Fully automatic. Here the destination and path plan are chosen by preprogrammed on-board decision processes. Earth control functions are limited to monitoring and override, and possible reprogramming on the basis of early experience on the mission. This mode also includes possible adaptive and learning capabilities which might be incorporated on the roving vehicle.

Probably no practical system will answer exactly to these descriptions. There will always be some degree of overlap. For example, in the fly-by-wire mode, one would probably always include means for abruptly stopping the roving vehicle whenever it encounters hazards which threaten to permanently incapacitate it. Since transmission and decision times would generally not allow this action to originate on earth, a degree of on-board decision capability must be incorporated. Similarly, it seems likely that either of the more sophisticated modes should incorporate the capability to operate in the more basic modes as a backup, override, or failure capability.

Nevertheless the above characterizations have proven useful in distinguishing between fundamentally different modes of operation and are used in the following discussion with the understanding that they allow a reasonable amount of flexibility commensurate with practical considerations. In the following sections, the implications of these missions or modes are examined from the standpoint of detailed system requirements, and general system configurations are defined for each.

3.0 SYSTEM FUNCTIONAL REQUIREMENTS

3.1 INTRODUCTION

There are several methods by which a requirements analysis may proceed. Each of these methods involves stating the requirements at successively more detailed descriptive levels, starting with a level of almost complete generality and reducing the generality with each succeeding breakdown until a level is attained at which the desired system configurations can be constructed.

Because these configurations do not deal with actual hardware or specific methodologies, the ultimate means of meeting a functional requirement is not prescribed. In this study, detail is supplied by breaking down the system requirements in the following manner.

1. A general statement of RVMC system requirements is made, in terms of the RV and its control agencies. A systems configuration drawing (Figure 3-1) is used to outline the vehicle-control interface.

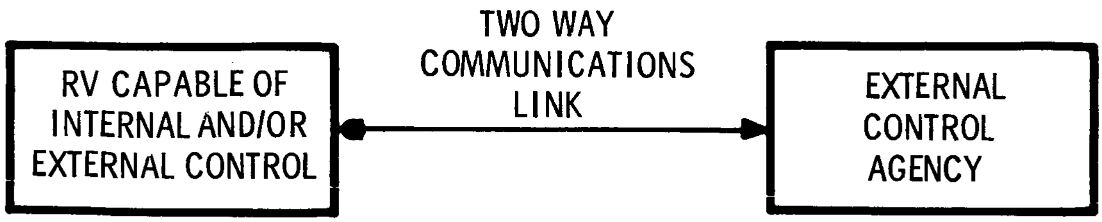


Figure 3-1 Top-Level Configuration of a Controllable Roving Vehicle

2. From this top-level configuration the control function is partialled out and described in gross terms as a series of relationships between paired information processing functions. This represents the first-level breakdown of RVMC system functional requirements; it is shown pictorially in Figure 3-2.
3. Second, third and fourth levels of generality are then derived, in each case by specifying the requirements of the preceding level in greater detail.

The above steps are carried out in Section 3.2, ending with a listing of fourth-level requirements.

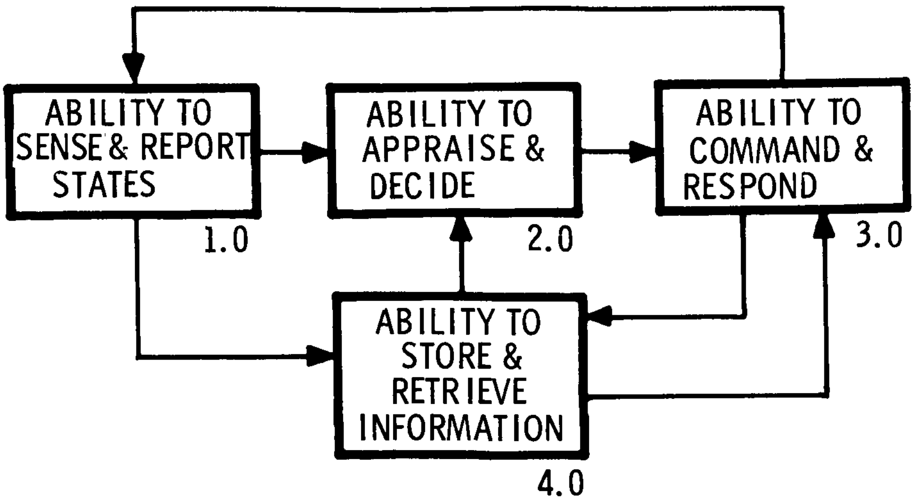


Figure 3-2. Functional Relationships for First-Level Breakdown of RVMC Systems Requirements

The initial statement of the functional requirements for a Roving Vehicle Control system is not made with reference to any specific mission, or class of missions. Since the RV control function is accomplished by processing meaningful information, the requirements imposed by this processing can be stated in functional terms as they apply to a general mission - one, in fact, which involves consideration of all of the mission functional characteristics represented in Figure 2-1.

In order to describe a particular mission or class of missions, assignment of specific mission functional characteristics is made, and the requirements list for the general mission at the fourth level is then screened to determine which of the requirements are applicable to the mission under consideration. Each selected requirement is then examined to determine whether or not the nature of the mission imposes additional constraints upon it.

The Mission-Characteristics Tree given in Figure 2-1 defines six individual missions by assigning an appropriate combination of mission functional characteristics to each mission. It is important to note, however, that any given mission differs from another in a manner more complex than that described by the simple presence or absence of requirements associated with the individual characterizing functions.

These functions interact. For example, a fully automatic RVMC system specifying Mars as the target body has different requirement implications with regard to automaticity than one specifying the moon as the target body. Thus, each mission-applicable requirement must be studied in relation to the mission as a whole.

There is an additional reason why the specific mission requirements should be examined further. When these requirements are used as a basis for the construction of mission functional configurations, differences between missions due to unequal loadings on corresponding communications channels, different choices of primary and secondary modes, different degrees of confidence in the reliability of certain kinds of data, and other differences related to information processing may be masked by the fact that, if a functional relationship exists at all, it must be represented in the configuration.

An effort is made in Section 3.3 to develop a methodology for systematically examining the requirements at the several levels in order to be able to state mission differences with greater specificity than that provided by a simple listing of mission requirements or by general mission configuration drawings, and to illustrate the method by using it to differentiate between a general lunar and a general Martian mission.

In essence, the method consists of classifying the functions in terms of

a. the applicability of the requirement to the mission
b. the site where the process originates
c. the kind of information involved in the process
d. the agency which executes the function
e. the time of execution of the function;

and characterizing each function (or requirement) at an appropriate level accordingly. Identification may then be made of the requirements which have the same description in the requirements breakdown for both missions, but which are characterized differently by the above classification. When this difference, if it exists, is expressed for each common requirement the results allow the individual missions to be described with greater uniqueness than was possible before.

It has been noted that a requirements breakdown is not unique. Various criteria may be used to move from a given level to the next; or the same criterion may be applied at different levels. In the present study it is useful to take the first-level breakdown, where the functions are grouped in four homologous pairs, and to separate these pairs into individual functions before applying the criteria.

Thus, the paired functions, sensing-reporting, appraising-deciding, commanding-responding and storing-retrieving are broken down into the eight individual component functions.

In general, the further along in the breakdown process the criteria are applied, the greater will be the mission differentiation achieved. Therefore the highest available level, usually the fourth, also was used to select common requirements which differed according to the criteria. The list of differences between the general lunar and general Martian missions was then augmented with the resulting characterizations.

3.2 FUNCTIONAL REQUIREMENTS BREAKDOWN

At the most general level, the requirements for a Roving Vehicle Motion Control system may be considered as functional relationships between a roving vehicle and its control agencies. Simply stated, a requirement exists for a Roving Vehicle Control system which will allow the vehicle to be operated safely on extra-terrestrial surfaces by external and/or internal control in such a manner that scientific instrumentation can be moved from one place to another. Figure 3-1 shows this relationship.

Control is essentially an information-processing function. Therefore, a first-level breakdown based upon related information-processing components is derived, as below.

3.2.1 First-Level RVMC Systems Requirements

A requirement exists for a RVMC system which incorporates the ability to process information relating to the vehicle and/or its control agencies in a manner which will allow:

- The sensing and reporting of system states
- The appraising of situations and the making of decisions
- The issuing of system-relevant commands, and the responding thereto
- The storing and retrieving of information.

The first-level functional relationships are shown in Figure 3-2.

A second level of detail may be achieved by specifying categories which further differentiate the functions under each heading. Table 3-1 gives this breakdown.

Table 3-1
SECOND-LEVEL RVMC SYSTEMS REQUIREMENTS BREAKDOWN

The Ability to Sense and Report States 1.0	The Ability to Appraise & Decide 2.0	The Ability to Command & Respond 3.0	The Ability to Store & Retrieve Information 4.0
1.1 RV States 1.2 Terrain States 1.3 Navigation Parameters 1.4 Environmental States	2.1 Regarding System States 2.2 Regarding System Operation 2.3 Regarding Mission Conduct	3.1 Enable and/or Disable Communications System 3.2 Operate Sensors 3.3 Operate Mobility System 3.4 Initiate, Modify, Retain or Abandon Programming	4.1 Sensor Data 4.2 Command Data 4.3 Data-Bank Data

As the development of the systems requirements hierarchy progresses it becomes necessary to define more accurately what is meant by the functions of sensing, reporting, etc. This is done in the following outline, which carries the requirement to a fourth level of proliferation in most cases. Even at this fourth level, the paired groupings have not been broken down into single functions. This is because nothing within one function takes place without a concomitant function existing for its paired associate. That is, nothing will be sensed that cannot be reported; nothing will be stored that cannot be retrieved, etc.

The fourth level gives further definition to the conditions under which the system is expected to operate by interpreting the mission functional characteristics – mission functions, control configurations, terrain types, navigation procedures and other constraints as described in Section 2 – in terms of more specific requirements.

The outline below carries the requirements analyses to the fourth level.

SYSTEMS REQUIREMENTS BREAKDOWN

1. THE ABILITY TO SENSE AND REPORT

   1.1 The system must have the ability to sense and report data allowing the determination of RV states.

1.1.1 RV Attitude

1.1.1.1 Orientation with respect to local gravity.

1.1.1.2 Orientation on azimuth with respect to an acceptable horizontal reference.

1.1.1.3 Orientation of RV with respect to astronomical reference bodies (earth, sun, stars, etc.).

1.1.2 RV Control Variables

1.1.2.1 Steering angle, over a given range and within the limits of allowable error and response latency.

1.1.2.2 Orientation with respect to an acceptable fiducial reference within the limits of allowable error and response latency.

1.1.2.3 RV drive speed, over a given range and within the limits of allowable error and response latency.

1.1.2.4 Braking, in terms of retarding force applied in either continuous or discrete mode.

1.1.2.5 Sensor operating parameters, including on/off, adjust, orient, override, change sense/report mode.

1.1.2.6 Other; component status, etc.

1.1.3 Engineering Parameters

1.1.3.1 RV temperatures over a given range, within the limits of allowable error.

1.1.3.2 RV power levels over a given range and over meaningful time intervals, within the limits of allowable error.

1.1.3.3 RV vibration over given ranges of frequency and intensity within the limits of allowable error.

1.1.3.4 Shock; time and enumeration data over a given range of intensity within the limits of allowable error.

1.1.3.5 Other; component status, etc.

1.2 The system must have the ability to sense and report data allowing the determination of terrain states.

1.2.1 Obstacles

1.2.1.1 Step heights; distance and bearing from RV, within the limits of allowable error.

1.2.1.2 Outcroppings, overhangs, hang-ups, cliffs; distance and bearing from RV, within the limits of allowable error.

1.2.1.3 Fissures; width, distance and bearing from RV, within the limits of allowable error.

1.2.1.4 Craters; width and depth, distance and bearing from RV, within the limits of allowable error.

1.2.2 Slopes

1.2.2.1 Angle of inclination of line of maximum slope.

1.2.2.2 Azimuth of line of maximum slope with respect to a suitable reference.

1.2.3 Unstable Terrain

1.2.3.1 Insecure rocks, potential avalanche sites (distance and bearing).

1.2.3.2 Vulcanism and similar surface phenomena (distance and bearing).

1.2.4 Gaps in Terrain Barriers

1.2.4.1 Gap widths and vertical profiles.

1.2.4.2 Gap locations in distance and bearing from RV.

1.2.5 Soil Parameters

1.2.5.1 Flotation characteristics

1.2.5.2 Impact strength

1.2.5.3 Traction characteristics

1.2.5.4 Resistance to sliding.

1.3 The system must have the ability to sense and report data allowing the determination of navigation parameters.

1.3.1 RV Heading

1.3.1.1 Heading with reference to some fiducial line.

1.3.1.2 Heading with respect to some astronomical reference.

1.3.2 RV Positions

1.3.2.1 With respect to a lunar or planetary coordinate system

1.3.2.2 Relative to landmarks or previous vehicle position.

1.3.3 RV Distance Travelled and Velocity

1.3.3.1 Distance

1.3.3.2 Velocity.

1.4 The system must have the ability to sense and report data allowing the determination of environmental states.

1.4.1 Wind Parameters

1.4.1.1 Direction

1.4.1.2 Velocity

1.4.1.3 Gusts (average and maximum).

1.4.2 Meteorological Phenomena

1.4.2.1 Blowing dust

1.4.2.2 Visibility

1.4.2.3 Cloud coverage.

1.4.3 Ambient Fields

1.4.3.1 Light intensity and direction

1.4.3.2 Temperature and temperature gradients involving external (RV) temperature

1.4.3.3 Magnetic field intensity and direction

1.4.3.4 Other (meteoritic flux, particulate radiation, etc.).

2. THE ABILITY TO APPRAISE AND DECIDE

2.1 The system must have the ability to make appraisals and decisions regarding system states.

2.1.1 RV States

2.1.2 Terrain States

2.1.3 Navigation Parameter States

2.1.4 Environmental States

2.2 The system must have the ability to make appraisals and decisions regarding system operation.

2.2.1 Communication Parameter Selection

2.2.2 Programming Modes (retain, discard, modify)

2.2.3 Choice of Decision/Appraisal Modes

2.2.4 Selection of Sensor Parameters

2.2.5 Selection of Control Commands

2.3 The system must have the ability to make appraisals and decisions regarding mission conduct.

2.3.1 Choice of Objectives

2.3.2 Risk vs Potential Data Return

2.3.3 Path Planning

2.3.4 Use of Backup Modes and Redundant Systems

3. THE ABILITY TO COMMAND AND RESPOND

3.1 The system must have the ability to give and respond to commands which enable/disable communications systems.

3.1.1 Antenna Control

3.1.1.1 Select antenna

3.1.1.2 Orient antenna

3.1.2 Electric Power Control

3.1.2.1 Enable/disable electric power

3.1.3 Change Communications Parameters

3.1.3.1 Enter/leave transmit mode

3.1.3.2 Enter/leave receive mode

3.1.3.3 Enter/leave other communication states.

3.1.4 Verify Receipt and/or Execution of Communications Commands

3.2 The system must have the ability to give and respond to commands to operate sensors.

3.2.1 Enable/Disable Sensors

3.2.2 Change Sensor Parameters

3.2.3 Orient Sensors

3.2.4 Route Data Flow from Sensors

3.2.5 Override Sensor Activated Functions

3.2.6 Extrapolate Selected Parameters in Distance or Time

3.2.7 Allocate Between Decision Modes and Between Reporting Modes to Maximize System Functioning

3.2.8 Verify Receipt and/or Execution of Sensor Operative Commands

3.3 The system must have the ability to give and respond to commands involving RV mobility.

3.3.1 Readiness Commands

3.3.1.1 Unlock from lander

3.3.1.2 Enable/disable motive power

3.3.1.3 Enable/disable mobility sensors

3.3.1.4 Other (specific to situation)

3.3.2 RV Drive Commands

3.3.2.1 Start

3.3.2.2 Stop

3.3.2.3 Back

3.3.2.4 Accelerate

3.3.2.5 Decelerate

3.3.2.6 Select progress mode

3.3.2.7 Select continuity mode (step or continuous)

3.3.2.8 Brake

3.3.3 Other Commands

3.3.3.1 Verify receive/execute mobility commands

3.3.3.2 Extricate self

3.4 The system must have the ability to give and respond to commands initiating, selecting, modifying or abandoning programming.

3.4.1 From Signal

3.4.2 From Storage

4. THE ABILITY TO STORE AND RETRIEVE DATA

4.1 The system must have the ability to store and retrieve sensor data.

4.1.1 Discrete Status Data

4.1.2 Continuous Status Data

4.1.3 Limits for Sensor Parameter Values

4.1.4 Navigation Parameter Values

4.1.5 Path Planning Data

4.2 The system must have the ability to store and retrieve command data.

4.2.1 Operational Command Data

4.2.1.1 Mobility commands

4.2.1.2 Sensor commands

4.2.1.3 Telecommunications commands

4.2.1.4 Programming commands

4.2.2 Mission Conduct

4.2.2.1 Path planning data

4.2.2.2 Mission strategies

4.2.2.3 Command logic

4.2.2.4 Computation algorithms

4.2.2.5 Destinations

4.3 The system must have the ability to store and retrieve data-bank data.

4.3.1 Derived From Previous Measurements or Experience

4.3.2 Derived From Analysis

3.3 USE OF SYSTEMS REQUIREMENTS TO CHARACTERIZE MISSIONS

The mission to be considered may be identified by a unique combination of the mission characteristics described in Section 2 and displayed in Figure 2-1.

The functional characteristics do not simply combine additively, but rather, when combined they give rise to interactions. The requirement imposed by specifying a particular characteristic element may alter the requirements associated with any or all of the remaining elements. It is convenient therefore to consider the separate missions as interactions, the level or order of which depends upon the degree of specificity of the mission.

Let [K] represent the group of four mission functional characteristics common to all relevant missions, i.e., [F1, N1 and 2, C1, T1 and 2]. Then the single elements [K], [M2], [M3], [D1], [D2], [B1], [B2] may be considered as zero-order interactions. First-order interactions are represented by terms of the type

[K x M2] , [D2 x B2] etc.

Second-order interactions involve three elements

[K x D1 x B2] , [M2 x D1 x B2] etc.

Third-order interactions contain four elements

[K x M2 x D1 x B1] , --- etc.

It will be noted that there are six third-order interactions, each representing one of the six mission control configurations which have been selected as germane to the study, viz.,

[K x M2 x D1 x B1]: Lunar Fly-by-Wire Mission

[K x M2 x D1 x B2]: Martian Fly-by-Wire Mission

[K x M2 x D2 x B1]: Lunar Semi-automatic Mission

[K x M2 x D2 x B2]: Martian Semi-automatic Mission

[K x M3 x D2 x B1]: Lunar Fully Automatic Mission

[K x M3 x D2 x B2]: Martian Fully Automatic Mission.

Similarly, interactions between various combinations of the elements may be used to differentiate mission types. For example, if it is desired to compare a general Martian mission with a lunar mission, each may be considered as a first-order interaction of the form

[K' x B1] and [K' x B2] ,

where K' represents the commonality between the two missions as expressed by the sum of the requirements associated with all of the mission functional characteristics except B1 and B2. It should be noted that the requirements of both M2 and M3, as well as those of both D1 and D2 must be included in K'.

In order to characterize missions uniquely, the commonality (in this case K') should be made as small as possible.

We note that a requirement common to both missions and stated identically for both at a given level may, when examined by a further set of criteria, show aspects which are met in different ways for the two missions. That is, at a given level, the differences between the two missions may be stated in terms of

(1) The requirements applicable to one and not the other
(2) The differences in the ways in which the same requirement must be met for both missions.

Obviously, if the breakdown is carried to a sufficiently advanced level, (2) above may be expressed in terms of (1), differences between requirements. Lacking such a breakdown, it may be profitable to establish suitable criteria and to express the differences between missions on the basis of both (1) and (2). Such an expression is qualitative, since it can only reflect stateable differences in both categories.

Differences found in (2) do not necessarily exist in isolation. Once such a difference is noted, each of the remaining common requirements should be examined in relation to it. If a new difference is now observed, it should be added to the list of mission differences already assembled. In this manner the interaction between mission requirements can be assessed.

In order to systematize the examination of systems requirements, a method will be described showing the derivation of each of the two types of differentiation listed above.

3.3.1 Methodology for Mission Differentiation on the Basis of Systems Requirements Characterizations

We begin by defining a set of criteria which will enable each of the eight functions involved in RVMC to be classified for each mission configuration.

(a) A functional requirement is either applicable (A) or nonapplicable (N/A).
(b) A functional requirement is either earth-based (EB) or space-based (SB).
(c) A functional requirement is based on either current (C) or extrapolative (E) data.
(d) A functional requirement is met by either a human agency or a machine agency.
(e) A functional requirement is executed in either present (P) or future (F) time.

NOTE: A functional requirement is unassigned (U) if it cannot be classified by a single category at the level of requirements breakdown under consideration.

These descriptive terms are defined as follows:

- Applicable means that the requirement must be met if the system is to function as designed.
- Nonapplicable means that the requirement need not be considered in system design.
- Space-based means that the information processing takes place in space (moon, planet or orbiting satellite).
- Earth-based means that the information processing takes place on earth.
- Current means that the information, when processed, reflects a known existing system state or state change.
- Extrapolative means that the information, when processed, reflects an estimated state or state change.
- Human means that information is processed predominantly by an individual or individuals.
- Machine means that information is processed predominantly by machine.
- Present means that the requirement is met by current, real-time action.
- Future means that the requirement is met by programming an action or actions to be carried out at some future time.

For purposes of clarification, a system state is defined as a set of single-parameter values associated with a corresponding set of parameters. A change of one or more of these parameter values is a state change.

Using the criteria as defined above, any desired comparison between individual missions or between classes of missions may now be made by

(1) Examining, at an appropriate level, the requirements for each mission or class of mission for differences between requirements.

(2) Examining, also at an appropriate level (not necessarily the same as that used in (1)), the requirements for differences within the same requirements.

(3) Combining these differences and evaluating each of the common requirements, at the most advanced level available, for interaction with the differences. (If the requirements are now shown to differ markedly, the process may have to be iterated.)

The method stems from the need to deal with requirements as generally as possible in order to allow systems configurations to be developed which are applicable to a number of specific missions. As previously noted, if the systems requirements breakdown were carried far enough, all of the differences could ultimately be expressed as differences between requirements. Lacking this specificity, a more general assessment must be made.

For step (1), identification of common requirements, the most advanced breakdown available should be used wherever possible. In the present case, this is represented by the fourth level. A single criterion is all that need be employed. Either a requirement is applicable or it is not.

The level which appears best suited for the purposes of step (2), characterization of common requirements, is the first level, provided, as noted before, that the paired functions are treated individually. Selection of a particular level should be made in terms of maximum usable information return for effort expended.

As an example of mission differentiation by the above methodology, a comparison is now made between the general lunar and general Martian missions.

First, each requirement as given in the Systems Requirements Breakdown outline is examined to determine whether or not it is applicable to both missions. Where differences exist, they are shown in tabular form below in Table 3-2.

Table 3-2
FOURTH-LEVEL SYSTEMS REQUIREMENTS APPLICABILITY DIFFERENCES FOR GENERAL LUNAR AND GENERAL MARTIAN MISSIONS

Fourth-Level Requirement	General Lunar Mission	General Martian Mission
1.4.1.1 Wind Direction	N/A	A
1.4.1.2 Wind Velocity	N/A	A
1.4.1.3 Gusts (average and max.)	N/A	A
1.4.2.1 Blowing Dust	N/A	A
1.4.2.2 Visibility	N/A	A
1.4.2.3 Cloud Coverage	N/A	A
1.4.3.3 Magnetic Field Int. & Dir.	N/A	A

Secondly, each system requirement at the first level is evaluated according to each of the criteria listed.

Table 3-3 shows the classification by the established criteria for the first-level functions. At this level all of the functions are applicable to both missions. The criterion A/NA is included here only so that its use at the fourth level will be more readily understood.

Table 3-3
MISSION ANALYSIS, BY SITE OF RV DEPLOYMENT

Mission	Sense					Report					Appraise					Decide				
General Lunar	A	U	C	U	U	A	U	U	U	U	A	U	U	U	U	A	U	U	U	U
General Martian	A	SB	C	M	U	A	SB	U	M	U	A	U	U	U	U	A	U	U	U	U

	Command					Respond					Store					Retrieve				
General Lunar	A	U	U	U	U	A	U	U	U	U	A	U	U	U	U	A	U	U	U	U
General Martian	A	U	U	U	U	A	SB	U	M	U	A	U	U	U	U	A	U	U	U	U

LEGEND

A, N/A: Applicable or Nonapplicable
SB, EB: Space-Based or Earth-Based
C, E : Current or Extrapolative
H, M : Human or Machine
P, F : Present or Future
U : Unassigned

NOTE: An entry U means the function is unassignable to a specific category at this level, for any of a number of reasons (lack of information, confounding of functions, etc.).

The differences between the general lunar and general Martian missions which are indicated in Table 3-3 are differences within requirements, since all of the requirements at this level are applicable to both missions. A difference arises wherever the entry in a lunar cell of Table 3-3 is distinct from that in the corresponding Martian cell. Preliminary statements, corresponding to these cell entries, are made below which characterize the missions accordingly.

1. (a) Sensing of state parameters on Mars will be a space-based function. Even though a certain amount of information might be obtained by earth-based observation, it would have little value compared to similar observations made from a space-based agency.

   (b) Sensing of state parameters on the moon may be either space-based or earth-based. Either as backup modes or primary functions, certain information-collecting procedures could conceivably be carried out to advantage from the earth as well as from space. For example, the signal from an optical laser beacon placed on the RV might be used to determine RV position, cumulative distance, and other related parameters.

2. (a) Data reporting on a Martian mission must correspondingly be space-based; data reported from earth-sensing will be too general to be of much value.

   (b) Data reporting on a lunar mission may be either earth-based or space-based. Even though the system is designed for complete automation, backup modes for executing functions such as those covered under 1. (b) above may very well be incorporated into the system.

3. (a) State-sensing and data reporting on Mars will be a machine function exclusively.

   (b) Both sensing of state parameters and data reporting on a lunar mission, fully automated or not, may in some cases be a human function, in others a machine function. Lunar missions will thus have more flexibility.

4. (a) Responding in the Mars case will be limited to a space agency.

   (b) Responding to commands in a lunar mission might be either space-based or earth-based, because of the large channel capacities, available power and extended periods during which the system could be operated. In a fully automated lunar mission, for example, some data might well be stored on earth and accessed by command from the RV.

5. (a) Responding in the Martian case must be exclusively a machine operation, since commands from the RV will not be sent to earth.

   (b) Responding in the lunar case might be either a machine or a human function. For example, the response in item 4. (b) above might be carried out by a human.

The above list, when augmented by the differences summarized in Table 3-2, represents the stateable difference between the general lunar and general Martian missions without taking into account the interactions between requirements. A third step is required to complete the analysis. Each of the advanced level requirements common to both missions is now examined in the light of the disclosed mission differences to determine if the commonality remains intact. This is done by characterizing each requirement according to the criteria and noting any new differences that arise, either in the assigned criteria or in interpretation of the requirement. Where fourth-level requirements are not suitable, or are unavailable, earlier levels are used.

The differences between the general lunar and general Martian missions shown by the above method are reflected in the totality of entries in Tables 3-2, 3-3, and 3-4, those in Table 3-2 arising from the criterion of applicability, those in Table 3-3 from the application of the remaining criteria as defined, and those in Table 3-4 from interaction between the requirements.

It must be recognized that none of the above tables is complete, except in the sense that it applies to a general breakdown. As the breakdown is carried further, new interpretations of the criteria may be made, and further interactions disclosed.

The method outlined is not restricted to any given level. Its advantage is that certain conclusions may be drawn before the systems requirements breakdown has been carried out to an ultimate level. Its weakness is a loss of specificity because the ultimate levels are lacking.

Table 3-4
EVALUATION OF GENERAL LUNAR MISSIONS AND GENERAL MARTIAN MISSIONS ON THE BASIS OF REQUIREMENTS INTERACTIONS

Requirements	Differences Between Lunar and Martian Missions	Interactions
1.2.1.2, 1.2.1.4, 1.2.3.1, 1.2.3.2 Sensing and Reporting	Outcroppings, cliffs, craters and unstable terrain may be sensed and reported from earth as well as from space in a lunar mission. In a Martian mission these must be sensed from space.	With Req. 2.1 Some appraisals and decisions regarding terrain states may be made on the basis of current earth-based data for lunar missions. For Martian missions this will not be possible. With Req. 2.3 Some appraisals and decisions regarding choice of objectives, risk vs potential data return and path planning may be made on the basis of current earth-based data for lunar missions. For Martian missions this will not always be possible. With Req. 3.2 Sensor operation, where such obstacles are involved, can, in some cases, be carried out on the basis of current, earth-based data for lunar missions. For Martian missions this will not be possible. With Req. 3.3.2 RV drive commands may in some cases be made on the basis of current earth-based data where such obstacles are involved, in lunar missions. For Martian missions this will not be possible.
1.4.1, 1.4.2, 1.4.3.3 Sensing and Reporting	Wind parameters, meteorological phenomena and magnetic field intensity and direction need not be sensed and reported for lunar missions. For Martian missions these must be sensed and reported.	With Req. 1.1.2 Wind pressures may affect RV control parameters and engineering parameters such as vehicle attitude, power reserves, etc. With Req. 1.2.5 For all Martian missions, the presence of an atmosphere implies possibility of moisture inclusion in soil. With changing temperatures this may change soil parameters. Sensing moisture content of air and/or soil should therefore be a requirement under 1.4.2. With Req. 2.1 For all Martian missions the presence of atmosphere implies possibility of sensor deterioration (corrosion, pitting due to blowing dust, etc.). Req. 2.1 should include a requirement to make appraisals and decisions regarding sensor states. With Req. 3.3 For all Martian missions the presence of moisture in an atmosphere implies the freezing of drive components, etc. Req. 1.1.2 should include the capability to sense and report locked states in which received commands cannot be executed. With Req. 3.3.1 For all Martian missions, since atmospheric pressure may vary, RV component pressures should be sensed and reported as part of Req. 1.1.2 and the capability to control these included in Req. 3.3.1 and 4.1.
1.1.1.1 through 1.1.3.5 Reporting Only	All lunar missions can report current data. Some Martian missions must report some extrapolative data back to earth, since, because of transmission delays, states may change before the signal is received on earth.	None at this level, since the difference does not apply to all Martian missions.

4.0 SYSTEM CONFIGURATIONS

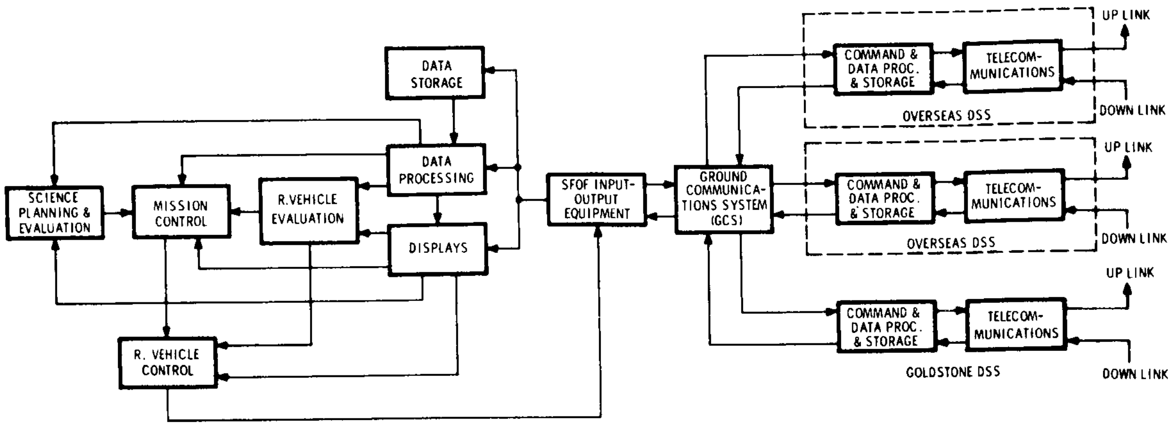
The previous section described, to the extent possible, how the system requirements might be defined for each of the three lunar and three Martian mission modes of Section 2.

For each of the three mission modes (fly-by-wire, semi-automatic, and fully automatic) a general system configuration was evolved. There are innumerable ways in which systems could be assembled, depending upon the degree of automaticity desired, the location of specific functions (on earth or in space), the degree of complexity desired or permitted, and the performance levels and characteristics required. In this section, the rationale for configuring systems for each mission is discussed.

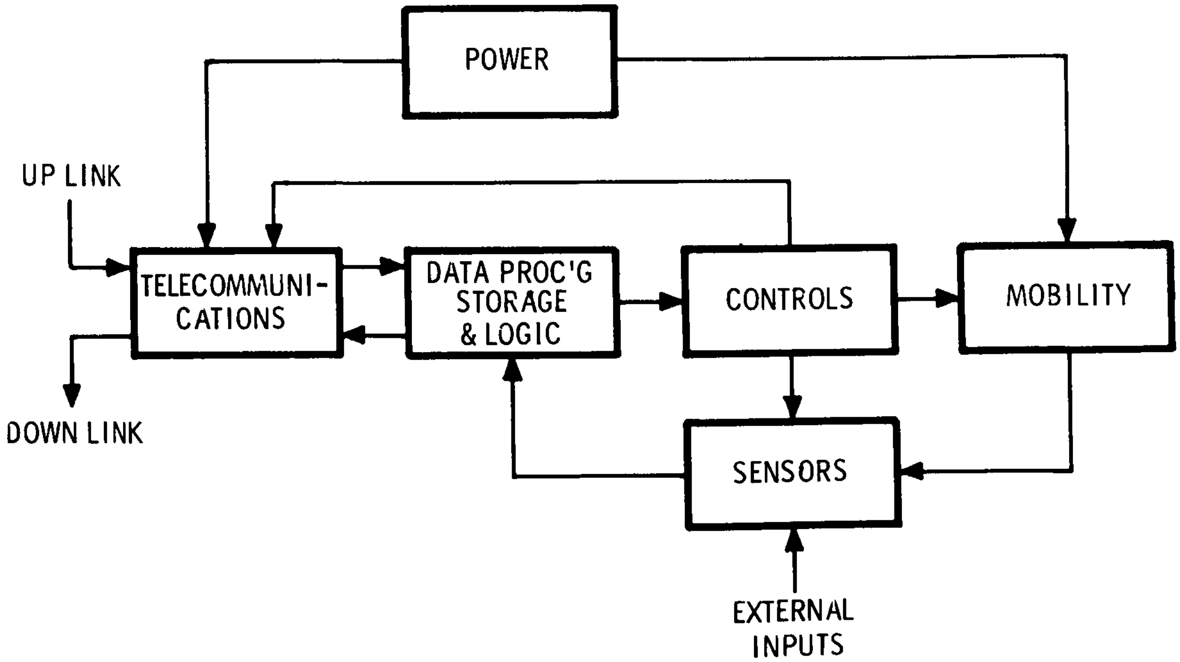
Figure 4-1 shows, in general form, the elements of any remote control system for extra-terrestrial roving vehicles. The ground-based portion, shown in Figure 4-1(a) consists of a mission operations center (SFOF), a network of transmitting and receiving stations, and an interconnecting ground communications network. One of the constraints assumed for this study is the use of the JPL Deep Space Network, and Figure 4-1(a) is based upon that constraint. It is further assumed that, as a general rule, the placement of mission-dependent personnel, equipment, or software at DSIF Deep Space Stations (DSS) is undesirable and should be avoided to the maximum extent possible. Therefore most such elements are placed at the SFOF.

At the SFOF, there will in general, be five functions: 1) Mission control, 2) Science planning and evaluation, 3) Roving vehicle evaluation, 4) Roving vehicle control, and 5) Data processing and display. While any or all of these may be combined into a single person, equipment, or station, functionally they may be thought of as distinct. Each function is described in greater detail below.

The Mission Control function provides overall direction of all mission operations. This includes functions not directly related to RVMC, and in complex missions such as Voyager (which may involve orbital, fixed-landed, and mobile operations) it includes all of them. With respect to the direction of RVMC, it concerns mainly the establishment of roving vehicle objectives upon recommendation of the science planners and the



a) Ground-Based Equipment



b) Space-Based Equipment

Figure 4-1 RVMC General Configuration

ordering of suitable precautionary measures to alleviate dangerous conditions reported by Vehicle Evaluation. This function is not further broken down herein.

Science Planning and Evaluation, as the name implies, is concerned with the scientific aspects of the mission, and may also include functions not directly related to RVMC. Since it is assumed that the overall objective of any mission is scientific in nature, this function is of cardinal importance to the overall mission operation, and is therefore shown in relation to other functions for completeness. It likewise is not developed in greater detail herein, since it does not play a central role in the RVMC operation.

Vehicle Evaluation is concerned with the present state of the vehicle and its subsystems, both internally and with respect to the environment. This function involves monitoring on-board temperatures, voltages, currents, pressures, state of charge, conditions of operation, and other variables indicative of or affecting the operation of the vehicle itself, as well as reporting internal conditions which threaten the future effectiveness of the roving vehicle system. It is also responsible for being continuously aware of external conditions, slopes, obstacles, soft soil conditions, sun glare, dust or wind storms, ambient temperature conditions, etc., which endanger the vehicle or any of its subsystems, and for recommending appropriate precautionary measures. In performing this evaluation, use is made of both real-time and delayed displays of incoming data related to vehicle status, and processed data. In addition, appropriate stored data representing events of the past may be recalled as needed.

Vehicle Control must formulate a plan for achieving the objectives defined by mission control and, as appropriate to the level of automaticity involved, must formulate the commands and command sequences to execute that plan. It must also provide for reprogramming of on-board decision processes, where applicable, on the basis of past performance and present conditions as reported by vehicle evaluation.

The SFOF is connected with the transmitting and receiving stations of the Deep Space Instrumentation Facility (DSIF) through the Ground Communications System (GCS). The GCS is assumed to be equivalent to that described in JPL, Engineering Planning Document EPD-283, Rev. 2, dated 1 January 1967. The GCS does not provide capacity for routine data transmission from overseas sites to SFOF at rates which are likely to be realized between the moon and earth, and perhaps not even those achievable from Mars. The use of overseas transmitting and receiving stations will be affected by this limitation and, in some instances, may be ruled out entirely as far as motion control is concerned. Therefore, these sites are enclosed in a dotted line on Figure 4-1(a), indicating that in some configurations they may not be part of the RVMC system.

At each Deep Space Station (DSS) there is a data processing and storage function which processes outbound commands, programming instructions, etc., and inbound telemetry. At these stations there is also a telecommunications function consisting of transmitters, receivers, antennas, and their associated equipment.

The space-based portion of the system, shown in general form in Figure 4-1(b), consists of the telecommunications equipment forming the other end of the RF link, data processing, storage and logic functions, sensors, controls, and the mobility subsystem, control of which is the ultimate objective of the RVMC system. There must, of course, also be a power subsystem which, while not an element of the control loop itself, must nevertheless be considered in tradeoff analyses involving information transfer rates and mobility under weight and/or volume constraints. Controls are generally applied not only to the mobility subsystem, but to many of the sensors and to the telecommunication system, particularly the antenna.

4.1 CONFIGURATIONS FOR THE THREE MISSION MODES

Starting from this general RVMC system configuration and the detailed system requirements defined in Section 3, generalized configurations were evolved for each of the three modes of operation. These configurations conveniently break down into SFOF-based, DSIF/GCS, and space-based portions. These system configurations were intended to be as detailed as possible while retaining a great degree of generality with respect to each mode.

In many cases, the system requirements could (conceptually, at least) be met in a variety of ways. Rather than attempting to generalize to include all possible concepts, engineering judgment was used to eliminate some which were clearly inferior and those which violated some ground rule of the study. For example, no system is considered which depends upon relay communication through either a lander or an orbiter. Lander relays were eliminated by the ground rule requiring that no system be inherently range-limited. Orbiter relays were eliminated as a prime mode on the basis of availability and reliability, although they might be considered as a backup.

4.2 DSIF CONFIGURATION

As a direct result of the desire to avoid placing mission-dependent elements at DSIF sites, the general configuration of the DSIF sites is identical for all three modes. Figure 4-2 shows this general configuration. At each site, up-bound commands are passed through a command processor to the transmitter. The command processor also performs the function of command verification and, if commands are not verified, it inhibits transmission of the command and notifies the operations center (SFOF). (The word "command" is here used to include such things as roving vehicle destination coordinates, computation instructions, addresses, path plan data, etc., when applicable.)

All up-link traffic is assumed to be transmitted on the 210-foot antennas at Goldstone, Madrid, and Canberra, while down-link data reception may be on either or both the 210- and 85-foot dishes, divided on the basis of data rate, operational importance, permissible error rates, and perhaps operating costs. All data received are recorded, and active operational control data are processed in the telemetry data processor and transmitted to SFOF.

As noted above, the use of overseas sites is affected by data rate limitations in the GCS. In some cases, where incoming data rates are expected to exceed GCS capabilities at the overseas sites for short intervals or only for certain kinds of data, it might be appropriate to use some form of data compression at these sites. Therefore, for generality, data compression is shown in Figure 4-2 at the Madrid and Canberra sites, but not at Goldstone where the wide-band microwave link to SFOF should be capable of handling any anticipated data rate requirements.

In the case of lunar missions, the anticipated data rates are significantly higher than projected GCS capabilities so that the GCS could become a major operational bottleneck. One way around this problem is to duplicate much of the operations control center capability at the overseas sites, but this does not appear practicable. Therefore, it seems quite likely that lunar missions which require considerable telecommunications traffic would be conducted almost entirely through the Goldstone site, with overseas sites used mainly for monitoring the vehicle status during nonoperational periods.

The capabilities of the GCS anticipated by 1973 will probably not be severely taxed by either up-link or down-link control traffic in the case of Mars, although a detailed operations analysis should be performed to determine what limitations, if any, are

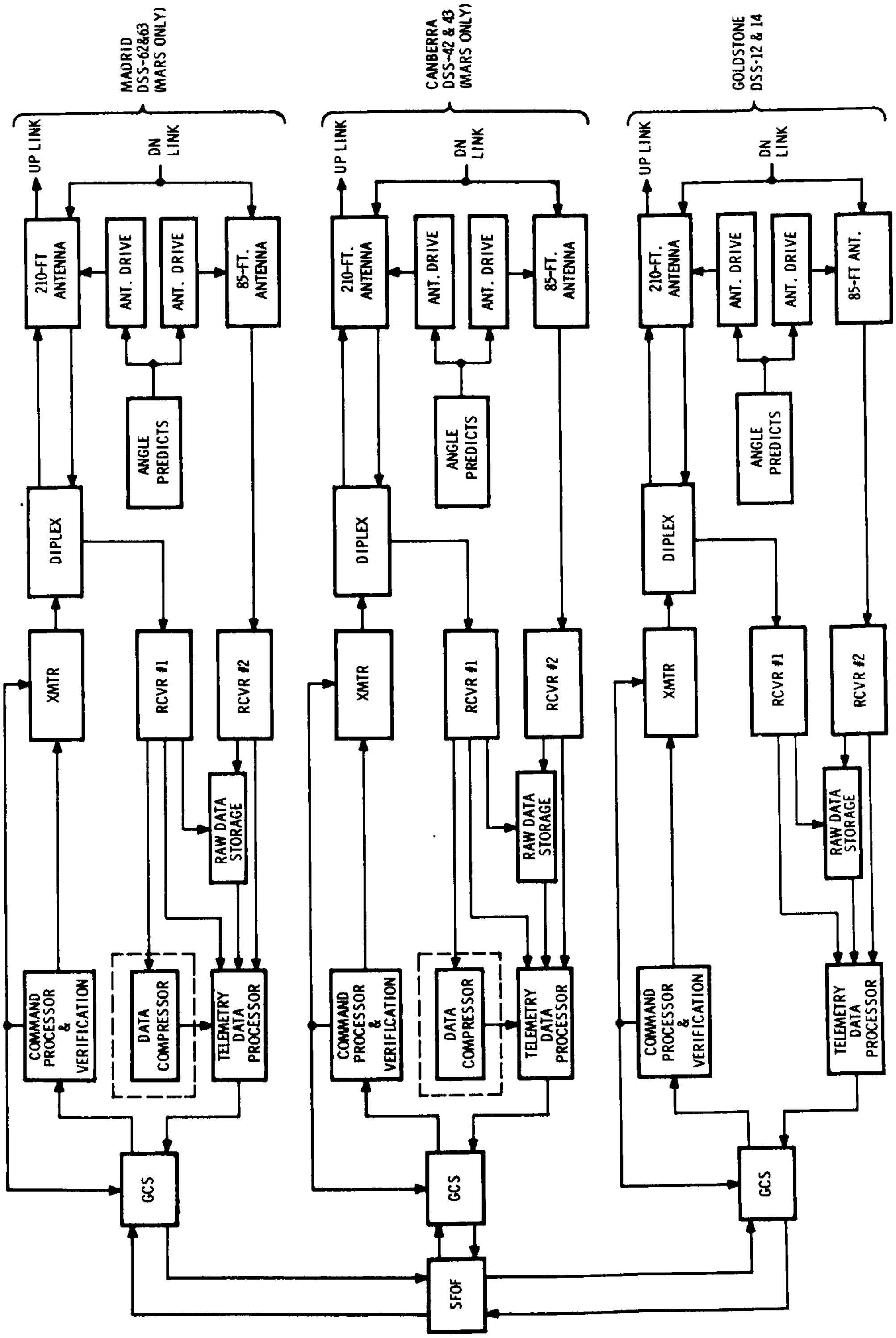


Figure 4-2 DSIF/GCS Configuration

imposed by the GCS. Although it is conceivable that Mars-Earth data rates could, at times, saturate the 4800-bps high-speed data lines between overseas DSIF sites and SFOF, they are unlikely to exceed GCS capability by more than a factor of two or three because of power-gain limitations on the vehicle. This can be handled either by transmitting data to SFOF through buffer storage at a rate slower than received at the DSIF, if this happens only occasionally, or by using some data compression technique at the DSIF site, or by a suitable combination of the two. Although most forms of data compression are best accomplished as close to the data source as possible, many forms depend upon high signal-to-noise ratio to realize maximum advantage, and many forms entail some loss of information. Thus, if data compression is, in fact, needed because of GCS limitations, it might be advantageous to accomplish it at the DSIF site after recording and with potentially high S/N, in the subsequent transmission channels.

In the Martian case, therefore, the use of overseas sites is warranted. Indeed, because of the rotation of both Mars and the earth, it is necessary in all Martian cases to use overseas DSIF sites during surface operations to assure a reasonable operating window for communications. Although this may impose data rate restrictions that could slow down operations, as noted above, the alternative use of Goldstone only could result in communications windows frequently approaching zero for large areas of Martian surface and, therefore, vastly reduced overall data flow. Accordingly, the use of DSIF sites at Goldstone, Canberra, and Madrid, is assumed for Martian missions. Each of these sites is to be equipped with both 85-foot and 210-foot-diameter antennas after 1971.

In the following sections the SFOF-based and space-based portions of the systems configurations are discussed for each of the three modes – fly-by-wire, semi-automatic, and fully automatic.

4.3 FLY-BY-WIRE MODE

4.3.1 SFOF-Based Configuration

In the fly-by-wire mode, all control decisions are made at the operations control center and all commands emanate from this center except those for which the safety of the vehicle requires a reaction time shorter than that allowed by the system and the applicable constraints. Basically this means that the only decisions made on board the vehicle are those which stop the vehicle because of the occurrence of a physical condition which poses an immediate threat, such as tilt or loss of a wheel contact.

The operations control center, shown in Figure 4-3, consists of several levels of control as discussed above. Mission Control, having overriding control of all aspects of the mission, receives advice on scientific objectives from Science Planning and Evaluation and current data on the status of the RV system from RV Evaluation. The Mission Controller is kept constantly aware of RV position by means of a navigational display, and is aided in establishing objectives by a continuously updated terrain model (discussed below). On the basis of these inputs, Mission Control establishes a long-range objective (LRO) which is perhaps tens or hundreds of vehicle lengths from the present position. Alternatively, he might demand a prearranged search pattern or some other objective.

In response to this objective, and with the use of the terrain model, the path planner establishes a sequence of intermediate and/or short-range objectives (IRO and SRO) which define the path to be taken to achieve the LRO. This path plan is formulated on the basis of a knowledge of vehicle capabilities relative to the local terrain features as defined by the terrain model. Since these will not generally be known in detail, a lower level of control is embodied in the RV Controller, who issues all detailed start, stop, and steering commands as well as commands needed to control the RV sensors.

When terrain conditions permit, the RV Controller may choose to transmit a sequence of commands, rather than resorting to a one-command-at-a-time mode. To illustrate this alternative, a Command Sequence Generator is shown, although this may not be a separate piece of equipment.

All commands issued by the RV Controller are subjected to review by RV Evaluation to assure that they will not endanger the vehicle. No command is transmitted to the GCS without such safety clearance.

All incoming data are stored as received, and processed in a central decoder before being routed to users. Current environmental data, engineering parameters, roving vehicle attitude and proximate terrain data, are fed directly to Roving Vehicle Evaluation. As described below, terrain sensors on the roving vehicle are categorized as short-range or long-range. The data from the latter are appropriately processed to meet the particular needs of each user and are stored for call-up on demand. These data are used for various purposes for Science Planning and Evaluation, Roving Vehicle Evaluation, and for the updating of the Terrain Model. Science Planning and Evaluation

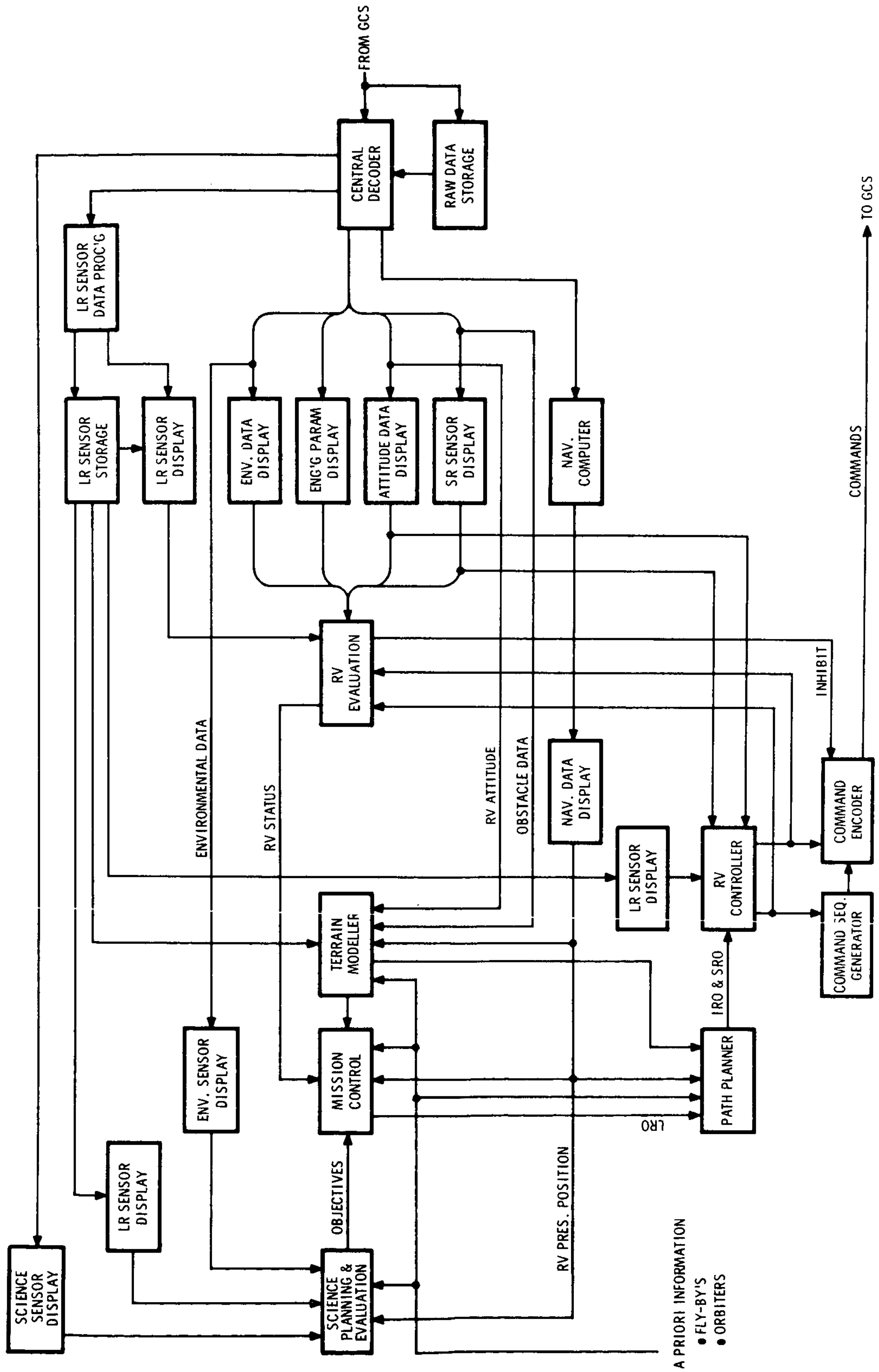


Figure 4-3 Fly-By-Wire Configuration, SFOF-Based Equipment

also uses environmental data, while raw navigational data are fed through a navigation computer to get present position which is displayed to Science Planning, Mission Control, and the Path Planner, and is used in Terrain Modeling.

To assist all earth-based functions, but primarily path planning, a terrain modeller is envisioned. This assimilates all available data concerning the nature of the surface in the area of interest. These data are used to provide a model which represents a "best estimate" of terrain conditions and which is continually updated as further data are obtained. The model should also provide a measure of the confidence in the estimate. Such a model might well be started prior to launch through the use of pictures taken on fly-by missions such as Mariner 4. Pictures from orbiting and landing spacecraft may provide a level of improvement in the model prior to the start of actual roving vehicle exploration. As the roving vehicle moves out from the landing site, its own sensors provide a further improvement in both the level of detail of the model and the confidence in the estimate. Also, correlation of vehicle-derived terrain data with wide-area data such as those derived from orbiters will probably permit extrapolation of the model in unexplored regions to levels of greater detail with improved confidence. This, in turn, should assist the Science Planning Staff in the choice of interesting new destinations and the Path Planner in choosing preferred paths with greater confidence. It might also provide the means for improving on-board preprogrammed decision processes which are at least partly based upon terrain statistics.

The actual implementation of the terrain modeler will probably involve a rather intimate man-computer-display interface. As such, it might be patterned after any of several computer-assisted design systems (e.g., the General Motors DAC-1 System). Several important potential differences can be conceived, however. For example, it might be quite sufficient from the vehicle control standpoint to represent mobility hazards symbolically, or in outline only, rather than to generate a mathematical model and a display of the actual surface. Also, as noted above, it would seem to be quite desirable to provide statistical measures of confidence on the location, the number, and the size of mobility hazards plotted, so that the vehicle controller would have some measure of control latitude open to him as well as the relative desirability of two symbolically similar routes. The means to do this could well be the basis of a separate study.

4.3.2 Space-Based Configuration

The space-based portion of the fly-by-wire configuration, shown in Figure 4-4, consists for the most part, of sensors and controls together with the on-board telecommunications

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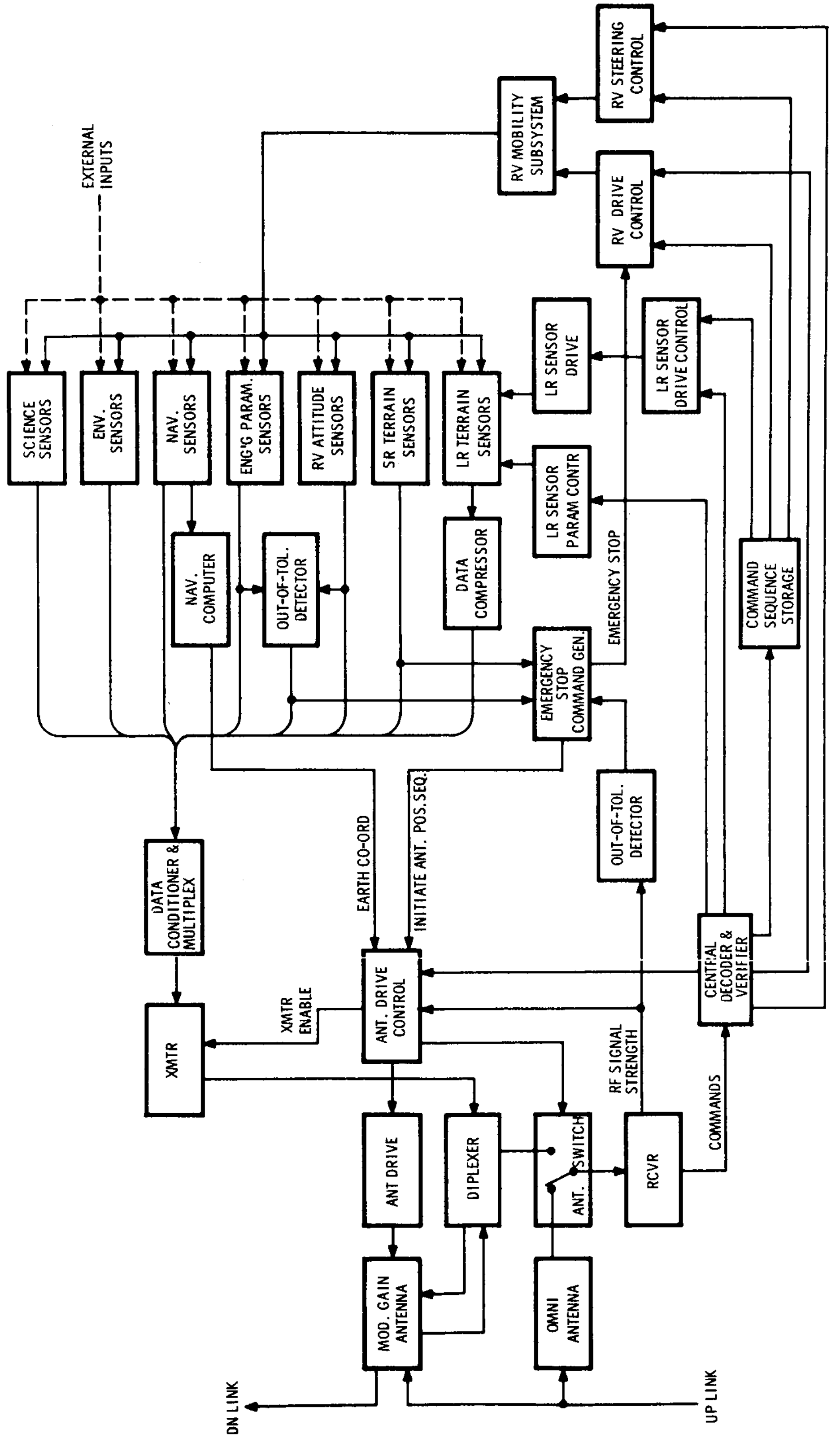

Figure 4-4 Fly-By-Wire Configuration, Space-Based Equipment

equipment needed to transmit data and commands between the earth and the roving vehicle.

Based on the ground rules of the RVMC study, it is assumed that the space-based roving vehicle control functions are integral with the vehicle itself, i.e., no communication relay is made through either the lander or an orbiting spacecraft. This does not mean to eliminate the use of orbiter pictures in the guidance, however.

The sensors are classified into eight separate categories, seven of which are explicitly shown in Figure 4-4. These are as follows:

1. Vehicle engineering parameter sensors – sensors which monitor the engineering quantities of vehicle performance, e.g., temperatures, pressures, voltage, etc.
2. Navigation sensors – sensors which measure quantities used to determine position with respect to some reference coordinate system.
3. Control sensors (not shown) – sensors which measure the state of any controlled quantity for purposes of comparison with command reference inputs.
4. Short-range terrain sensors – sensors which detect actual physical encounter with mobility hazards.
5. Long-range terrain sensors – sensors which are capable of detecting mobility hazards at some distance from the vehicle, generally a few vehicle lengths or more.
6. Attitude sensors – sensors which measure the angular orientation of the roving vehicle with respect to a local coordinate system.
7. Environmental sensors – sensors which measure environmental variables affecting vehicle control in some manner.
8. Science sensors – sensors which gather scientific data to carry out the mission scientific objectives.

Vehicle engineering parameter sensors play no direct role in control of the roving vehicle, except possibly to initiate a STOP command or corrective action sequence whenever a sensed variable (or function thereof) falls outside some preprogrammed tolerance limits. The action to be taken and the related commands depend upon which variable is out of tolerance, and may also depend upon the amount and/or direction of the out-of-tolerance condition. An out-of-tolerance condition is transmitted to earth, and in some cases may also be transmitted to an emergency STOP Command Generator which automatically stops motion when system time delays would otherwise be too great for vehicle safety.

Navigation sensors generally do not directly sense those navigational quantities of interest but instead measure quantities from which the others may be derived. The existence of some sort of navigation computer is implied. For the fly-by-wire configuration this computer will normally be on the earth, since the basic philosophy of this configuration is to maintain maximum simplicity of the space-based equipment. There is, however, a possible need for some navigational computation, expecially in the Martian case, to assist in orienting the directional antenna, as will be discussed below. The nature of this computer depends upon the type of navigation scheme adopted.

Control sensors provide a means of confirming the execution of control actions in accordance with control commands. They sense antenna position, steering angles, sensor orientation (especially of the long-range sensors), controlled sensor parameters, and, if appropriate, drive and brake conditions.

Short-range sensors include miscellaneous switches or switch actuators, devices to measure soil properties, and possibly tactile arms, feelers, etc., which may be used to measure sizes of objects.

Long-range sensors include a wide variety of devices having very diverse characteristics and requiring widely different approaches to assimilation of their outputs. They are categorized by their ability to gather information about the mobility environment through means other than direct contact. This will generally involve reception of electromagnetic energy in some portion of the spectrum, either passively or by means of reflection of energy emitted from the vehicle. In some cases it might be possible to conceive the use of acoustic energy for this purpose, but the application of such an approach is not clear at this time.

Long-range sensors include imaging systems such as television or facsimile which inherently have a high bit content and great amounts of redundancy. Anticipating that this will, in some cases, tax the capabilities of the RF link, a data compressor is shown at the long-range sensor output. Long-range sensors, in general, also require orientation and may have controllable parameters. For these functions a sensor parameter control and a sensor drive control are shown in Figure 4-4.

Attitude sensors are concerned primarily with determining the orientation of the roving vehicle with respect to the local gravity vector to prevent overturning and perhaps to assist in the assimilation of other sensor outputs, e.g., long-range sensors. In the case of articulated vehicles, each unit may require such sensors.

Environmental sensors and science sensors play no direct role in the control function but are only included in Figure 4-4 for completeness.

In the fly-by-wire configuration, sensor data are fed directly into the telecommunication channel through a Data Conditioner and Multiplexer. Down-link transmission is accomplished through use of a moderate gain (perhaps 20 to 30 dB) antenna, although from the moon narrow-band data might be transmitted on an omni-directional antenna. Transmission may be initiated either automatically by an emergency STOP command arising from an out-of-tolerance condition, or upon command from earth.

So that commands from earth may be received at all times, an omni-directional antenna is provided. Upon reception of a command to orient the antenna, coarse positioning of the antenna begins, using coordinates supplied by the navigation computer. When the antenna is positioned so that signal reception can occur on the directional antenna, an antenna switch is actuated and the antenna drives are actuated to maximize RF signal strength. Until this action has taken place, the transmitter is prevented from operating by a disabling circuit from the antenna drive control. RF signal strength is also monitored during motion of the vehicle and causes an emergency STOP command whenever it becomes weak, indicating occulting of the earth by some local terrain feature.

Commands are decoded and verified and sent directly to the controls. In the event that the terrain permits command sequences to be sent, the system provides storage capability for these sequences.

The ability to transmit narrow-band data to and from the moon on an omni-directional antenna makes it possible to eliminate the navigation computer on lunar configurations. The raw navigational data could be transmitted to earth where the antenna pointing coordinates could be computed. Of course, on the moon, the disc of the earth is large enough and often bright enough that it might be sensed directly to get antenna position.

4.4 SEMIAUTOMATIC MODE

4.4.1 SFOF-Based Configuration

Consistent with the placement of decision making capability on board the roving vehicle in the semiautomatic mode, the ground-based complex tends to be somewhat simpler. In particular, the RV Controller function is moved to the roving vehicle and the related displays are eliminated. The semiautomatic SFOF-based configuration is illustrated in Figure 4-5.

Roving Vehicle Control in this case consists mainly of path planning, which is accomplished using both the a priori information and the updated terrain model. Once the general route is mapped out, a sequence of interim navigational goals is transmitted to the roving vehicle for storage. These goals are transmitted through the Command Sequence Generator. In addition to the interim navigational goals specified by the path planner, the command sequence generator handles all requests for readout of stored data from the roving vehicle sensor storage. In a degraded mode of operation, or under special terrain conditions or mission requirements, the Command Sequence Generator also assumes the role of generating sequences of detailed step-by-step steering and drive commands, as in the fly-by-wire mode.

The present position of the roving vehicle is a quantity which must be available on the vehicle itself, thereby requiring a full navigation computer capability there. This requirement thus eliminates the computer on earth.

4.4.2 Space-Based Configuration

The space-based portion of the semiautomatic configuration is shown in Figure 4-6. The core of this configuration is the Master Control Logic. Here are stored all computational algorithms, control strategies, and destination descriptors. Raw and processed sensed data are acted upon in the Master Control Logic to produce control signals which start, stop, back up, and steer the vehicle, as well as control signals which operate certain of the sensors. (The Master Control Logic is not necessarily a single physical module, but rather a basic functional block.)

In this system, data are not transmitted continually to earth, but only when "significant" control information is acquired, or when an automatic STOP command is issued, or upon special command from earth. Normally, control commands are generated within

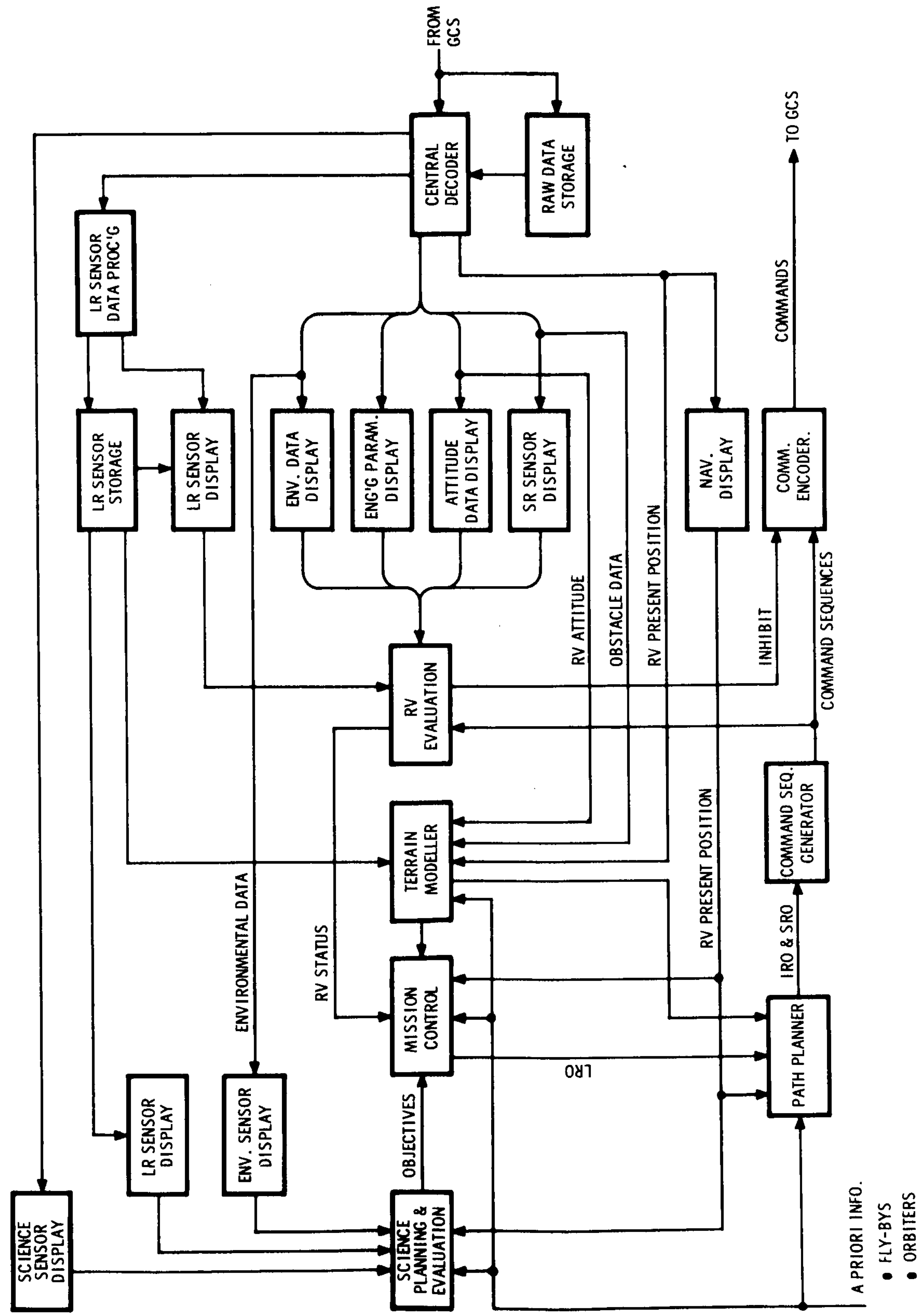

Figure 4-5 Semiautomatic Configuration, SFOF-Based Equipment

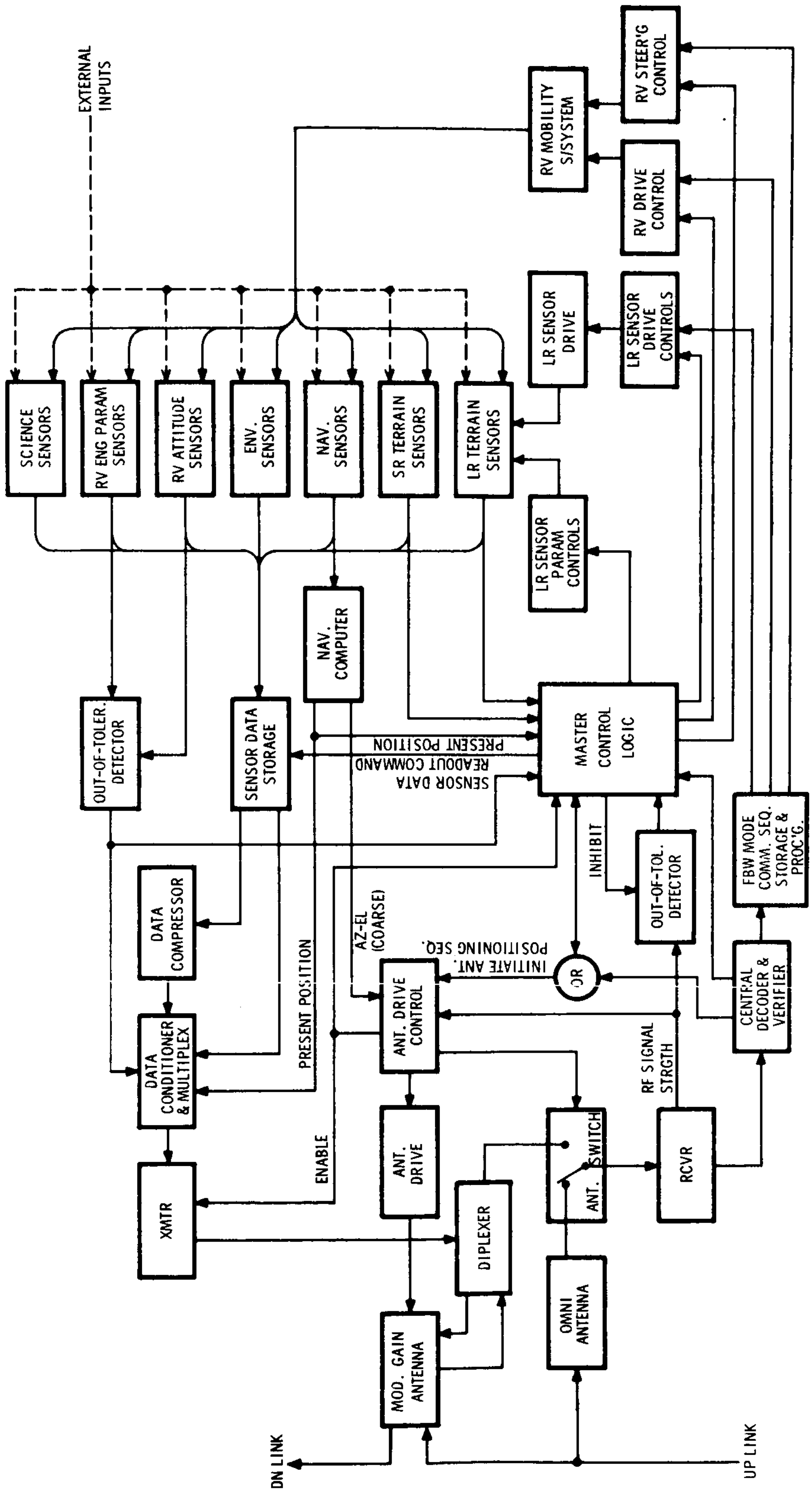

Figure 4-6 Semiautomatic Configuration, Space-Based Equipment

the Master Control Logic in response to data which originate with the on-board sensors or are inserted ahead of time by earth sources. Sensor data are stored on board. In some cases a continuous time recording may be made until readout occurs. In other cases only the latest values will be stored.

As noted above, the navigation computer for determination of present position is placed on the roving vehicle. The outputs of this computer are compared with the destination coordinates in the Master Control Logic. Mechanization of this computer is, of course, strongly dependent on the choice of sensors and the performance level desired. The navigation computer also provides coarse positioning data for the antenna, as in the fly-by-wire mode.

Sensor outputs which are used in the on-board control function are fed to the Master Control Logic (either directly, or appropriately processed as in the navigation computer and out-of-tolerance detectors). The Master Control Logic then, in accordance with its stored decision algorithms, generates appropriate control commands to move the vehicle in a manner which will safely achieve the navigational goal, or to gather additional data if needed to reach appropriate control decisions. The latter function may involve orientation of long-range sensors and/or variation of long-range sensor parameters.

After any STOP command is issued, the antenna is automatically oriented in accordance with data from the navigation computer, and is ultimately finely oriented by locking onto and tracking a beacon signal from earth. Alternatively, for lunar missions this might be accomplished by an earth-seeking sensor, as noted in Section 4.3. Selected sensor data are then automatically read out of storage, appropriately conditioned, and transmitted to earth. Data compression is shown as a possible additional feature. After automatic readout of these data the roving vehicle rests while awaiting further instructions from earth.

As with the fly-by-wire mode, data transmission is accomplished through an orientable, moderate-gain antenna providing a direct link with the three 210-foot DSIF antennas. Up-link control traffic normally consists of the location coordinates of navigation goals, reprogramming of on-board stored decision processes, and any special commands to read out stored sensor data that are not automatically transmitted. As a backup mode, with degraded performance, or for certain short-term special requirements, the up link can also carry detailed steering, drive, and sensor control commands normally generated on the vehicle.

Down-link traffic normally consists of the values of specified subsystem or system state parameters at the time of execution of any STOP command, and indications of an out-of-tolerance condition for any tolerance-limited variable. Also, stored sensor data are read out on command from earth and additional sensor readings are made and transmitted if and when required.

After the automatically transmitted data are assimilated and evaluated at earth, any of several courses of action may be undertaken upon command from earth.

1. A new destination and path plan may be inserted.
2. Additional sensor data may be requested.
3. A fly-by-wire mode may be entered.
4. Scientific experiments may be undertaken.
5. Special command sequences may be transmitted to alleviate a troublesome control situation.

4.4.3 Master Control Logic

Figure 4-7 shows conceptually what is contained in the Master Control Logic function. Inputs originate from four sources: sensors used directly in the control function, earth commands, the navigation computer, and the transmitter.

As noted above, long-range sensors include imaging systems such as television or facsimile, as well as pulse ranging systems using lasers or radar techniques and radiometers. The use of such sensors implies a concomitant ability to assimilate their outputs to appraise the significance of the data so acquired, and to make valid control decisions based thereon. Although this is clearly true of any sensor, it becomes a much more complex matter in the case of the majority of long-range sensors which might be considered. Thus, one must evaluate not only the usefulness of the type of data acquired by a given long-range sensor, but the means which are required to realize that usefulness. This is discussed more fully in Section 5. Whatever form the long-range sensors take, one of the most difficult portions of the Master Control Logic to implement appears to be the LR Sensor Data Processing function.

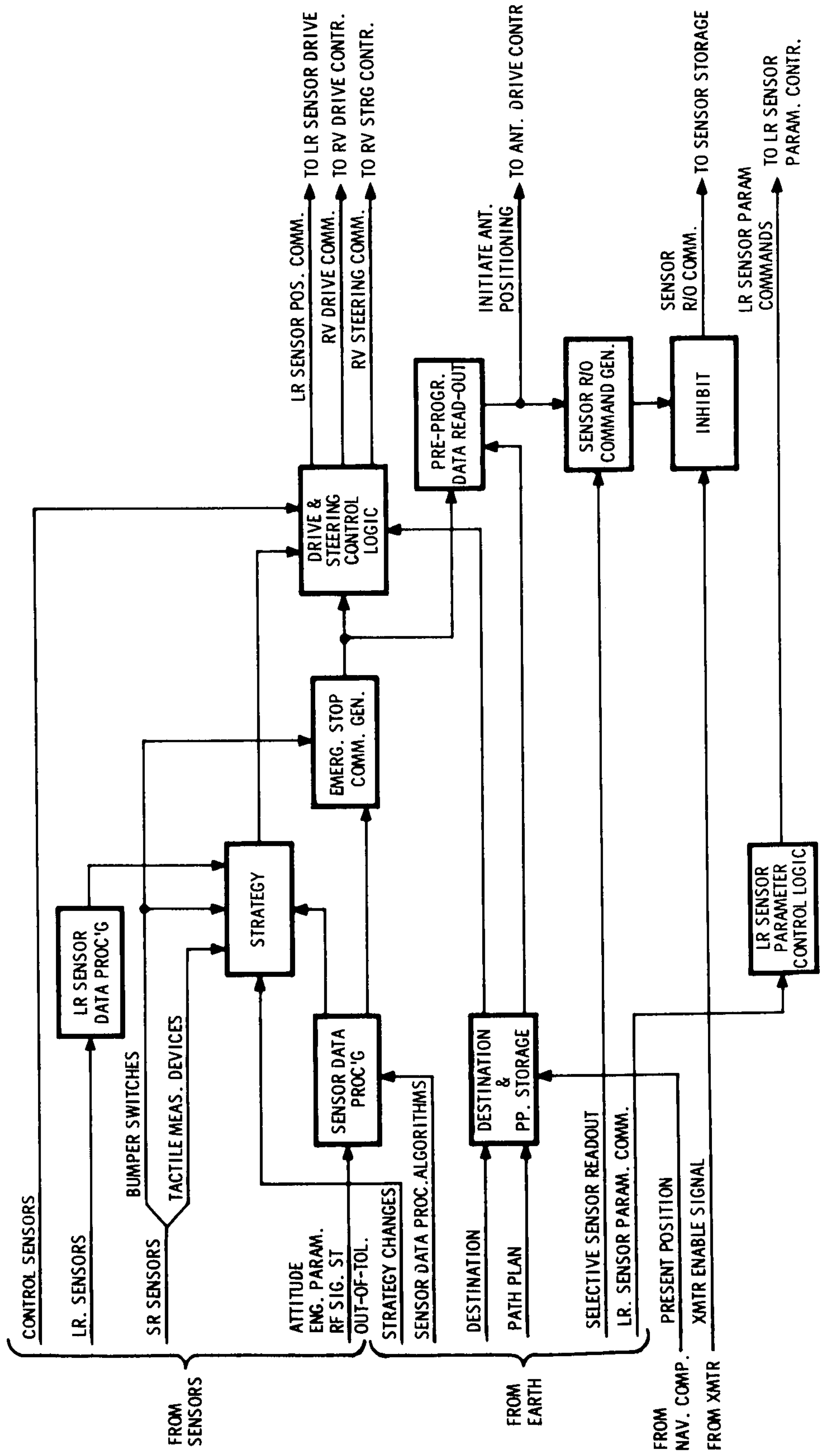

Figure 4-7 Semiautomatic Configuration, Master Control Logic

Sensor data, appropriately processed, are inputted to a stored strategy which, in effect, is a set of preprogrammed responses to various possible conditions that might arise. (One such response will, of course, be to stop the vehicle and await further instructions because the sensor data indicate a situation with which the stored strategy is unable to cope.)

Actions formulated by the stored strategy are transmitted to the Drive and Steering Control Logic, resulting in the appropriate drive and steering control signals to carry out the action. Consistent with the strategy and subject to override by the emergency STOP command generator, this function generates drive and steering control signals to follow the stored path plan transmitted from earth.

Upon issuance of an emergency STOP command, the antenna is automatically oriented, and selected stored sensor data are automatically read out of storage.

4.5 FULLY AUTOMATIC MODE

4.5.1 SFOF-Based Configuration

In the fully automatic mode, the ground-based operational equipment looks much like that for the semiautomatic mode shown in Figure 4-5. The major difference is the removal of the path planning function to the space-based Master Control Logic. This, in turn, eliminates the Command Sequence Generator as an element of the basic system. The SFOF-based complex assumes a monitoring role. Of course, it is desirable that the fully automatic system be capable of operating in the semiautomatic or even fly-by-wire mode, so that these functions are not completely eliminated but are relegated to a backup status.

It is likely that initial programming of a fully automatic system will be based on incomplete information about the environment. Therefore, one of the chief functions of the ground-based operation is to observe the efficiency with which automatic control of the vehicle is carried out and to reprogram the control processes when this would improve effectiveness.

4.5.2 Space-Based Configuration

At the level of detail described in this section the space-based configuration of the fully automatic system, shown in Figure 4-8, is quite similar to that of the semiautomatic.

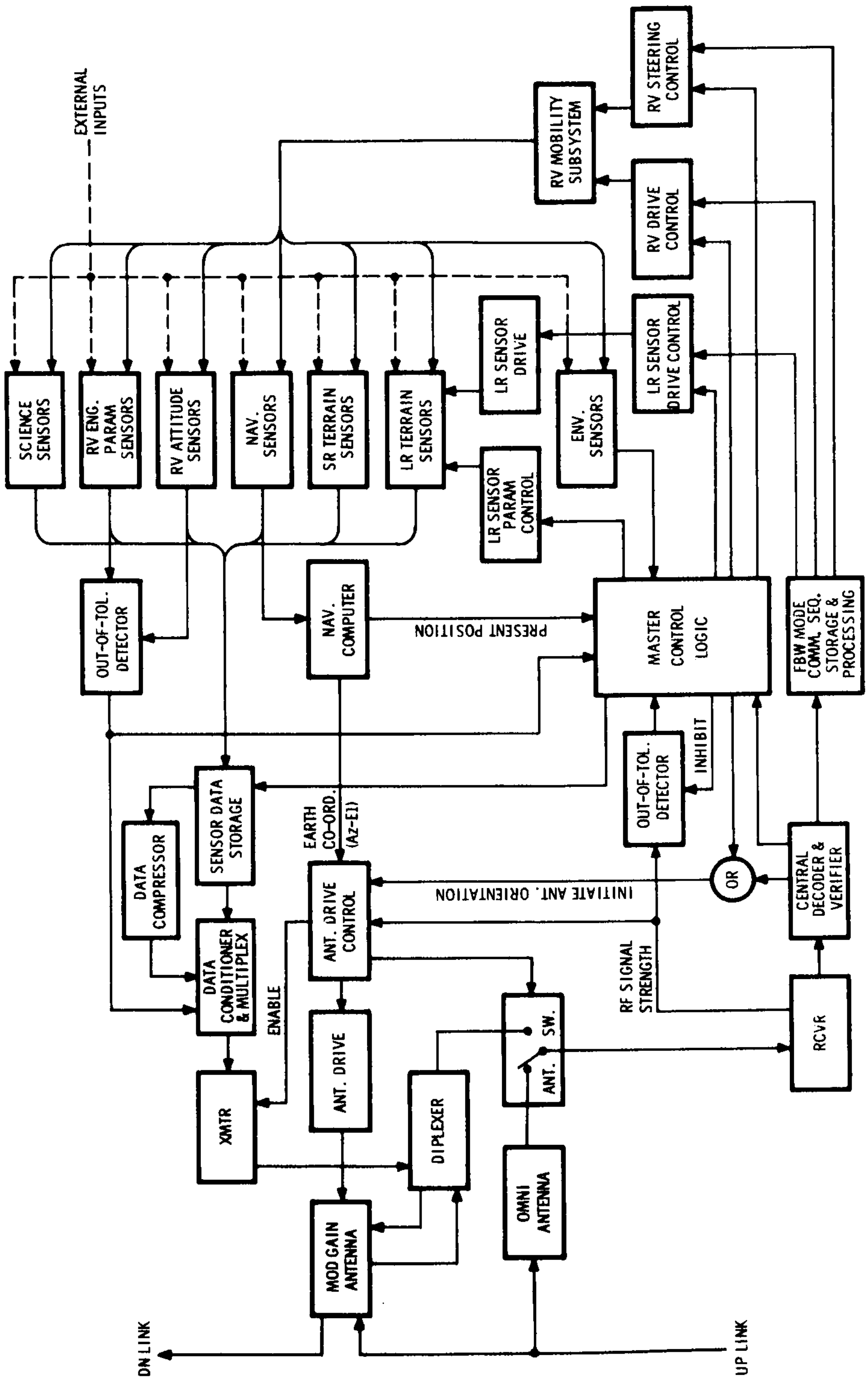

Figure 4-8 Fully Automatic Configuration, Space-Based Equipment

The major differences will be in the Master Control Logic, which must be substantially more sophisticated for the fully automatic system. At the present stage of the RVMC study no means of implementing this capability have been worked out, but it would appear to be a very fruitful place to consider the possibility of learning and adaptive control techniques. Such techniques, at least for this kind of application, are in very early stages of development but show considerable promise where the control problem itself has been clearly defined. Within the Master Control Logic, these techniques would seem to be particularly applicable to the generation of an evolving strategy.

5.0 APPROACHES TO IMPLEMENTATION

In the preceding section, configurations were discussed for each of the six missions. In each case the system configuration consists of an assembly of more or less "standard" subsystems — mobility, telecommunication, sensory, data processing, displays, and operational personnel. The configurations differ mainly in the routing or flow of information and in the relative emphasis or importance of the role assumed by each of the elements. As one proceeds from the fly-by-wire to the fully automatic mode, increasing emphasis is placed upon space-based appraisal of sensed data and less emphasis is therefore placed on telecommunications and ground-based displays and personnel.

When one considers the ways of implementing each of the subsystems it soon becomes apparent that the most difficult problems arise in two areas: 1) Sensing and 2) Appraising. That is, the major difficulties are associated with gathering the information needed for valid and effective control decisions and then assimilating the data so acquired and making the appropriate decisions.

These are not independent problems by any means. The type, quantity, and quality of information needed are intimately related to the means applied to appraising it. If the appraisal is to be conducted on earth one can consider the use of human intelligence and its particular abilities of subjective interpretation and pattern detection and/or recognition. However, this requires transmission of the information across space at restricted bandwidths and significant time lags. If the appraisal is space-based the human cannot be used and the sensory elements must then be chosen to be compatible with realizable data processing mechanizations.

In this section the problems of sensory systems and appraisal are examined with respect to the ways in which they might be implemented. In the case of human appraisal the discussion is concentrated on the problem of getting the required data to the human appraiser — the sensor, communication, data processing, display chain. In the case of machine appraisal, which is less developed, the discussion deals with the sensor-data processing interaction.

5.1 APPROACHES TO SENSOR IMPLEMENTATION

Each quantity which may have to be determined for purposes of remote vehicle control is listed in the first column of Tables 5-1 through 5-4. For each quantity, alternative techniques and associated sensors are shown. It is necessary to establish criteria for choosing between candidate techniques and sensors in order to fulfill the requirements for particular RV missions. The following discussion primarily covers those quantities not sensed directly.

5.1.1 Geometrical Surface Assessment

For purposes of remote vehicle control it is necessary to choose a path which leads toward the goal and which does not exceed vehicle mobility capability. A priori information about the terrain will generally be insufficient to make all judgments ahead of time. Furthermore, uncertainties in the drive and steering controls and navigation errors would make such a predetermined path infeasible even if data were available. Therefore, it seems quite certain that the vehicle will be required to carry sensors to assess local terrain conditions.

Basically, techniques and associated sensors for surface assessment which will permit collection of the required information fall into three classes:

- Imaging Systems
- Ranging Systems
- Tactile Devices

In general, imaging systems require a high order of intelligence for interpretation of oblique views of the surface. This is reflected in difficulties associated with making the appraisal and decision processes automatic, and it therefore generally requires the transmission of data to earth for assimilation. Ranging systems can be mechanized in relatively simple fashion to perform the functions required for control. On the other hand the quantity of information produced (both useful and not useful) is much greater from existing imaging systems than from existing ranging systems. This need not be the case and solutions are suggested.

In addition to their relative adaptability to automation, other functional considerations in choosing techniques and sensors are

- Maximum Range and Ranging Accuracy

Table 5-1
TECHNIQUES FOR DETERMINING RV STATES

Quantity to be Determined	Technique	Quantities Sensed	Possible Sensor	Required Data	Computation and/or Interpretation
RV Attitude With respect to local vertical	Direct measurement	Local vertical	Liquid pendulum, Pendulous Accelerometer, Clinometer	None	None
RV Attitude With respect to horizontal reference	Observe terrain	Horizon	Imaging system, Horizon sensor	Sensor orientation relative to RV	Coordinate transformation
	Inertial	Vehicle attitude relative to stable platform	Angle readout transducers	None	None
RV Attitude With respect to astronomical bodies	Direct observation	Azimuth & elevation of sun, earth or stars	Imaging system	Star charts, orientation of sensor relative to vehicle	Correlation, coordinate transformation
			Sun, star or earth sensor	Orientation of sensor relative to vehicle	None
Temperature Motors Compartments Sensors Battery RTG	Direct measurement	-	Thermocouple Thermistor Other	None	None
Electrical Power Current Voltage	Direct measurement	Power	Microcoulombmeter Wattmeter	None	None
		Voltage & current	Voltmeter Ammeter	None	None
Force & Torque Wheels Steering	Direct measurement	Force	Strain gages Motor currents	None	None
Pressure Compartments Wheel housings	Direct measurement	Pressure	Pressure transducers	None	None
Angles Steering Sensors Antennas Solar Array	Direct measurement	Angle	Transducers	None	None
			Imaging system	Sensor orientation	Coordinate transformation
Positions RI Pellet Clutches Brakes	Direct measurement	-	Limit switches Linear potentiometer		
Vibration, Shock	Direct measurement	-	Accelerometer	None	None

Table 5-2
TECHNIQUES FOR DETERMINING TERRAIN STATES

Quantity to be Determined	Technique	Quantities Sensed	Possible Sensor	Required Data	Computation and/or Interpretation
Terrain Slope Relative to local vertical & vehicle heading	Direct measurement	Attitude of axles with local vertical	See Vehicle Attitude	None	Adjustment for twisting of vehicle
Terrain Slope Relative to vehicle	Direct contact	Surface height relative to vehicle as functions of range and azimuth	Mechanical feelers	None	Compute slope from sample points
	Judgement from monoscopic image	Azimuth and elevation of surface points relative to camera axis	Vidicon Camera Secon Camera Facsimile Camera Photographic Camera Solid State Camera	See text	See text
	Judgement from stereo images (measurement where necessary)	Azimuth & elevation of surface points relative to each of two camera axes	Vidicon Camera Secon Camera Facsimile Camera Photographic Camera Solid State Camera	Length of baseline Attitude of optical axes	Stereo viewing Photogrammetric measurements
	Ranging to surface points	Azimuth, elevation and range to surface points	Laser Range Finder Optical Pulse Range Finder Split Field Range Finder Radar Ranging Sonic Ranging	None	Direct measure of roughness
	Motion parallax and spatial filtering	Relative rates of movement of points in image of surface	See text	None	Safe path selected by the device
Protruding Features Relative to vehicle	Direct contact	Presence of protruding feature	Mechanical feelers Bumper switches	None	
	Judgement from monoscopic image	Same as slope	Same as slope	Same as slope	Same as slope
	Judgement from stereo images (measurement where necessary)				
	Ranging to surface points				
	Motion parallax and spatial filtering				
Concave Features Relative to vehicle	Direct contact	Presence of concave feature	Mechanical feelers	None	Compute slope from sample points
	Judgement from monoscopic image	Same as slope	Same as slope	Same as slope	Same as slope
	Judgement from stereo images (measurement where necessary)				
	Ranging to surface points				
	Motion parallax and spatial filtering				
Soil Characteristics	Surface contact	Bearing strength Cohesiveness	Bevameter Soil Mechanics Inst.	Previous calibration	Can be direct readout
	Judgement from monoscopic image	General appearance	Vidicon Camera Secon Camera Facsimile Camera Photographic Camera Solid State Camera	Previous experience	Photointerpretation
	Judgement from stereo image (measurements where required)	General appearance and three-dimensional characteristics	Same	Previous experience	Photointerpretation
	Seismic	Sound reflections	Microphone-thumper	-	-

Table 5-3
TECHNIQUES FOR DETERMINING ENVIRONMENTAL STATES

Quantity to be Determined	Techniques	Quantities Sensed	Possible Sensor	Required Data	Computation and/or Interpretation
Wind Direction	Direct	Angle	Wind vane, pressure transducer array	None	None
Wind Velocity	From pressure	Pressure	-	Atmospheric density	Calibration
Wind Pressure	Direct	-	Pressure transducer	None	None
Blowing Dust	Indirect	Pressure	Pressure transducer	-	Wind or dust
	Direct	Contact frequency	Particle detector	None	-
Visibility	Observation	Obscuration	Imaging system	Prior images	Judgement
Cloud Coverage	Observation	Obscuration	Imaging system	Prior images	Judgement
Light Intensity	Direct	-	Imaging system, Light sensor	Sensor calibration	Photometric
Temperature	Direct	-	Thermocouple Thermistor Other	None	None
Magnetic Field Int.	Direct	-		None	None
Radiation Flux	Direct	-		None	None
Meteoritic Flux	Direct	-		None	None

Table 5-4
TECHNIQUES FOR DETERMINING NAVIGATION PARAMETERS

Quantity to be Determined	Technique	Quantities Sensed	Possible Sensors	Required Data	Computation and/or Interpretation
Vehicle Position Relative to a lunar or planetary coordinate system	DSIF tracking from earth	In-flight track, Doppler shift	-	-	
	Optical tracking from earth	Position of laser or sun reflector on surface	Telescope	Reference maps or photos	Correlation
	Observe from orbiting module	Position of vehicle on surface	Telescope Camera	Location of visual field relative to coordinate system	
	Celestial fix from RV	Location of star or stars Location of sun	Television Star tracker Sun sensor	Reference star field or star tables	Correlation
Vehicle Position Relative to landmarks and/or previous vehicle positions	Dead reckoning	Distance traveled (history)	See distance traveled below	None	Vector summation
		RV Heading (history)	See vehicle heading below	None	
	Pure inertial	Acceleration components of velocity vector	Inertial system	Initial position	Integration and vector summation
	Correlation	Terrain characteristics	Imaging system	Map or photo	Visual correlation
		Slope	Clinometers	Contour map	Cross correlation
	Observe from orbiting vehicle	RV relative to terrain features	Telescope, camera	Previous terrain data	Visual correlation
	Measurement from surface features	Distance & bearing to one feature	Laser range finder Optical range finder Stereo imaging Radio range & bearing	None	None
		Bearing to one feature from two known points	Theodolite Imaging system Radio direction finder	Distance apart of points	Trigonometric calculation
Vehicle Heading Relative to lunar or planetary coordinate system	Celestial	Sun position Star positions	Fixed sun compass Stabilized sun compass Imaging system	Roll, pitch, ephemeris	Coordinate transf. Trig. calculation
	Inertial heading	Azimuth deviations from initial azimuth	Stable platform & directional gyro	Initial heading	None
	Gyro compass	Rotation rate of body	Stable platform	None	None
	Magnetic field	-	Magnetic compass	Declination	Subtraction of angles
	Observe from orbiting module	RV heading relative to visual field	Telescope, camera	Relation of visual field to coordinate system	Subtraction of angles
Vehicle Heading Relative to surface features	Direction to surface features	-	Theodolite Imaging system Radio direction finder	Angle of sensor with vehicle	Identification of surface feature
Distance Traveled	Wheel rotation	Wheel rotation	Odometer	Distance/revolution	Integration
		Wheel rotation	Wheel pulse transducer	Distance/revolution	Addition
	Speed x time	Wheel speed	Speedometer	Movement time	Multiplication or Integration
	Inertial	See vehicle position	-	-	From positions
	Measurement from surface features	See vehicle position	-	-	From positions

- Demands on the data link to earth to give the required resolution, geometrical surface information and frame rate
- Commonality of equipment for performing different functions.

a. Monoscopic Images. A single image contains a record of the azimuth and elevation of surface points with respect to the camera lens axis. No information is available concerning the absolute range of points except for focus changes with distance.

Using visual focus, ranging capability of monoscopic imaging would be about as shown in Figure 5-1. This assumes sufficient fine, high-contrast subject detail. For a 100mm lens at f/8 a subject in focus with a 50-foot lens setting could actually be at a range of from 39 to 71 feet. A subject in focus at 20 feet could actually be from 18 to 23 feet. Focusing is an iterative process and is wasteful of pictures and power.

The frequency content of the video is the convolution of the television bandpass and the spatial frequencies present in the subjects as reproduced by the lens. If the subject contains sufficient high-frequency information, the system video output could be passed through a wave analyzer and best focus accomplished by maximizing the amplitude of frequencies at the upper end of the band-pass. This might reduce the range error over that resulting from visual focus. However, it is still a wasteful iterative process.

In theory, one might measure range without focusing by determining the frequency spectrum of a subject relative to the spectrum when it is in focus. This would require ways of isolating portions of scans for analysis. Probably this would give range accuracy comparable to that using visual focus and with only one picture. This could be automated for rapid ranging but would require extensive development.

A human viewing a single image can often make a judgment as to the negotiability of a proposed path using some of the following clues:

- Relative sizes of known objects or texture
- Comparison with previous experience
- Perspective
- Position of one object in front of another
- Variations in sharpness as a function of range
- Shadows
- Color and shading
- Texture compression.

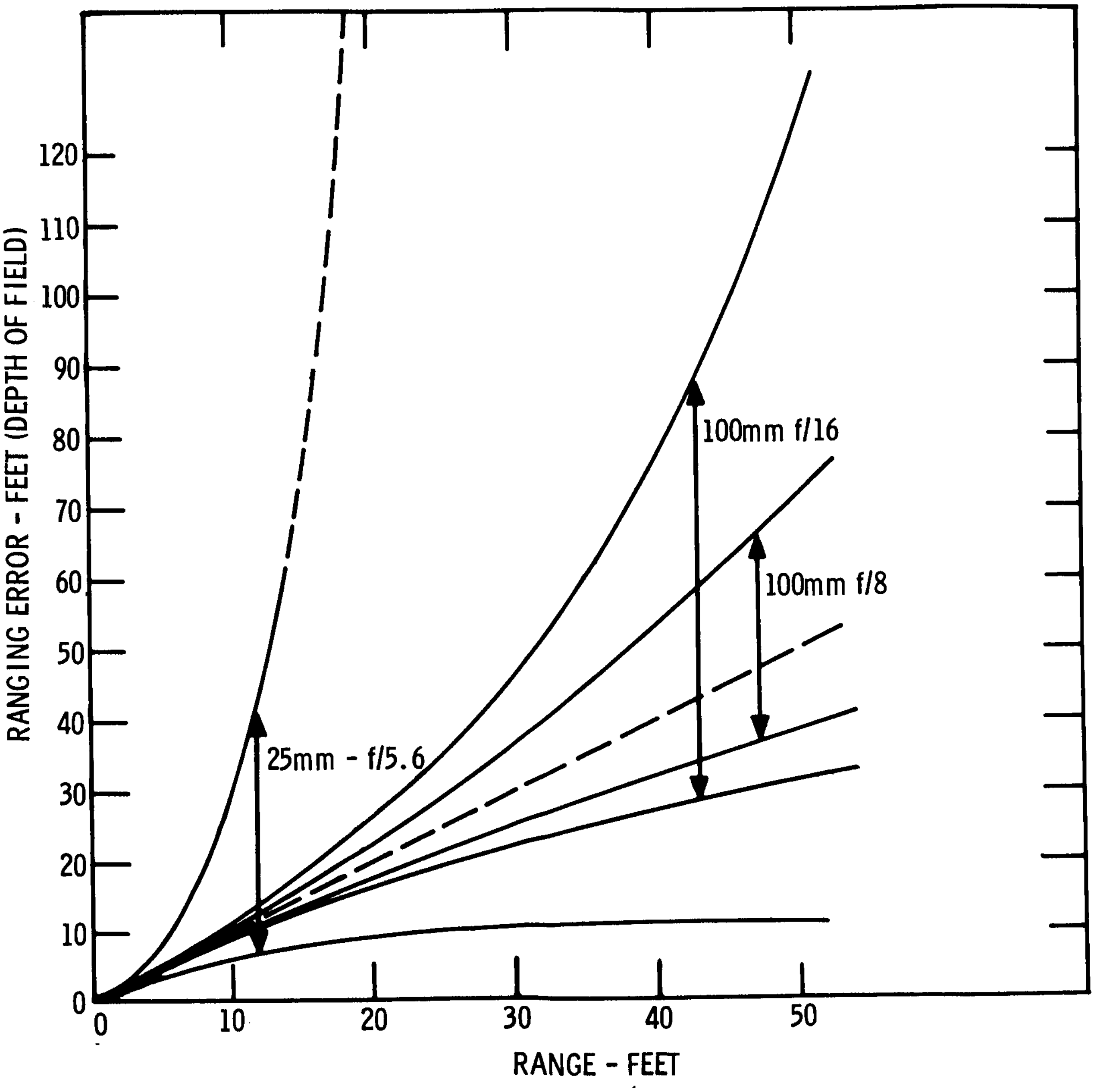

Figure 5-1 Television Lens Depth of Field vs Range and Aperture

In many cases these clues are not sufficiently well defined for the interpreter to make a valid judgment. Except for very special subjects, machines are not available to make such judgments at all. From the above, it can reasonably be concluded that, where monoscopic images are used for terrain assessment, they must be transmitted to earth for human interpretation.

b. Stereo Images. Each member of a stereo pair contains a record of the azimuth and elevation of each surface point with respect to its respective camera lens axis. A human interpreter can usually detect similar patterns representing the same feature in the two pictures and fuse them visually to determine qualitatively, the three-dimensional nature of the subject. If the length of the stereo baseline and the orientation of the lens axes are known, the size and distance of objects can be measured using visual aids or photogrammetric techniques.

No machines have yet been built to do this reliably in the case of oblique views containing abrupt discontinuities and subtle patterns. Development work at MIT is aimed toward a computerized solution to this problem. It remains to be seen whether this can be accomplished, and if so how such a mechanization compares with the direct ranging methods discussed in the following section.

c. Ranging to Surface Points. Ranging devices fall into four classes, as follows:

(1) A laser, noncoherent optical, radar or sonic type ranging device using time of return for a pulse provides direct readings of range from the vehicle to a reflecting surface point as a function of azimuth and elevation. Pulse rate must be low enough, as a function of maximum range, to prevent ambiguous returns. Only laser ranging or noncoherent optical pulse ranging would appear to offer adequate resolution and signal-to-noise ratio for vehicle control purposes.

One or several such devices, with fixed axes, would be adequate to detect a large obstacle in front of the vehicle. Many such devices would be required to provide sufficient coverage at close enough spacing for accurate surface assessment. This does not appear practical but if one rangefinder were used in a scanning mode, surface coverage could be adequate.

Published information[1, 2] indicates that most commercially available laser rangefinders of this class are for high-power (kW), long-range (miles) applications. It is not yet evident whether laser equipment suitable for an RV can be or will be developed.

Optical pulse-ranging experiments,[3] using a noncoherent source, have demonstrated accuracies within a few cm at ranges from 10 to 100 meters. Short-burst repetition rates of about 10^4 pps are possible. Equipment reportedly would be simple and light weight.

(2) A number of optical systems have been built which sense objects at fixed ranges as established by the point of intersection of converging transmitter and detector beams. Transmitters have included lasers[1] and GaAs[4, 5] diode emitters. For discrimination against ambient light, the output of the diode emitters is usually pulsed at a frequency such as 10 KHz.

In order to scan a volume it is necessary to vary convergence of the two beams as well as vary azimuth and elevation. This, plus the fact that such triangulation devices are inherently only accurate at short ranges, makes them most useful as fixed range sensors for nearby obstacles.

(3) Various split field or coincidence type ranging schemes could be incorporated into imaging systems. Since operation depends on pattern recognition, they could not be easily automated.

(4) It is possible to evaluate surface roughness using motion parallax and spatial filtering techniques. If two or more images are made from different vantage points, relative displacements of points in the images vary as a function of subject distances. If the images are formed with an open shutter while moving, the length of motion-blur of objects will vary with distance. This fact has led to a variety of concepts for automated photogrammetry. One is the synthetic aperture camera.[6] All such concepts suffer from certain theoretical difficulties in automating the process of forming an image (perhaps a profile or contour) of features at a given distance and at the same time removing multiple or blurred images at other distances.

However, it is also characteristic of an image formed in such a manner, that points at different distances move at different rates relative to one another during image formation. Thus if an image-forming device were pointed in the direction of vehicle travel, all surface points would move radially from the velocity vector as shown in Figure 5-2.

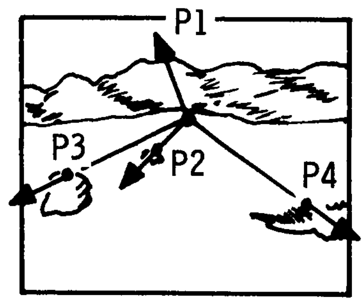

Figure 5-2 Apparent Radial Motion of Points

Image points would move at increasing rates as they became nearer. For any given radial line, the rates would vary with displacement of features from a flat surface. Thus spatial filtering techniques and frequency measurement might be suitable for detection of surface roughness exceeding some maximum value. Jitter of the vehicle velocity vector might require such a device to supply its own motion.

Figure 5-3 shows how such a device might look.

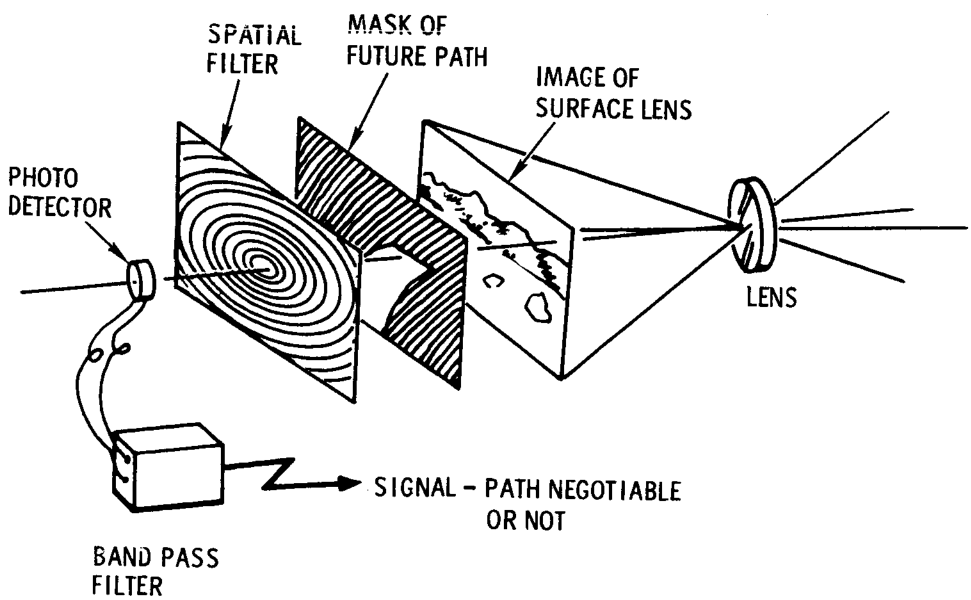

Figure 5-3 Spatial Filtering Arrangement

One mask would be used for each possible future vehicle path.

In theory this system would provide go-no-go outputs from very-high-quality imputs with the exception of occulted surface features. A study should be made of this approach to determine if it seems feasible using practical hardware.

5.1.2 Navigation

It will quite likely be necessary to accurately know RV position relative to a frame of reference based on surrounding surface features. Only secondarily is it necessary to know the location of such a reference frame relative to lunar or planetary coordinate systems.

Therefore, in Table 4-4, techniques for determining RV position are divided into those relative to lunar and planetary coordinate systems and those relative to surrounding surface features.

DSIF tracking from earth requires no special equipment in space for determination of initial position of a RV relative to lunar or planetary coordinates. Initial position on the moon could be known within an area 400 meters by 2800 meters[7] from in-flight tracking and subsequent doppler information. Initial position on Mars would be known with less accuracy.

Optical tracking, from earth, of a laser or solar reflector on the RV would permit accuracy of ± 40 meters in location with respect to both surface features and selenographic coordinates. This is a function of earth-based telescope resolution and would obviously be much poorer for Mars. Optical tracking would also be limited by atmospheric seeing conditions.

For the moon, correlation of orbiter information with surface features as observed from an RV would permit even greater accuracy. Location of the RV with respect to selenographic or areographic coordinates would then be primarily dependent on knowledge of the location of an orbiter photograph with respect to that coordinate system.

A celestial fix from the RV would require use of on-board equipment and at best would give location accuracy comparable to that obtained by this method on earth. Such accuracy, about one km, would probably not be suitable for traverses.

It seems likely that DSIF tracking is best for determination of initial position considering hardware requirements and the accuracy on initial position likely to be required for vehicle control.

For determination of RV position relative to landmarks and/or previous vehicle positions, a combination of dead reckoning and measurements from surface features is a practical approach.

Dead reckoning position would be calculated from distance traveled as a function of wheel rotation and azimuth heading determined from an inertial heading reference or possibly from a sun compass.

No existing pure inertial system appears to be practical because the accelerometers would have to operate in the low nonlinear region of their operating curves. The necessity for periodic calibration would also pose a serious problem. This possibility should be looked at more carefully, however, especially in view of recent work in inertial components.

Although correlation of observed surface features with features in orbiter photographs may be practical for a lunar RV (assuming the ability to identify objects in both views) it might not be practical for Mars because of the lower resolution proposed for Mars orbiters. In any case it would appear more useful as an auxiliary or backup mode rather than as a routine navigation tool.

In summary, then, it seems that DSIF position fixing is best for determination of initial position with respect to body coordinates. Dead reckoning, in combination with periodic fixes from surface features, appears suitable for positioning along the traverse.

5.2 COMMENTS ON IMPLEMENTATION OF THE APPRAISAL AND DECISION FUNCTIONS

In the fly-by-wire mode, sensor data are transmitted to earth and the appraisal and decision processes are carried out by human beings. Computers may assist in these functions by converting the data to a form more suitable for human evaluation, but the final appraise/decide activity is a human one.

As these processes are moved to the vehicle in the semiautomatic and fully automatic modes, it becomes necessary to replace the human with increasingly sophisticated automatic equipment. Since the situations which the system will be called upon to appraise are highly unpredictable and diverse, it is unlikely that a unique response can be preprogrammed for every possible situation. Even if situations could be grouped into classes and the most likely classes were to be handled this way, reverting to fly-by-wire in unusual situations, it seems to be a very difficult matter to describe these classes in a quantitative manner suitable for preprogramming a set of responses. Each class would contain a myriad of minor detailed nuances which are handled by the human through subjective judgment and intuition, but which must be made much more explicit for a machine. For example, as noted above, the human is able quickly to detect and recognize patterns in visual images and to fuse them into a stereo image. Techniques to do this by machine are in their infancy.

These factors lead to the consideration of concepts such as adaptive logic, learning machines, and self-organizing machines. The various terms used to describe such concepts reflect a desire on the part of the designer to imbue the system with a modicum of human-like intelligence. Presumably this would enable the RVMC system to change its operating parameters in accordance with its immediate environment, to recognize and interpret patterns, and perhaps also to profit from mistakes.

The possibilities are fascinating and are very tempting, especially in the Martian case. A sizable literature is accumulating on these subjects, indicating a great interest and considerable effort. Most of the literature, however, seems to deal with theoretical aspects and is concerned only superficially with practical implementation problems. Most cases where experiments have been carried out indicate that data processing requirements are extensive and that a considerable amount of research and development is needed before these approaches will be practical.

This is not to minimize the potential that exists here. It is indeed great. Current trends in data processing hardware indicate some very much increased data storage and processing capabilities per unit weight, volume, and power in the not too distant future. One writer(8) has predicted a 200-fold increase in data processing speed and a reduction in size by a factor of 1000, together with substantial improvements in reliability over the next ten years. Progress in software is needed now if these trends are to be exploited in applications of the RVMC type.

6.0 MISSION OPERATIONS ANALYSIS

6.1 SYSTEM VALUE MEASURES

The systems requirements analyses of Section 3 and the mission characterizations of Section 2 provide a basis for functional configuring of RVMC systems as accomplished in Section 4. In proceeding toward system implementation it is eventually necessary to reconsider the basic constraints and, in the light of hardware capabilities, to determine for the system its feasibility, effectiveness in accomplishing the mission, cost, and desirable values of subsystem and system parameters. This is considered in this section in terms of a general mission operational analysis.

The initial problem associated with mission operational analysis is to devise rational, measures of performance and cost. It is then necessary to combine these measures into meaningful criteria of performance. A number of measures have been conceived for the RVMC study, and these are listed in Tables 6-1 and 6-2. Techniques for utilizing these measures in mission operations analyses are discussed in Section 6.2 and means of quantifying some of these are considered in Section 6.3. The listing of a factor does not imply that it will (or should) be an output of the RVMC study but only that it must, at some time, be considered in the final choice of a system.

Evaluation of RV systems can be subdivided into two major categories:

1. Benefit factors — factors of the type one normally wishes to maximize
2. Cost factors — factors of the type one normally wishes to minimize.

Within these divisions, comparison of competing systems and optimization of system parameters depends upon evaluation parameters of three primary types, viz.,

1. Mission-related measures — i. e., measures of the RV system's effectiveness in accomplishing its mission;
2. Development factors — i. e., measures of the risks, costs, and benefits associated with a program to develop the necessary hardware and software for an RV mission;
3. Operational parameters — i. e., measures of the hardware and software capabilities needed to conduct an RV mission including measures of system and component reliability, operating costs, and human and equipment duty cycles.

Table 6-1
BENEFIT MEASURES

Mission-Related Measures

Realizable (expected) total traverse
Realizable (expected) total travel
Effective vehicle mobility
Realizable (expected) vehicle mobility (% of surface area accessible to vehicle)
Duty cycle for each mode
Realizable (expected) mission duty cycle
Payload weight
Ratio of payload weight to gross vehicle weight (g. v. w)
Payload packaging envelope
Vehicular functions and functional utility
Political and sociological values

Development Factors

Contributions to other NASA and US programs

- Vehicle mobility systems
- Terrain sensor systems
- Vehicle-borne logic and computer systems
- Earth-based logic and computer systems
- Earth-based display systems
- Telemetry systems, vehicle-borne
- Telemetry systems, earth-based
- GCS systems
- Vehicle navigation systems
- Other vehicle sensor systems
- Materials
- Methodology
- Computer software
- Human engineering

Economic value to A/S industry
Effect on employment
Political and sociological values

Operational Parameters

Alternate mode capability
Auxiliary mode capability
Ability to adapt to changing and/or unexpected operation conditions within primary, auxiliary, and alternate modes
Contributions to DSIF, SFOF, GCS and personnel
Capability of use to other NASA or US programs
System and subsystem equipment reliabilities
System and subsystem operational reliabilities in each mode
Emergency backup control devices availability and capability
Emergency mobility devices availability and capability

Table 6-2
COST MEASURES

Mission-Related Measures

- Gross vehicle weight
- Payload interface requirements
- Boost vehicle interface requirements
- "Spacebus" interface requirements
- Lander interface requirements
- RV storage requirements
- Realizable (expected) ratio travel distance/traverse distance
- Realizable (expected) time p.u.t. (per unit traverse)
- Realizable (expected) number of internal (i.e., internal to RV) commands p.u.t.
- Realizable (expected) number of external (i.e., external to RV) commands p.u.t.
- Realizable number of internal commands p.u.t. in each mode
- Realizable number of external commands p.u.t. in each mode
- Realizable (expected) amount of information transmitted downlink p.u.t.
- Realizable (expected) amount of information transmitted uplink p.u.t.
- Realizable amount of information transmitted downlink p.u.t. in each mode
- Realizable amount of information transmitted uplink p.u.t. in each mode
- Realizable (expected) number of downlink transmissions p.u.t.
- Realizable (expected) number of uplink transmisstions p.u.t.
- Realizable number of downlink transmissions p.u.t. in each mode
- Realizable number of uplink transmissions p.u.t. in each mode
- Realizable (expected) energy expenditure for mobility and control p.u.t.
- Realizable energy expenditure for mobility and control p.u.t. in each mode
- Realizable (expected) power profiles for mobility and control p.u.t.
- Realizable power profiles for mobility and control p.u.t. in each mode
- Power system interface requirements
- Political and sociological costs

Development Factors

- Direct development expenditures
- Development risk
- Development time required
- Amount of mission dependent equipment development required
- Amount of mission dependent software development required
- Skilled labor requirements for development program
- Political and sociological costs of development

Operational Parameters

- Control mode restraints on operational period(s)
- Control mode restraints on launch operations
- Sensitivity to telemetry quality
- Sensitivity to astrodynamic constraints
- Sensitivity to human operator skills
- Sensitivity to DSIF, SFOF, and GCS operations
- Sensitivity to success of other NASA programs
- Dependence on overseas operations
- Quantity and quality of personnel required
- DSIF, SFOF, and GCS requirements
- DSIF, SFOF, and GCS duty cycles
- Diversion of DSIF, SFOF, and GCS capability from other US programs
- Realizable (expected) number of automated decisions p.u.t.
- Realizable (expected) number of human decisions p.u.t.
- Realizable number of automated decisions p.u.t. in each mode
- Realizable number of human decisions p.u.t. in each mode
- Probability of machine error resulting in mission abort
- Probability of human error resulting in mission abort
- Flight hardware procurement costs
- Flight software procurement costs
- GSE hardware procurement and/or modification costs
- GSE software procurement costs
- Operating personnel costs
- GSE and facilities operating costs
- Overhead and maintenance costs
- Operational political and sociological costs

In Tables 6-1 and 6-2, the terms "effective," "expected," and "realizable" occur repeatedly. The terms are used to reflect three of the stochastic influences on the mission and are to be interpreted as follows:

1. Effective - Vehicle performance is affected by the finite precision with which it can be built. Furthermore operational requirements will, in general, dictate that the RV systems not be used to their fullest capability. The "effective" value of a parameter is then a degraded value which allows for equipment imprecision and operational restraints.
2. Realizable - The RV operates over a terrain which is described in a statistical manner. The "realizable" value of a parameter denotes the statistical average of the parameter for a real RV operating over such a terrain excluding the effects of human and equipment failures or errors. The term "real RV" indicates that "effective" values of parameters are used in the analysis.
3. Expected - The "expected" value of a parameter is a statistical average of the parameter for a real vehicle operating on a stochastically described terrain including the effects of human and equipment fallibility.

Three general types of operational modes are envisioned, viz.,

1. primary mode(s) - The primary modes are the usual operating modes assuming no particular operating difficulties and no equipment failure.
2. auxiliary mode(s) - The auxiliary modes are special modes entered because of particular operational difficulty assuming no equipment failure.
3. alternate mode(s) - Alternate modes are operating modes employed because of equipment failure.

Traverse distance refers to actual progress in the direction of a mission objective. Travel distance refers to actual distance traveled regardless of progress toward an objective. "Guidance" and "navigation" are used in the usual sense to denote a priori and a posteriori navigational situations.

6.2 EVALUATION CRITERIA

A number of evaluation parameters have been listed in Tables 6-1 and 6-2. Two central problems remain.

1. Quantifying the parameters to be used in evaluating a given system.
2. Devising criteria to evaluate systems and the methodology to apply the criteria.

This section is concerned with the evaluation criteria and discusses a possible methodology in a general way. The problem of quantifying the parameters is discussed in Section 6.3.

One technique for evaluating systems is to combine a benefit factor and a cost factor into a mission effectiveness factor. For example, expected total mission traverse and expected total mission time may be combined to give expected mission speed. This factor might then be optimized through parametric tradeoffs and in turn traded off with total development, hardware, and operational monetary costs. Such studies would undoubtedly be of considerable interest. Unfortunately, further extension of such an approach leads to serious difficulties in interpretation of the results, while failure to consider all significant parameters may lead to an inaccurate appraisal of total RV system desirability. Thus, the need for a more sophisticated analysis to at least provide a check on this simple approach is apparent in view of the complexity of roving vehicle systems.

It is desirable, therefore, to devise a composite measure of merit for RV systems which considers all parameters of importance (or at least those whose desirability can be rationally quantified) giving an accurate appraisal of overall system desirability. The inclusion of several parameters in the computation of a figure of merit complicates the analysis in three ways.

1. Means of measuring and quantifying the additional factors must be devised
2. The construction of a composite measure must be carried out and justified, properly accounting for differences in the significance of the various parameters
3. The derivation of a computational algorithm becomes increasingly difficult as the number of parameters increases.

This section is concerned primarily with the second of these complications; the first is considered in the following section. The third has not been considered in detail as of this writing.

A straightforward approach which has been widely used is to utilize a weighted sum of measures as a composite figure of merit. Normalization of each factor is desirable for interpretational convenience and nonlinear normalization curves may be employed to account for nonlinear effects such as the law of diminishing returns. Such procedures have been developed and are of considerable value in evaluating complex systems. The primary difficulty in implementing this approach is the rational assignment of weighting factors to the parameters of interest. The problem is particularly acute if the parameters employed are interdependent and particularly if this interdependence cannot be explicitly expressed. The nature of the RVMC problem is such that these problems make implementation of a weighted sum approach extremely difficult. Another approach has been derived to alleviate these difficulties. It is described below.

Recognizing that any evaluation criterion involving more than one measure must include engineering judgment as to the relative importance of the various measures, the approach outlined here attempts to apply this judgment at as elementary a level as possible. The values of each parameter, from the ideal value attainable to the worst value acceptable to an RV mission, are plotted against the numbers from zero to one with one corresponding to the ideal value and zero to the worst value acceptable. It is required that the curves be drawn so that the values of all factors associated with a given number m, $0 \leq m \leq 1$, be considered equally desirable; i.e., if f and g are two parameters being considered, then f (m) and g (m) must be equally desirable. These curves are called "desirability curves" and the number, m, associated with a given value of a factor is called its "desirability number."

Systems are then evaluated as follows:

1. The values of each factor to be considered are computed.
2. The desirability number of each factor is derived by comparison of the value with the factor's desirability curve.
3. The set of desirability numbers for each system may be ordered to form the "desirability vector" of the system.
4. The "figure of merit" for the system may be defined as the minimum of its set of desirability numbers (the least component of its desirability vector).

Step 4 essentially states: "A system is as desirable as its least desirable characteristic." This criterion may be debated, but it is felt that it has merit for this type of study.

In the evaluation of systems, the desirability vector identifies immediately the weaknesses and strengths of the system. Computerized studies in which design parameters are varied and the desirability vectors are computed may then serve to identify the areas where further development would do most to improve system desirability. The "figure of merit" may be used in design synthesis by varying design parameters and using a computer search routine to determine combinations of design parameter values which maximize the system's figure of merit. (The net effect of such an optimization procedure is to move the various measures toward a "desirability contour.") There is no requirement that the system measures be independent in this procedure. Furthermore, if system constraints make a system unfeasible, this fact may be readily identified through the impossibility of computing a complete desirability vector for the system.

Secondary criteria may also be used in evaluating or comparing systems such as:

1. maximizing a sum or a weighted sum of desirability numbers (in general, such a procedure should be limited to mutually independent parameters)
2. maximizing the length of the desirability vector (again this procedure should generally be limited to mutually independent parameters).

The exclusive use of such secondary criteria reintroduces the problems associated with weighted sum evaluations.

The desirability curves could be generated from detailed analysis of the scientific missions. The engineering judgment inherent in the curves could then be exercised at an elementary level within the mission analysis. Such studies are beyond the scope of the present analysis, so the generation of desirability curves is not further considered.

6.3 MISSION SIMULATION

The central problem of quantifying the measures of system performance and cost listed in Section 6.1 remains. Since it is extremely difficult, if not impossible, to rationally quantify all of these measures, verbal descriptions of some must suffice. The remainder may be quantified through analytic, computer, or experimental simulation of RV missions. Due to the multiple stochastic influences on an RV mission only statistical measures may be expected, with analytic studies couched in terms of probabilities and statistical averages, and computational studies generally of a Monte Carlo type. Only analytic approaches have been utilized to date, and it is this work which is summarized in this section.

Figure 6-1 is a simplified flow chart of a portion of the analytic (or computer) simulation of an RV mission. Each circle represents a sub-study with input and output

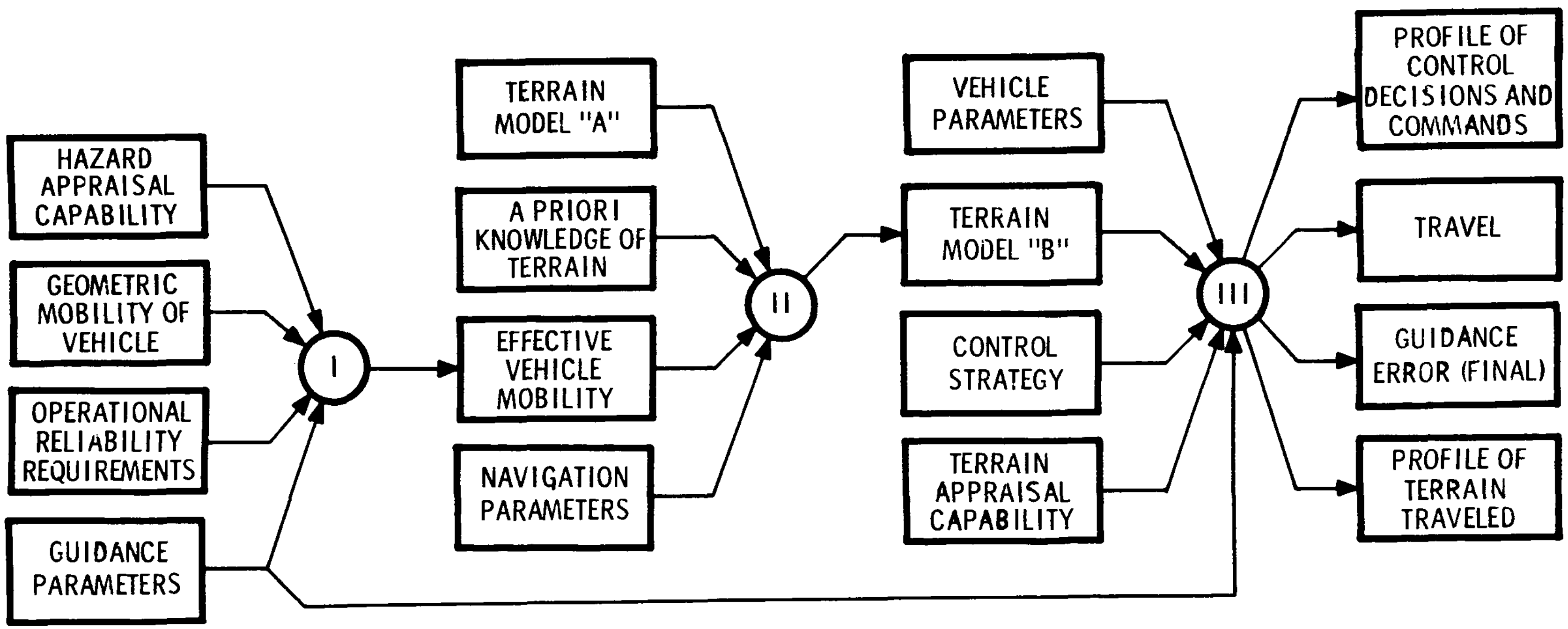

Figure 6-1 Simplified Analysis Flow Diagram

parameters indicated in the customary manner. Note that the input parameters are themselves outputs from analyses which may be complex and that the boxes, in general, represent a family of parameters. Study I is a straightforward computation in which the ideal mobility performance of the vehicle is degraded to allow for uncertainties in the measurement of obstacles by the sensor system, inability to precisely control the vehicle's motion and restraints on vehicle operation imposed by safety or operational considerations. Study II utilizes a terrain model consisting of a power spectral density description of a terrain overlaid with a random distribution of hazards satisfying a statistical size distribution as discussed in the First Quarterly Report. The study recognizes that mission planners may have preflight information (say from orbiter photographs) which may be used to set an upper limit on the size obstacles to be avoided by the roving vehicle, depending upon the ability to locate the RV with respect to known features. Effective vehicle mobility may be used to establish a lower size limit on obstacles to be considered so that a new terrain model is defined which includes only those obstacles of operational concern. Both of these studies may be conducted analytically provided the necessary inputs are available.

An analytic approach to Study III is outlined below. If the range at which obstacles can be effectively sensed and appraised is small in comparison to the mean distance between obstacles, the average number of obstacles of mean diameter between d_i and $d_i + \Delta_i$ encountered per unit travel is given by

$$n_i = N_i (\bar{d}_i + w) \tag{6-1}$$

where

N_i = number of obstacles of mean diameter between d_i and $d_i + \Delta_i$ per unit area (derived from terrain model "B")

$\bar{d}_i$ = average mean diameter of obstacles with mean diameters in the range from d_i to $d_i + \Delta_i$

w = <u>effective</u> vehicle width.

Equation (6-1) is derived as follows: an encounter with an obstacle occurs whenever the distance from the center of the obstacle to the center of the vehicle path is less than $(d/2) + (w/2)$ where d is the obstacle diameter and w is the vehicle width. The average number of encounters with obstacles of diameter d per unit travel may then be computed by multiplying the area swept by a vehicle of width $(d + w)$ traveling a unit length by the areal density of such obstacles. (Essentially, all obstacles are considered to be points and the vehicle is assumed to have width $(d + w)$.)

Total travel, T, in traversing a distance, τ in a given mode is given by

$$T = \tau + \sum_{i=1}^{K} P_i n_i T \qquad (6\text{-}2)$$

where P_i is the average extra distance (penalty) required to negotiate around an obstacle of mean diameter between d_i and $d_i + \Delta_i$. The summation is carried out over the size range of obstacles to be considered. The ratio T/τ is then

$$\frac{T}{\tau} = \frac{1}{1 - \sum_{i=1}^{K} P_i n_i} = \frac{1}{1 - \sum_{i=1}^{K} P_i N_i (\bar{d}_i + w)} \quad . \qquad (6\text{-}3)$$

This ratio increases without bound when $\sum_{i=1}^{K} P_i n_i$ approaches one. Noting that the average distance between encounters (mean free path length) is

$$\lambda_m = \frac{1}{\sum_{i=1}^{K} n_i} = \frac{1}{\sum_{i=1}^{K} N_i (\bar{d}_i + w)} \qquad (6\text{-}4)$$

it is apparent that this occurs whenever the average penalty associated with negotiating around the obstacles equals the mean free path. In this situation the vehicle would engage in a sort of two-dimensional random walk. To avoid this unpleasant possibility the range capability of the sensors should not be small in comparison to λ_m, if the average penalty associated with avoiding obstacles is comparable in length to the mean distance between obstacles.

The above analysis is useful if, and only if, the range at which obstacles of a given type and size are detected is small in comparison to the mean distance between those obstacles ($\lambda_i = 1/n_i$) and the P_i can be computed. Since this fundamental restriction on the analysis applies with respect to specific obstacles, one may expect to be able to use the approach as part of a general analysis even though the restrictions violated for certain types and/or sizes of obstacles. It is important that the range capabilities of the sensor utilized in this connection be degraded to allow for masking of terrain as well as for sensor system performance.

Computation of the P_i is sensitive to control strategy (see Figure 6-2 for a typical strategy), to terrain appraisal capability (measurement capability and area coverage including masking effects), to vehicle parameters (turning radius and control flexibility), and to vehicle guidance parameters (particularly the ability to determine a priori the

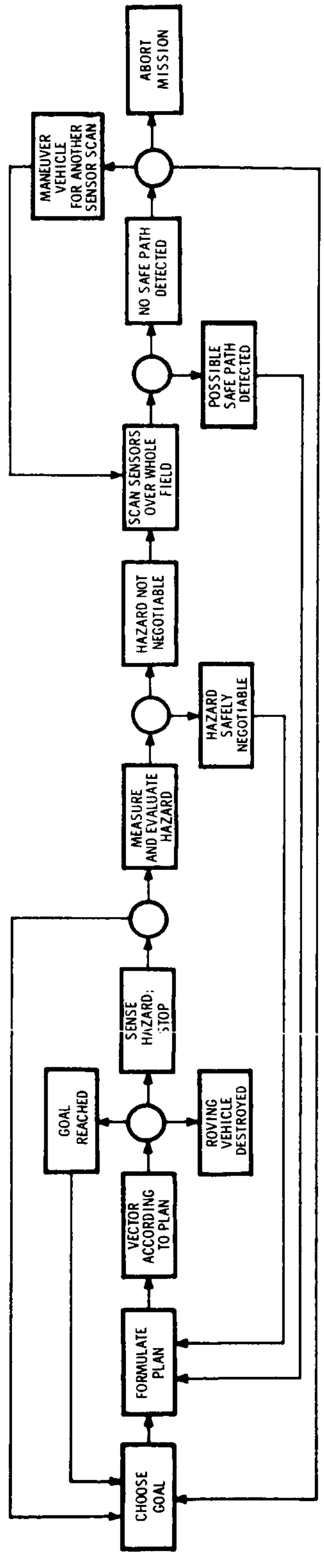

Figure 6-2 Typical Control Strategy

vehicle's path). In general, the P_i must be computed separately for each operational mode. To obtain realizable and expected values of the P_i, the probabilities of entering each auxiliary and alternate mode would be computed and used as weighting factors to yield a weighted average of the individual mode values. Analytic expressions for the P_i have been deduced for specific control modes where sensor capabilities are quite limited and/or control strategies are simple.

Complex strategies used in conjunction with extensive sensor capabilities have not been successfully treated. (Note that such a combination would probably violate the basic assumption of the above analysis that the range capability of the sensor with respect to the obstacle considered is small in comparison to λ_i.) It seems, therefore, that Monte Carlo and/or experimental simulations are needed to obtain definitive results in this area. The above analysis could be modified (that is the means of computing n_i changed) to permit inclusions of cases violating the basic assumption. However, since the only feasible method of computing the n_i in such cases may be through computer simulation, it might be preferable to simulate the entire problem.

As indicated in Figure 6-1, Study III also yields a statistical description of the control and command history of a traverse. This control profile may be used in conjunction with guidance parameters to yield the cumulative guidance error in executing a traverse. This in turn may be used to ascertain the need for navigation fixes in accomplishing a particular mission. The control profile may also be used in conjunction with the power spectral density terrain model to produce a statistical description of the terrain traveled which would be useful in computation of energy expenditures, power profiles, and vehicle dynamics.

The total time required for a unit traverse, t_i, is given by the expression

$$t_i = \sum_{i=1}^{13} t_i - \sum_{i=1}^{13} (T_i \bigcap_{i \neq j} T_j) \qquad (6\text{-}5)$$

where

t_i refers to the length of time required to accomplish function i,

T_i refers to the actual time period(s) when function is carried out,

and the following functions are included:

i=1 gathering of control information including sensor orientation, sensor operation, and sensor readout i=2 conditioning and formating of data and commands

i=3 antenna acquisition and orientation and telemetry transit time both uplink and downlink

i=4 command execution exclusive of telemetry and locomotion

i=5 command verification

i=6 locomotion forward

i=7 locomotion backward

i=8 transmission of control information downlink

i=9 transmission of commands

i=10 control decision making including computation and appraisal of data

i=11 navigation, including navigation fixes required for guidance and a posteriori navigation

i=12 dormancy during operational period due to operational restrictions

i=13 telemetry relay when present.

The outputs of Study III are, therefore, necessary inputs to the computation of total time as well as telemetry characteristics and constraints, astrodynamic constraints, vehicular-borne equipment, operational constraints, decision modes, data processing characteristics, etc. Fortunately, the same study used to compute total time can, with a minimum of effort, also produce system and subsystem duty cycles. Thus a large number of the measures listed in Tables 6-1 and 6-2 may be produced through the studies described. The time and duty cycle computations are simple in principle but require a large amount of bookkeeping and would probably be done by computer.

Two major portions of the analysis not considered here are the analyses required to provide the inputs denoted in Figure 6-1 as "Hazard Appraisal Capability" and "Terrain Appraisal Capability." These analyses are extremely complex and involve the total terrain sensor subsystem. Some work has been done in this area and is documented elsewhere.[9-11]

A final area of considerable importance to the above analysis, and to the RVMC study in general, is the area of control strategy. Since the performance of an RV system may be quite sensitive to the control strategy employed, it is desirable to compare systems on the basis of the best strategy which might be employed within the capabilities of the system. More generally, it is desirable to include control strategy within the set of parameters to be optimized. At the present time almost nothing is known about what constitutes an optimal RV control strategy (with respect to any reasonable criteria of optimality and reasonably complex control situation) in the case of fixed hardware parameters. The inclusion of strategy as a parameter in a more general tradeoff study has not been attempted.

In either case, it seems likely that "optimization" would be attempted only with respect to a discrete set of strategies.

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