

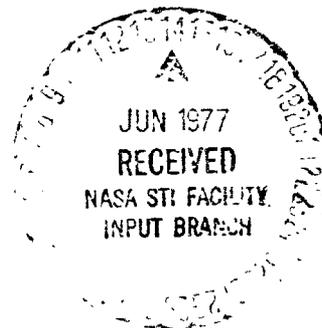
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**CIVIL MINI-RPA'S FOR THE 1980'S:
AVIONICS DESIGN CONSIDERATIONS**

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16. Abstract <p>A number of remote sensing or surveillance tasks (e.g., fire fighting, crop monitoring) in the civilian sector of our society may be performed in a cost effective manner by use of small remotely piloted aircraft (RPA). This study was conducted to determine equipment (and the associated technology) that is available, and that could be applied to the mini-RPA and to examine the potential applications of the mini-RPA with special emphasis on the wild fire surveillance mission. The operational considerations of using the mini-RPA as affected by government regulatory agencies were investigated. These led to equipment requirements (e.g., infra-red sensors) over and above those for the performance of the mission. A computer technology survey and forecast was performed. Key subsystems were identified, and a distributed micro-computer configuration, that was functionally modular, was recommended. Areas for further NASA research and development activity were also identified.</p>					
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CHAPTER I INTRODUCTION

A number of remote sensing or surveillance tasks (e.g., fire fighting, crop monitoring) in the civilian sector of our society may be performed in a cost effective manner by use of small remotely piloted aircraft (RPA). The RPA can reduce fuel costs, equipment expense, maintenance costs and operator costs. Also, the boredom of directly conducting long surveillance jobs with a single manned aircraft can be eliminated. Thus, there appears to be sufficient reason to motivate detailed analysis of the costs and benefits of implementing an RPA for civilian uses.

To conduct such a study requires further investigation of its uses, the potential market, the laws and regulations affecting its use, the environmental impact, and the available technology to construct appropriate vehicles. This survey was conducted to determine equipment (and the associated technology) that is available, and that could be applied to the RPA. The results of this survey can aid in system design, cost estimation, and determination of requirements for further technical development.

This report is organized as follows. Chapter II discusses further the potential applications of the RPA with special emphasis being placed upon the wild fire surveillance mission. Chapter III presents operational considerations of using the RPA as affected by government regulatory agencies. Chapter IV presents the survey of various equipment which would be a part of the RPA. Chapter V presents concluding remarks. Considering the breadth of the subject and the level of effort (three man-months), the report is necessarily of a preliminary nature.

The bibliography is a list of references associated with specific aspects and uses of the RPA which should be useful to both the systems analyst and the design specialist. For an overview of current thinking in RPA systems and programs, Refs. 1-9 are suggested.

CHAPTER II REMOTE SENSING MISSION SCENARIOS

A significant portion of NASA's research effort in earth resources evaluation has been devoted to identifying and developing remote sensing application areas and associated system requirements. Recent internal studies have attempted to assess the data acquisition and handling requirements for remote sensing platforms in aircraft and spacecraft [10,11]. This chapter is devoted to identifying remote sensing missions and associated scenarios, suitable for mini-RPA's, based on a number of earlier reports [10-16]. The principal thesis of this chapter is that for application areas where aircraft are currently being used or planned for future usage, mini-RPA's constitute a potential replacement, provided that the sensor package cost, size, weight, and power requirements can be met.

Potential Application Areas

Typically, a remote sensing system consists of a carrier vehicle (e.g., mini-RPA), a navigation, guidance and control system, a sensor package (e.g., visible band, color infrared radiation detectors), data processors (e.g., onboard microprocessors, data link, and a controller and interpreter (e.g., remotely located human user). It is important to note that the effectiveness of remote sensing depends both on sensor data accuracy and ease of interpretation/utilization. The requirements for data accuracy and utilization of the system are quite mission dependent.

Several applications of the RPA have been suggested, and many of these are listed in Table 2.1. Specific application areas that are most promising include:

- (1) fire prevention, detection and control;
- (2) pollution monitoring (location, extent) and RF noise monitoring for satellite communication systems [21];
- (3) crop census/disease;
- (4) mapping land use/drainage/soils;

TABLE 2.1 - EXAMPLE OF RPV CIVIL APPLICATIONS

1. Law Enforcement Agencies	<ul style="list-style-type: none"> ● Traffic surveillance and control ● Monitoring of large crowd events - parades, sporting, conventions ● Monitor emergencies both natural and man-made, e.g., floods, earthquakes, fires, riots, etc. ● Search and rescue - especially rough terrain and hazzardous areas ● Lake, river and beach patrols ● Industrial security patrol
2. State, County, and Municipal Governments	<ul style="list-style-type: none"> ● Assessing land values ● Urban land use planning ● Mapping, surveying
3. Coast Guard	<ul style="list-style-type: none"> ● Harbor patrol for polluters ● Search and rescue ● Great Lakes and St. Lawrence Seaway ice formation ● Ocean dumping ● Oceanic research - sea state measurements
4. Treasury Department	<ul style="list-style-type: none"> ● Border Patrol - land, water and low flying ● Surveillance of other events of activities
5. Environmental Protection Agency	<ul style="list-style-type: none"> ● Pollution monitoring, measurement and surveillance, air water, land ● Monitor stationery and line sources ● Tracer, inversion layer research studies ● Monitoring of off shore oil drilling and rigs ● Monitor thermal pollut' of Nuclear power plants
6. Department of Agriculture	<ul style="list-style-type: none"> ● Surveillance for forests and national parks ● Command post information during forest fires ● Crop and foliage monitoring ● Wildlife management
7. National Oceanographic and Atmospheric Agency	<ul style="list-style-type: none"> ● Weather research ● Severe storm data gather ● Ocean research studies
8. NASA	<ul style="list-style-type: none"> ● Aerodynamic research and validation ● Avionics evaluation ● Structural experimentation ● Propulsion system test ● Stability augmentation research ● Air Traffic Control Systems validation
9. Commercial Organizations	<ul style="list-style-type: none"> ● Railroad switch yards ● Fishing fleets - location of schools ● Ranches - live stock management ● Communications - relay station ● Prospecting ● Cheap "satellite" for undeveloped countries, "earth resources study" ● Advertising, public announcements

- (5) crime control [15] (dangerous missions-fugitives, snipers, riots, surveillance-remote roads); and
- (6) corridor monitoring (remote pipelines, roads, canals).

Although a number of other applications are feasible [10], the above have been chosen on the basis of: (1) the urgency of the problem, (2) remoteness or inaccessibility of the region, (3) significant cost impact, (4) danger to human life, and (5) monotony of the task. At this stage, most of these applications are just in the planning phase. A definitive cost/benefit analysis is required before further system development can commence; this report will aid in such an analysis. For further information on the potential applications refer to Refs. 19-21.

Among the six specific areas noted above, the present study focuses on wild fire surveillance because of potential cost savings and because this mission has the essential features of most surveillance tasks. In a 13-day period in 1970, fire burned over a half million acres of wild land in California. Almost 800 houses were destroyed, and 16 lives were lost as a direct consequence of this series of wildfires. Costs and losses were estimated at over 200 million dollars; not counting substantial expected future damage from flood and erosion [16]. Thus, the RPA has the potential of substantially reducing wildfire losses by improving the intensity of surveillance. This application provides a strong motive to conduct further studies as well as providing a focus for this effort.

Fire Fighting Mission

The wild land protection areas in California total 61 million acres (10^5 square miles) and are shown in Fig. 2.1 [16]. The specific sensor measurement parameters which have been derived herein are presented in Table 2.2. The table also identifies the sensor type, minimum resolution required, minimum number of missions per day, and preferred sensor platform. Note that satellite sensor data is of a lower resolution and sampling rate compared to the mini-RPA sensor data. The utilization of these two different sensor platforms gives the following benefits:



FIGURE 2.1 AREAS OF WILD LAND FIRE PROTECTION RESPONSIBILITY IN CALIFORNIA

- (1) Redundancy and, therefore, reliability of data sources.
- (2) Distributed (local) control of mini-RPA's to achieve variable sampling rates, geographic location and multi-mission objectives (search, rescue, warning).

Consequently, it is recommended that wild fire control systems utilize satellite generated data for a macro-assessment and mini-RPA generated data for a micro-assessment of the fire control function. The specific activities requiring mini-RPA data will be:

- (1) Fire detection: to swiftly detect (locate) and estimate the size of a fire.

TABLE 2.2 - FIRE FIGHTING MISSION PARAMETERS

Measurement Parameter	Sensor Type	Minimum Resolution	Minimum Missions Day	Sensor Platform	Comments
Fuel Type	Multispectral scanner (dual)	10 m ²	3	Mini-RPA	
Fuel Moisture	Multispectral scanner (dual)	10 m ²	3	Mini-RPA	6 a.m., 2 p.m., 10 p.m.
Fuel Density	Multispectral scanner (dual)	10 m ²	3	Mini-RPA	
Cartography	Multispectral scanner (dual)	10 m ²	1/300	Satellite Mini-RPA	Macro Features Macro Features
Land	Multispectral scanner (dual)	10 m ²	1/300	Satellite	Can be obtained from other government agencies
Weather	Wind estimator	.2 km/sec 1°	24*	Mini-RPA	Micro weather prediction
			3	Satellite	Macro weather prediction
Fuel Ignition	Multispectral scanner	1 m ²	24*	Mini-RPA	

* For the fire suppression mission the data required included fire location and size, fire fighting crew/equipment deployed (e.g., fire line laced), wind vector, local topographical detail; some of this information is required as rapidly as one sample/minute.

- (2) Fire spread and danger models: to generate accurate parameters for input into the fire spread and fire danger rating (FDR) equations (see Table 2.3).
- (3) Fire suppression: to generate quickly and accurately the optimum dispatch instructions for fire fighting units to control the fire.

In addition to these primary functions, other activities include:

- (1) search for missing persons (visible spectrum-TV);
- (2) supply of medical aid and communication equipment to stranded persons (stores release);
- (3) relay of warnings: (a) illegal activities, and (b) inclement weather (remote loudspeaker-speech synthesizer); and

TABLE 2.3 - FIRE DANGER RATING MODEL--INPUT PARAMETERS [17]

SOURCE	PARAMETERS
From remote meteorological stations with RPA telemetry link	<ul style="list-style-type: none"> ● Station number ● Station elevation ● Date ● Wet and dry bulb temperatures ● 10 hrs and 1 hr time lag fuel moisture ● 24 hrs maximum and minimum relative humidities ● Precipitation kind ● Precipitation magnitude ● 24 hrs maximum and minimum temperatures
Local conditions generated by RPA and estimated by observer (when subjective)	<ul style="list-style-type: none"> ● Wind speed ● Wind direction ● State of weather (e.g., lightning activity) ● Slope class ● Precipitation--beginning, end, duration ● Vegetation condition

- (4) communication relay to fire fighting parties in hilly terrain.

For the fire fighting mission, the requirements will be generated in terms of sensors (e.g., purpose, type, resolution, sampling rate) and performance (e.g., range, hours, attitude, maneuverability).

The wild land in California is approximately 61 million acres (one hundred thousand square miles); only a certain portion of this vast areas poses a fire hazard and that, too, only during the summer months. Thus, it is reasonable to assume that mini-RPA surveillance will be judiciously utilized at a local level based on fire hazard history and other data sources (e.g., satellites). Moreover, knowledge of the special features of the local topography will be used to design flight trajectories so as to provide more frequent samples from areas with a higher fire danger rating (FDR) [17]. In other words, resources will be dynamically reallocated. Other reasons for the judicious use of mini-RPA's are pollution (noise, air), airspace usage, and communication channel usage. These operational aspects are considered in the next chapter.

To provide a numerical example, it is assumed that the surveillance mission is to cover ten thousand square miles ($\sim 100 \text{ miles}^2 \sim 160 \text{ km}^2$). Further, it is assumed that the resolution element is 1 m^2 ($\sim 3 \text{ ft}^2$) and the number of samples is two per day [17]. These requirements can be translated into the above mentioned sensor/performance specifications and the number of mini-RPA's required. Based on the material in Refs. 1-9, an all wing mini-RPA is selected; the principal reasons are ease of launch/recovery, lower wing loading, large flat area for sensors (TV, IR) and phased array antennas, and high endurance. The nominal cruise speed is assumed to be 150 nm/hr ($\sim 250 \text{ ft/sec}$, $\sim 270 \text{ km/hr}$), an operating altitude of 2000 ft ($\sim 0.54 \text{ km}$, $\sim 0.3 \text{ nm}$) and an operating radius of 200 miles ($\sim 320 \text{ km}$) for the surveillance mission. For a coverage region of 100 miles^2 and a coverage period of 10 hours for the fire danger rating (FDR) data collection task and a lane width of 1 mile (approximately 90° field-of-view), a fleet of seven sensor mission RPA's and one communication link RPA would be required. Such RPA configurations are referred to later in this report.

CHAPTER III OPERATIONAL CONSIDERATIONS

The development of mini-RPA's in the civilian environment will require the approval (tacit or formal) of a number of interest groups. These include Federal government agencies (FAA, FCC, EPA), local government (state, country, city) and the user community (police, fire department, FBI, EPA, Dept. of Agriculture, Forest Service, etc.). A summary of civilian RPA regulatory factors is presented in Table 3.1. The objective of this section is to project current regulations as they may be applied by the government agencies. Specifically, regulations concerning airspace usage (FAA) and communication frequency/bandwidth allocation (FCC) are discussed.

FCC Regulations

Besides other activities, the Federal Communications Commission (FCC) is responsible for the allocation of the electromagnetic spectrum among many users (government, industry, transportation, etc.). Essentially, the FCC controls the range of frequencies (band) and the power of the transmitting equipment.

TABLE 3.1 - CIVILIAN RPA REGULATORY FACTORS

Federal Aviation Agency
- License
- Certification
- Operating Areas
- Enroute Communications
- Navigation
Federal Communications Commission
- License
- Transmitter Power
- Frequency Allocations
Environmental Protection Agency
- Emissions
- Noise
- Visual Observables
State and Local Governments
- Approvals

Prior to transmitting remote sensor information to the ground processing facility, the particular user group would have to request a spectrum allocation from the FCC. A number of Federal agencies already have certain bands reserved exclusively for their use. Because the specific band allocation is largely dependent on the user, in the present study, engineering calculations assume a band allocation at 6 GHz with a 6 MHz bandwidth and a power restriction of 150 watts using directional antennas (e.g., phased/adaptive arrays). The usage of equipment is assumed to be restricted to rural areas (e.g., wild land).

FAA Regulations

The Federal Aviation Administration (FAA) is responsible for regulating the usage of airspace. In this capacity, the FAA tests and certifies aircraft and associated airborne and ground equipment as being acceptable for usage. The pertinent FAA documents are listed in Refs. 23-28.

The key elements of the 1982 baseline system include:

- (1) Discrete Address Beacon Systems (DABS) in high density areas;
- (2) data link in all high density terminal and most enroute Positive Control Airspace (PCA);
- (3) Terminal Control Areas (TCA's) at major hubs;
- (4) metering and spacing at major terminals; and
- (5) direct RNAV routing.

The proposed area navigation implementation for the enroute low altitude airspace (below 18K ft) is specified in a number of references [23-26], and is given in Table 3.2.

Because all routes are preplanned, the user (e.g., wild land surveillance-forestry service) can notify the required FAA route planning center of the proposed surveillance trajectories and assure noninterference with other aircraft. During a critical period (e.g., high FDR), the FAA can be requested to declare the area under surveillance to be a restricted airspace zone. Table 3.2 also indicates that the mini-RPA navigation system must be

TABLE 3.2 - LOW ALTITUDE EXAMPLE AIRSPACE
IN 1982 [23,24]

SYSTEM ELEMENT	AVAILABILITY
30	Available to equipped users
Preplanned routes	Yes
Horizontal route width	+2.5 nm
Vertical separation	1000 ft
Parallel routes	Preplanned

accurate enough to maintain the +2.5 nm horizontal route width and the 1000 ft vertical separation requirements.

Currently, the airspace below 1200 ft AGL (Above Ground Level) in the enroute phase, and below 700 ft AGL in the transition region near airports and major hubs, is uncontrolled. From 1200 ft AGL to 18000 ft MSL (Mean Sea Level), the enroute airspace is not currently under positive control; but in the post-1982 time phase, it will be. Consequently, all mini-RPA's must be equipped with a DABS data link system to provide trajectory data. A decision will have to be made concerning the applicability of enroute positive control commands from the air traffic control center. This requirement can possibly be removed by requesting a restricted airspace designation. In any case, the relay mini-RPA could be at 10,000 ft AGL, and in this case would require a transponder and possibly a Xenon flasher as a warning to VFR aircraft not operating on a flight plan.

The FAA currently does not certify RPA's and, consequently, no detailed certification requirements exist. However, from current practices it can be surmised that the overall FAA objective is to ensure safety, to preclude loss of human lives and damage to property. Thus, it is reasonable to assume that the onboard guidance system will be fail passive (i.e., built-in self-monitoring equipment to indicate to the remote operator any major subsystem failure) and it will have associated emergency recovery equipment and predefined emergency procedures.

CHAPTER IV SYSTEM COMPONENTS AND TECHNOLOGY

This chapter begins by formulating a RPA system configuration. Then each of the main subsystems are discussed together with the alternatives available. A substantial amount of work needs to be done prior to arriving at a final configuration.

System Configuration

Based on the previous discussion, a preliminary system scenario for the fire fighting mission can be graphically depicted as in Fig. 4.1a. The communication relay vehicle can be a blimp [8], a balloon, or an all wing mini-RPA. Moreover, instead of receiving/decoding/retransmitting video control data to and from the sensor RPA, a passive reflector can be used. Vehicle type and communications equipment are discussed more fully later. In any case, the Relay RPA will require a Xenon lamp and a transponder. Figure 4.1b depicts an all-wing RPA suitable for the Relay RPA with performance specifications corresponding to those of the example used in Chapter II. General material concerned with airborne and ground systems are found in Refs. 22-34.

The conceptual RPA designs can be determined in equal measure by mission requirements and by available technology, both existing and projected to 1985. The main subsystems which make up the RPA system include:

- (a) RPV type
- (b) Airframe
- (c) Propulsion and power (batteries, alternators)
- (d) Launch and recovery
- (e) Ground control
- (f) Man-machine interface
- (g) Data link, communications, and tracking
- (h) Onboard navigation, guidance and control
- (i) Sensors and payload applicable to various RPA missions
- (j) Safety equipment

In each category, items can be identified as either currently available, current state-of-the-art, probably available by 1980, or predicated on an advance in the state-of-the-art considered to be a possibility by 1985.

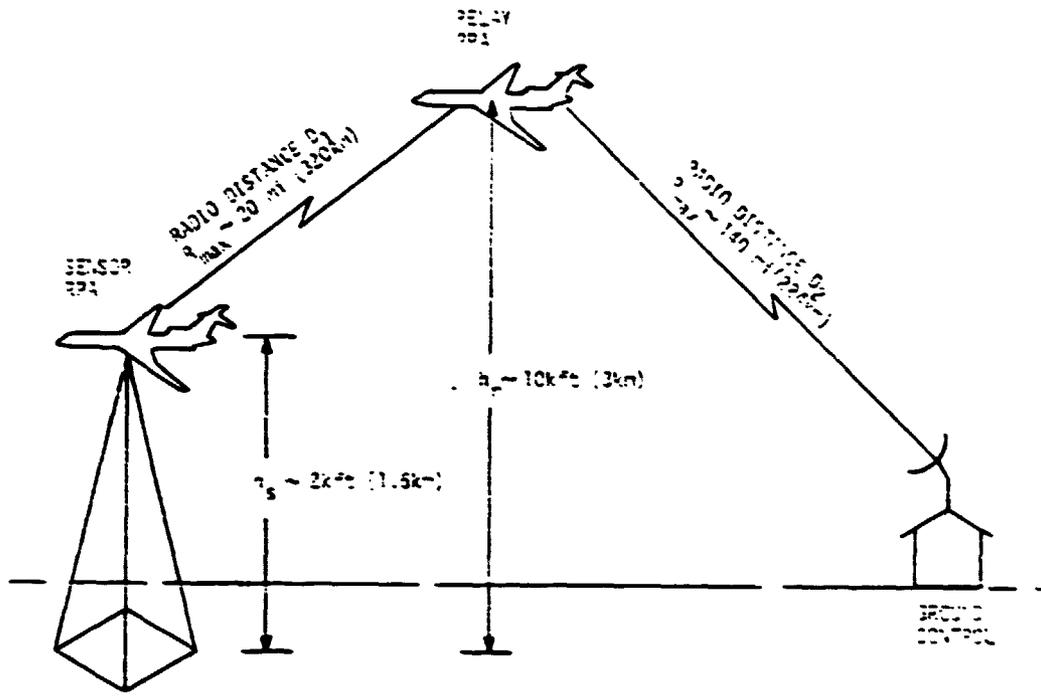
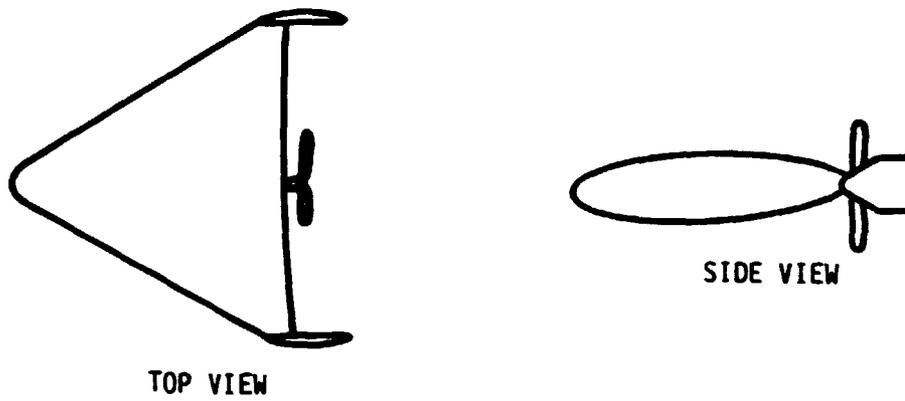


FIGURE 4.1a - PRELIMINARY MINI-RPA SCENARIO



Weight: 99 lb; span: 6.4 ft; Loading: 7.2 lb/ft²; Speed: 150 kts;
 Range: 1,200 nmi; Altitude: 5,000 ft; Payload: 30 lb

FIGURE 4.1b - ALL-WING MINI-RPA SUITABLE FOR RELAY VEHICLE

An example Sensor RPA is depicted in block diagram form in Fig. 4.2. The diagram has been partitioned on the basis of major subsystems, as well as the associated components.

For each of the subsystems which can be defined as a separate piece of hardware, an in-depth survey can be made of what is currently available (off-the-shelf) and what is anticipated. Such a survey would produce the following items: technology description, time of availability, cost assessment based on production quantity, power requirements, weight, size and shape, computational requirements, and accuracy of readout (digital or analog). Hardware components include those for propulsion, power, communications, flight control, and mission-related sensors. The following sections are the beginning of such surveys. Each of the elements shown in Fig. 4.2 as well as those listed above is discussed.

RPA Type and Airframe Alternatives

Several types of vehicles can be considered for civilian RPA applications. In order to match vehicle characteristics better to the requirements of each application, an analysis must be made of each type of vehicle to determine its generalized operating characteristics. The vehicle types include:

- (1) Fixed Wing - rigid, flexible
- (2) Rotary Wing - powered rotor, auto gyro
- (3) Lighter-Than-Air - blimps, etc.

The primary parameters are payload weight, endurance, speed, and power requirements. It is understood that this is not a unique or complete set of parameters. For instance, takeoff weight vs. range for a given payload may be more meaningful for a particular application. However, as a means of categorizing vehicles, these parameters are reasonably unambiguous for RPA applications.

As an example, vehicles can be compared as to speed and endurance for a given payload weight as depicted in Fig. 4.3. Such a figure compares the vehicle types with one another. When a specific application can be expressed by one or more points on the graph, this type of figure can be used to compare vehicles and requirements. Another vehicle comparison can be made on the basis of speed vs.

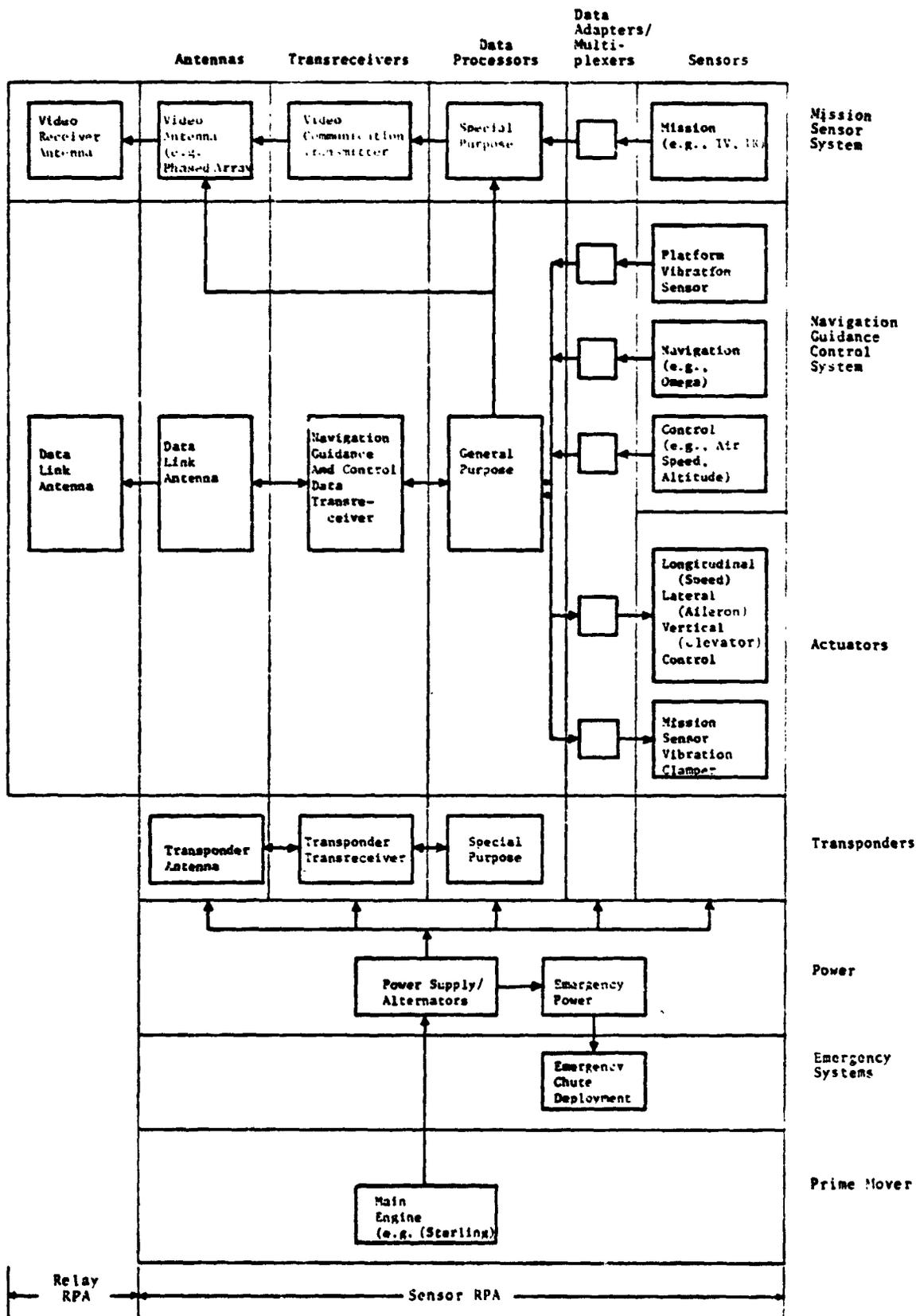


FIGURE 4.2 - SYSTEM BLOCK DIAGRAM FOR THE SENSOR AND RELAY MINI-RPA'S

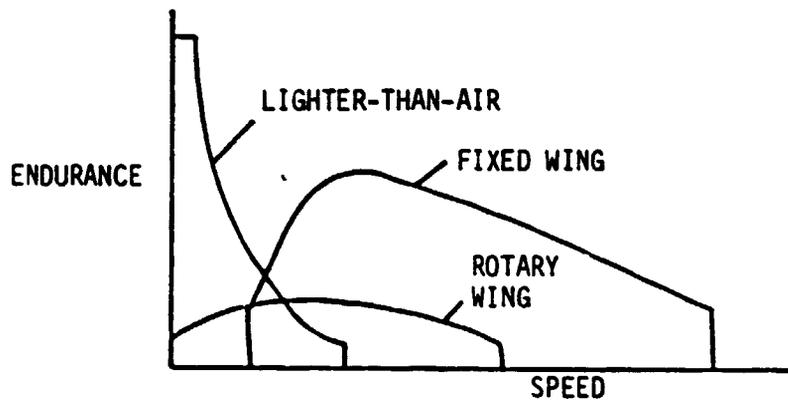


FIGURE 4.3 - COMPARISON OF VEHICLE TYPES WITH RESPECT TO SPEED AND ENDURANCE CAPABILITY

payload weight. This is especially a significant relationship for lighter-than-air vehicles.

Materials and construction methods applicable to the RPA airframe include:

Materials

- (a) Advanced fibers and composite materials
- (b) Pre-preg
- (c) Foam
- (d) Thermo-forming plastics
- (e) Coated fabrics for Lighter-Than-Air (LTA) vehicles
- (f) Light metal

Construction Methods

- (a) Conventional rib, stringer, skin
- (b) Foam core - single skin, double skin
- (c) Above with/without spar

With each concept goes a specific cost, weight, ease of construction, toughness, and other measures which can be used to assess which possibility is most promising.

Imaging Sensor Systems

Mission applicable sensors define the scope of the application and, to a large extent, size the airframe. A wide variety of sensors can be considered for RPA applications, and they can be characterized as follows:

- (1) Optical Imaging Sensors
 - (a) Visible and Near Infrared - Vidicons, CCD's, and Film Cameras
 - (b) Middle and Far Infrared - FLIR's, CDC's, and Pyroelectric Vidicons
- (2) Microwave Sensors
 - (a) Passive - Radiometers and Spectrum Analyzers
 - (b) Active - Scanning Radar and Synthetic Aperture Radar
- (3) Atmospheric Sensors
 - (a) Pollution Monitoring Sensors - Gas Chromatographs, Chemiluminescent Analyzers, Fluorescent Analyzers, Optical Transmissometers, IR Absorption Spectrometers, and Sample Collectors
 - (b) Meteorological Sensors - Temperature Sensors, Pressure Sensors, Humidity Sensors, and Variometers

A summary of optical sensors and their properties is given in Table 4.1.

Again, the choice of sensor payload is determined by the RPA mission. For example, a traffic surveillance mission would suggest some type of optical imaging system; since there is no advantage in using infrared for this mission, a television system using a vidicon or a CCD would be the most likely choice. As with any optical sensor, the presence of cloud cover would require the RPA to either operate below the cloud ceiling or to give up the mission. If neither choice is acceptable, a new type of sensor would need to be developed, with its attendant cost and lead time. In general, the user must decide to what extent he is willing to build his mission around available sensor technology, or develop better sensors for a less restricted mission.

TABLE 4.1 - OPTICAL SENSORS FOR RPA APPLICATIONS
(CURRENT TECHNOLOGY)

	RESOLUTION ELEMENTS PER FRAME	WEIGHT	COST	USABILITY
Visible Light	vidicon	1 lb	\$400-\$500	day
	SIT vidicon	5 lb	\$5000	day/night
	color vidicon	10-20 lb	\$7500	day
	CCD	1/2 lb	\$500-\$800	day/night
	color CCD	5 lb	\$1500	day
Infrared	FLIR	6-10 lb	\$5000-\$7000	day/night
	CCD (1980)	2 lb	\$3000-\$6000	day/night
	Pyroelectric	1 lb	\$1000	day/night (intense sources)

FLIR and CCD sensors operating in the far infrared require cryogenic (typically 77°K) cooling of the detector array. For short (~1 hr) operating times, cooling could be provided by a Joule-Thomson cryostat and a compressed nitrogen bottle, or by a liquid nitrogen dewar. Since RPA endurances of 12 hrs or longer are considered practical, a closed cycle refrigeration system running off the RPA engine would be a more likely choice. Consideration is being given to the use of a Stirling engine to provide both propulsion and cryogenic cooling.

In addition to fulfilling the mission requirements, the sensor payload, if it is an imaging system, could also be used for flying and recovering the RPA. For example, if the sensor is a gimballed TV camera, it should have the capability of looking straight ahead with the gimbals locked.

With respect to the fire-fighting mission, TV and infrared imaging systems are most suitable. The size, weight, and power requirements for solid state implementations of these sensors is currently quite minimal. As the manufacturers of these sensors become more proficient, cost can be expected to drop to allow civil applications to emerge. A large body of literature [36-54] exists in this area.

The most promising new TV imaging technology to emerge in recent times is the CCD (charge coupled device) technology. It is noteworthy that what is novel here is a new device structure; the processing technology is the same as that in the semiconductor industry. Besides imagers, CCD's have great potential in areas of mass memories and signal processing. State-of-the-art imaging arrays have been summarized in Table 4.2. Mini-RPA/remote sensing applications will probably require electronic exposure control and at least a (2:1) electronic zoom capability on a 500 x 500 element array. Imaging processing theory is reviewed in Appendix B and typical TV coverage/resolution calculations are performed in Appendix A. For further information concerning mission sensors, see Refs. 35-54.

Communication Systems

The RPA data link requirements are set primarily by the sensor data rate. Any image with the quality of commercial television requires at least 6 MHz bandwidth. The additional bandwidth required for transmitting RPA flight data (altitude, airspeed, etc.) is relatively small. At

TABLE 4.1 - STATE-OF-THE-ART CCD IMAGE CHARACTERISTICS

COMPANY	CHIP SIZE	ELEMENTS	TECHNOLOGY	COMMENTS
RCA	1/2" x 3/4"	60,000	P channel CCD Polysilicon	
RCA	.275" x .375"	20,000(128x160)	P channel CCD Polysilicon	
Bell Labs		(220 x 128)	P channel CCD Polysilicon	Three sensor/prism to give color
IBM	1.05" x 1.6"	(512 x 1024) 524288	N channel MOSFET	No defect free chips
GE		1024	MOS	10 shades of gray
Hughes			Surface and buried channel	Infrared imagers
Fairchild	.120 x .160	100 x 100	2 phase buried channel ion im- planted barriers	Commercially available
Fairchild		244 x 190 500 x 500	2 phase burried channel ion im- planted barriers	

S-band (2-4 GHz), a 10 MHz bandwidth transmitter weighs approximately 10 lbs using current technology. By 1980, a 5 lb system may be possible.

Against transmitter power and weight, one can trade off antenna gain. For RPA applications, the retrodirective phased array appears to be the most likely antenna choice. This antenna senses the direction of arrival of the uplink from the ground and directs the downlink back at the ground station. It is possible to make such a phased array conform to the surface of the RPA, and conformal phased arrays might be available for use by 1980.

The considerable advantages of an electrically steerable phased array antenna over the mechanically steered systems are widely appreciated. A number of techniques are required to make the overall antenna system practical in terms of weight, volume and cost. Some of the techniques which may be satisfactorily implemented by the 1980's include the following:

- (1) Nonredundant arrays: Certain unfilled, incomplete or "skeletal" arrays can provide angular resolution comparable to that of filled arrays with similar overall dimensions, but with a loss of gain.
- (2) Beam steering: Advances in solid state microwave sources (transistors, IMPATTs, TRAPATTs) will allow one source for each individual array element, avoiding bulky power dividing networks. The required phase relation between sources can be kept by harmonic locking to a reference oscillator.
- (3) Computer control: Advances in microprocessor hardware technology allow their usage for efficiently generating beam steering, beam shaping and attitude stabilization commands. This technology is presently within the state-of-the-art and will be fully utilizable by the 1980's.

Phased array antennas are currently being used in NASA satellite and military systems. It is reasonable to expect that by the 1980's this technology can be used for civilian RPA applications. It is noted that the two features of phased arrays that make them attractive for the fire fighting application are: (1) electronic beam steering to remove mechanical steering/mounting requirements, and (2) electronic

beam forming (e.g., narrow beam) to ensure that the transmitted power is propagated in the required direction. Phased arrays would make it easier to obtain FCC approval for higher transmitter power levels. Prior to a final selection of a phased array antenna as a viable system, detailed calculations pertaining to antenna gain, beamwidth, sidelobes, weight, power and maximum steering angles must be performed. For further information, see Refs. 55-75.

Approximate values of the communication system power and bandwidth requirements for the fire fighting mission can be obtained as follows. For line-of-sight (LOS) communication systems, the basic distance equation is

$$D = \sqrt{2h_s} + \sqrt{2h_r} \quad (4.1)$$

Here, h_s and h_r represent the Sensor and Relay RPA altitudes in ft; see Fig. 4.1a.

The required transmitted power P_T is given by the equation

$$10(\log P_T) = 10(\log P_r) + \alpha + L - G_T - G_R \quad (4.2)$$

where

P_r is the required power at the receiving antenna,

α is the path attenuation between isotopic antennas,

L is the sum of system losses,

G_T is the ground-based transmitter gain, and

G_R is the airborne receiver gain.

The path attenuation α in Eq. (4.2) is given by the equation

$$\alpha = 37 + 20 \log f + 20 \log D \quad (4.3)$$

in units of decibels, where f is the transmission frequency in megahertz, and D is the range in miles as given

in Eq. (4.1). For f of 6 GHz and D of 200 miles, α is 159 dB. The antenna gain in decibels is given by the equation

$$G = 20 \log f + 20 \log d - 52.6 \quad (4.4)$$

where d is the diameter of the antenna. Equation (4.4) was used to compute typical values of G_T and G_R for antenna diameters of 10 ft and 2 ft, respectively; these are presented in Table 4.3.

TABLE 4.3 - ANTENNA GAIN VALUES

ANTENNA PARAMETER	AIRBORNE	GROUND
d (diameter) ft	2 ft	10 ft
antenna gain	30 dB	43 dB

Now assume that the power required at the receiving antenna P_R is -70 dB and that system losses L are 6 dB. Then by using Eq. (4.2), the required transmitted power is found as $10(\log P_T) = -70 + 159 + 6 - 43 - 30 = 22$. Thus, the required power is about 100 watts.

The equation for computing bandwidth requirements is

$$B = C / \log_2 (1 + \text{SNR}) \quad (4.5)$$

where C is the channel information capacity, and SNR is the signal-to-noise ratio. If it is assumed that C is 8 Mb/sec and SNR (at the demodulator) is 31 dB, then B is 1.6 MHz.

If a passive reflector is used on the Relay RPA, the attenuation is given by the equation

$$\alpha = 10 \{ \log [1.25 \times 10^7 (D_1 D_2 / A)^2] \} \quad (4.6)$$

where D_1 and D_2 are the distances from the Sensor RPA to the Relay RPA and from the Relay RPA to the ground, as illustrated in Fig. 4.1a. The quantity A is the effective reflector area given as $\pi d^2/4$ in ft^2 . For an antenna diameter of 2.2 ft and distance D_1 and D_2 of 200 mi, the attenuation is about 197 dB. This is an increase of 38 dB over that given by Eq. (4.3). This must be made up by increasing the transmitter power beyond 100 watts which poses a major cost factor. Consequently, the passive reflector concept on the Relay RPA is currently considered to be impractical, although it may become practical if there are significant advances in phased array component technology.

Onboard Navigation, Guidance and Control

The functions of navigation, guidance, and control are to guide the RPA to its desired destination along a specified track, to maintain adequate attitude control so that the mission sensor systems can obtain information of adequate quality, and to return the vehicle(s) back when the mission is complete. The systems are made up of instrumentation, computers, software, and appropriate interface equipment. For RPA missions, some of the navigation, guidance, and control functions are conducted by ground control so that the data link is also a vital part of the system.

It is in navigation, guidance, and control that system redundancy should be placed to guarantee overall system safety. Thus, one method for implementing this system would be to use two parallel microprocessors with logic that allows cross-checking. The processors are discussed later.

Low cost instruments and systems which are candidates to complete the navigation and control system include pressure sensors (airspeed), angular accelerometers, electrostatic autopilots, and magnetometers. Whether these low cost devices can be used or not is dependent on the accuracy required, and whether the sensor errors can be adequately compensated for in the software.

These avionics functions will be different for each mission. Thus, the mission description can be used initially to describe in more detail the phases required for navigation (position determination), guidance (steering along predetermined path or to predetermined location), and control

(position and pitch/roll/yaw). Navigation accuracy requirements dictate which sensor combinations are applicable. The aircraft flight smoothness requirements (e.g., for stable optical viewing) will govern control component accuracy. Additional considerations include:

- (a) Whether homing techniques can be used to fly vehicle out and back.
- (b) Whether the imaging sensor return can be used for guidance and control in an open-loop sense.
- (c) To what extent multiple vehicles can be used for mutual navigation and control.

A variety of techniques will be reviewed for navigation of RPA's. Some of the most likely techniques, and their expected accuracies, are listed in Table 4.4.

TABLE 4.4 - SOME NAVIGATION SYSTEM CANDIDATES FOR RPA'S

SYSTEM	TYPICAL ACCURACY (FT) (2 σ)
1. Differential LORAN	200
2. Differential OMEGA	2,000
3. TERCOM	500
4. Dedicated Multilateration	20
5. Satellite Retransmission	20
6. Dead Reckoning Via Imaging Sensor	

Certainly the simplest navigation technique is to use an imaging sensor, if it is already on board the RPA. This does, however, require the constant or frequent attention of the operator, and may not be suitable if he is expected to control more than one RPA. It is also limited to clear weather operation. For operation within the continental U.S., an attractive positioning system is differential Loran. Since the RPA will already have a communication downlink, only a Loran receiver, which weighs a few ounces, need be added on board the RPA. Conversion of the Loran signal to map coordinates is performed by a microprocessor at the ground station. Omega retransmission operates in the same fashion, and offers worldwide coverage at reduced

TABLE 4.5 - TYPICAL AVIONICS SURVEY INFORMATION

SYSTEM	WEIGHT	POWER REQUIREMENTS	SIZE	ACCURACY	COMPUTATIONAL REQUIREMENTS	TECHNOLOGY TIME	DIGITAL READOUT	COST
ALTITUDE Collins ALT-50 Radio Altimeter Ham. Standard NSA 101	5.2 lb 1.7 lb	28 vdc .8 amp < 30 watts	3.5" x 3.75" x 12.5" 3" x 3" x 8"	± 25 to 2000' ANINC 575 - 20' Resolution to 50,000'	Self-contained	Solid State-Radio Vibrating Cylinder Pressure Sensor	No Yes	\$2.7K with display \$3.90K
COMPASS Collins MCS-107V An. Corp. Am. NSI 100524 111302	6.3 7.8 6.0	28 vdc .5 amp 35 va 10 va	3.4" x 6.5" x 3.4" 5" x 4.25" x 8" 5" x 4.25" x 6.5"	2° Resolution	Self-contained	Vacuum Directional Gyro Magnetic Compass Magnetic Compass	No Yes No	\$1.25K \$3.4K
ATTITUDE REF An. Corp. Am. ADI 102179 Systron Donner 7650-2	8.1 10.0	18 va 28 \pm 4 vdc	5" x 5.25" x 8"	3°, 3"/sec Accel: $\pm 10 g$ Attitude: $\pm 82^\circ$ pitch $\pm 360^\circ$ roll $\pm 160^\circ$ yaw	A/D	Power Conditioner Triaxis Accel., Vertical Gyro, 2-Axis, Free Gyro, Commanded Decoder Miniature Attitude Ref.	No Yes	\$3.7K \$10K
Systron Donner MARU 36040 ISI AHRS Strapdown Model 5152 System	14 oz. 30 lb	28 vdc 225 watts	2.1" x 3.1" x 2.8" 630 in ³	Accel Bias: $\pm .001 g$ Gyro Misalign: 3 min Air Data: Vel. Bias: ± 15 ips	A/D 1500 word 50K ops/sec	3 Rate Gyros, 3 Lin. Accels, Computer, Airspeed, Altimeter, Digital Computer	Yes	\$2.5K
WUP/PILOT Collins AP 106, 107 An. Corp. Am. P1A	22.3 lb 26.7	28 vdc 6 amp 28 v - 9 amp per servo	8 pgs. 4" x 4" x 8" 8 pgs.	Dependent on Directional Gyro		Computer, Pitch-Turn Control, Turn and Slip Indicator, 3 Servos Attitude Controller Gyro/Turn Controller, Roll/Yaw Servo Comp., Roll/Yaw Force Servo, Pitch Force Servo, Alt. Control Directional Gyro	Yes No	\$6K \$2.9K

accuracy. When extremely accurate positioning is required, a dedicated multilateration system could be used. At least three ground transmitters must be provided. When navigation satellites (GPS) become operational, the need for dedicated ground transmitters will be eliminated. To minimize on board weight, the received signals would be transmitted for ground processing.

Each avionics concept is used to estimate the associated instrumentation and software requirements for full implementation. The software requirements are used in turn to choose the processors in terms of core size, speed, word length, and instruction set.

The avionics that is available can be obtained by survey such as that presented in Table 4.5. Again, the specific components must be selected to match the mission requirements.

Distributed Processing System Technology

The impact of solid state integrated circuit (IC) technology has been noted in the area of sensors (visible and infrared) and communication equipment (e.g., low noise RF power source, phased array antennas and other microwave IC's). The impact in the area of digital data processing is equally spectacular.

The conventional block diagram of a computer is shown Fig. 4.4; the distinction between the micro-processor and the micro-computer has been delineated. Fig. 4.5 shows a one chip, 16 bit micro-processor, together with associated interface electronics on a printed circuit card; by the 1980's, this can be expected to be implemented on a single hybrid package approximately 1.5 in x 1.5 in x 3 in, with a power consumption of less than two watts. Thus, the major portion of the total computer volume will be occupied by memory. Some simple calculations in the following indicate just how much space is required, using 1975 technology. It is expected that there will not be a significant size reduction by the 1980's, unless a significantly different technology emerges, but the cost can certainly be expected to reduce substantially.

Memory size calculations.- A promising approach to reducing the volume and power requirements is to implement the memory in 1K, 16 bit slices by bonding 16 MOS memory chips in a single multilayer ceramic package. A picture

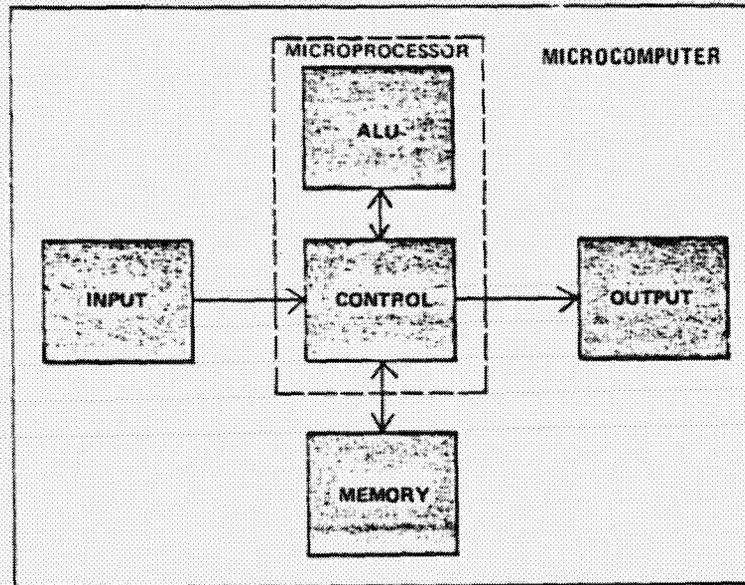


FIGURE 4.4 - CONVENTIONAL COMPUTER BLOCK DIAGRAM

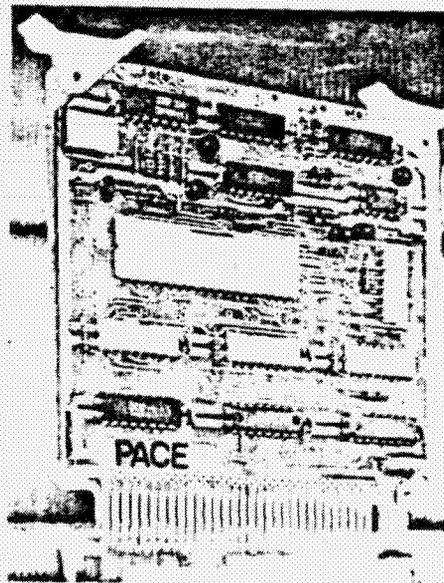


FIGURE 4.5 - A ONE-CHIP, 16 BIT MICROPROCESSOR

of this is shown in Fig. 4.6; the volume of this package is 1.6 in x 1.6 in x 0.3 in, and the power consumption is 0.9 watts. Hypothesizing a 32K memory computer, the total area occupied would be approximately a 10 in square with a power consumption of about 30 watts. It is noted that the packaging technology also results in a flat package suitable for the thin cross section of the delta wing mini-RPA.

Micro-computer Features.- In the interest of providing a summary of 1978 technology capabilities of micro-processors, the major technical features of micro-processors have been tabulated in Table 4.6, together with the projections. It is noted that the system costs will be reduced significantly; the micro-processors will be a standard component in electronic systems, almost as common as passive components like capacitors and resistors. To better assess the manner in which the projected trend will be accomplished, it is necessary to consider the semiconductor technology. The current technological innovations in this area have been very rapid, as can be seen from Table 4.7. Some major

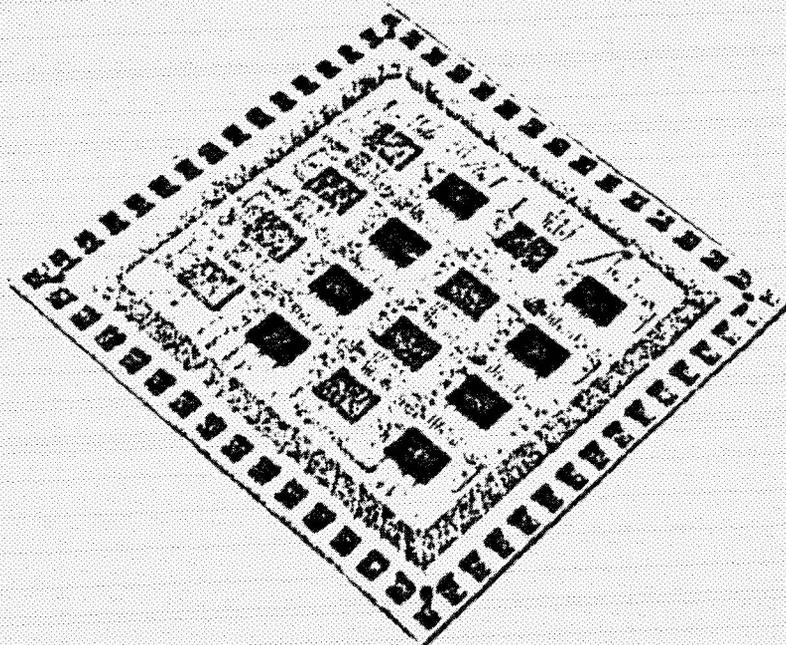


FIGURE 4.6 - MULTI-LAYER CERAMIC WITH 16 BONDED MOS CHIPS

TABLE 4.6 - A SUMMARY OF OVERALL MICRO-PROCESSOR FEATURES [99]

CHARACTERISTIC	MINI-MUM	TYPI-CAL	MAXI-MUM	PROJECTED (1980'S)
<u>Storage</u>				
Word Length (Bits)	1	8	16	16
Size (Words)	256	16K	64K	32K
Size Increments (Words)	64	256	1K	1K
Cycle Rate (kHz)	33	250	8000	1000
Cycle Time (μ sec)	0.125	4	30	0.1
<u>Central Processor</u>				
General Registers	2	5	64	64
Index Registers		1	2	4
Addresses	1	1	1	1
Price (CPU, Qty = 100)	\$30	\$175	\$500	30
Size	--	--	--	10x10 in.

TABLE 4.7 - MICRO-PROCESSOR FABRICATION PROCESSES [99]

	TECH-NOLOGY	CYCLE TIME (μ sec)	SPEED-POWER PRODUCT (pJ)	PACKING DENSITY (gates/mm ²)
1972	PMOS	20	40	30
1973	NMOS	0.2	10	100
1974	TTL	0.2	100	10
1975	IIL	0.2	0.5	100

advances can be expected to come in the years ahead; one promising new technology to watch is the molecular or sandwich semiconductor structures being developed at IBM facilities.

Other Subsystems

The other subsystems considered in this section are: (1) propulsion system, (2) launch and recovery procedure, (3) ground control, and (4) man-machine interface.

Propulsion.- A present, suitable powerplants are available only in broad horsepower steps and, in the lower power range, only in two-cycle designs. For example, suitable two-cycle engines are available in 2, 10, 35 and 70 horsepower sizes weighing about 1 pound per horsepower. Available four-cycle engines would require extensive modifications and still weigh approximately two pounds per horsepower. Rotary piston engines are certainly promising alternatives but are not available in suitable forms at present.

In order to represent properly the advantages in performance available to the RPV designer with a wide range of engine choices, the choice in the design studies will be open to existing engines requiring various degrees of modification and to developmental engines for which suitable data exists.

Such a decision will arise for missions with long endurance. Take for example a two-cycle engine weighing 1 pound per bhp making an sfc. of 1 and a four-cycle engine will have equal or lower takeoff weight than the same RPA with a two-cycle engine. In such a case, a modified motor-cycle engine will be a good solution even though its "off-the-shelf" form is not suitable. Similar decisions will have to be made for each chosen application.

Launch and Recovery.- While experience with manned aircraft gives builders and users of RPA's a sound basis for RPA structures, aerodynamics, and propulsion, such experience reveals relatively little about how RPA operations should be conducted. The areas of launch, recovery, pre-flight procedures, vehicle turn-around logistics, ground control, and other operational aspects of RPA's are still largely in the experimental stages. Important progress is being made in this area that will be surveyed and incorporated in this study. Of particular importance to many

civilian uses are the tests to be done by the U.S. Army as part of the Little "r" program which will include portable launch and recovery equipment and in-the-field logistic support. It is important that the RPA operation be characterized, for it will affect overall system design requirements and the manpower required for operation and maintenance mentioned earlier.

A number of unconventional launch and recovery methods need to be studied. These include:

- (1) Launch
 - (a) Linear (air, steam, bungee)
 - (b) Rotational (horizontal, vertical)
 - (c) Air launch (aircraft, balloon drop)

- (2) Recovery
 - (a) Net
 - (b) Snag onto pad
 - (c) Parachute
 - (d) Air bag

Ground control.- It will be important to assess the ground control requirements as part of the overall civilian RPA concept. A large amount of the RPA's sophistication will be in the ground equipment. The ground equipment also allows controlling several vehicles at once. Thus, the ground equipment represents two major costs of the total system--the hardware/software and the personnel required to operate the system. One possible mobile ground control center is shown in Fig. 4.7.

There exists a trade-off between whether the equipment for operation of the RPA should be airborne or part of the ground-based system. By use of data links and a centralized computer, it is possible to control several vehicles with less overall equipment. For example, all the navigation and guidance computations can be done on the ground with only navigation sensors and control servos required on the aircraft. Also, much of the data processing can be done centrally on the ground. This saves the cost of multiple computers on each vehicle, and it lowers the risk if one of the vehicles is lost. On the other hand, it increases the sophistication required in the data link and overall communications system. This trade-off should be examined in terms of lowering the overall system costs and enhancing reliability and performance.

Man-machine interface.- The assessment of the man-machine interface problems for a given mission will require consideration of the following factors:

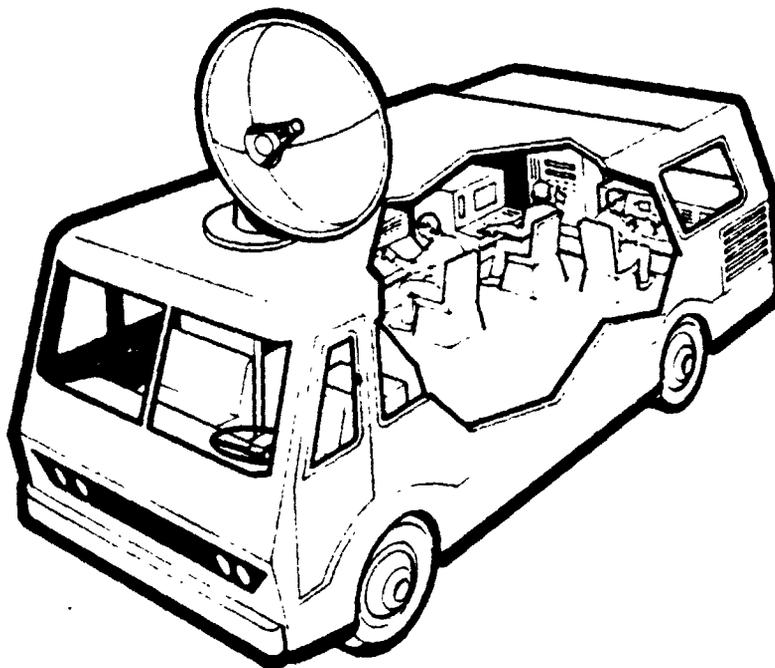


FIGURE 4.7 - MOBILE GROUND CONTROL CENTER [17]

- (1) The nature of the operator tasks for the entire mission. This will require partitioning of the overall mission into a sequence of operational phases. For example, in a cargo delivery mission, the operational phases can be described as:
 - (a) launch, takeoff, and climb;
 - (b) enroute navigation;
 - (c) target/destination acquisition;
 - (d) cargo drop;
 - (e) assessment of the success of the drop;
 - (f) return route navigation; and
 - (g) recovery, approach and landing.

The role of the RPA crew (controllers/monitors) for each phase of the mission should be defined in terms of task requirements, task constraints, etc.

- (2) The display/control requirements for each phase of and RPA mission should be defined on the basis of the task description discussed above.
- (3) The level of automation for each phase of the mission should be defined.
- (4) The number of RPA's possibly controllable by one operator should be investigated.
- (5) Then, the number of operators required as controllers and monitors can be specified.

Probable human operator tasks include:

- (1) Control tasks
 - (a) closed-loop tracking;
 - (b) closed-loop; and
 - (c) open-loop programmed commands using computer terminal/waypoint specification.
- (2) Decision tasks
 - (a) detection and acquisition;
 - (b) discrimination; and
 - (c) identification or recognition.

A representative collection of articles dealing with these topics is contained in Refs. 76-113.

CHAPTER V CONCLUDING REMARKS

The preceding chapters covered, in a preliminary manner, the mission-oriented system components. The principal items discussed in this section are: (1) main RPA alternatives, (2) system weight allocation, and (3) key technology areas describing NASA research and development support.

The mini-RPA system level alternatives identified during the course of this study are:

- (1) A mini-blimp or balloon could function as a communication link RPA; it would require a transponder and a Xenon flasher (benefit: cost reduction/weight saving).
- (2) An all-wing sensor RPA provides a flat area for the phased array antenna and the imaging sensor, but imposes a requirement for flat optics/avionics packaging.
- (3) Link RPA's may be able to provide sufficiently accurate line-of-sight (LOS)/time of arrival (TOA) navigation capability for the sensor RPA (benefit: weight saving).
- (4) Link RPA video/data link could be a passive reflector (benefit: weight/cost saving), but than higher quality/power communication equipment required on the ground/sensor RPA; but the navigation function of item (3) is not possible in this case. Finally, the 40 dB loss (approximate) may make the concept technically infeasible.

Table 5.1 presents the current and projected equipment configuration in terms of weight, size and cost breakdown. The main subsystem allocations follow the system block diagram presented in Fig. 4.2, namely, navigation, transponder/beacon, data link, image sensors, computer, actuators/flight sensors, power supply, propulsion/fuel and airframe.

In both the 1975 and 1985 projections, the combined weight of the power supply and the imaging sensor system comprises some 25% of the total avionics system weight. Thus, to reduce the weight of the avionics payload, greater emphasis is recommended in these two areas. Moreover, referring to Table 5.1, it is noted that major weight reductions will be

TABLE 5.1 - CIVILIAN RPA COMPONENT ESTIMATES, 1975 AND 1985

	WEIGHT (LBS)		SIZE (IN.)		COST (\$K)	
	1975	1985	1975	1985	1975	1985
Navigation - Omega	8	2	8x6x3	3x3x3	5	1
Transponder/Beacon	8	2	10x10x3	10x2x1	5	0.5
Data Link - 20k Baud, 10^{-5} Error Rate, 30 dB Margin, 150 Watts, 200 Mile Range	3	2	8x6x3	3x3x3	5	2
Image Sensors - Solid State CCD Camera, Lens, 1.0 m Rad/Line Pair	4	2	3x3x3	3x3x3	5	2
- FLIR, 0.25 m Rad/Line Pair	8	4	10x3x3	3x3x3	8	3
Computer - 32k Words, 16 bit Word, Solid State LSI - Hybrid 5 MIPS, 32 Registers	20	2	15x15x5	6x6x3	5	2
Actuators and Sensors - Magnetometer, Rate Gyros Barometric Sensor, Servo Motors	10	3	10x3x3	10x2x1	5	1
Power Supply	6	3	5x5x4	10x3x3	1	0.5
Total Avionics	67	20	990 in³	316 in³	39	12
Propulsion and Fuel	98	25	---	---	1	1
Airframe	58	15	---	---	1	1
Total Vehicle	223	60	2 ft³	1 ft³	41	14

realized mainly by the use of solid state technology; the most significant impact being in the digital computer system.

Table 5.2 presents a technology forecast of the various subsystem developments and recommends areas for NASA research and development support, to encourage mini-RPA applications in the civilian environment. The main objectives of NASA support should be in developing minimal cost systems.

One particular area receiving negligible government support is the development of A/D converters. This is a basic component required to utilize micro-computer technology in a cost-effective manner. NASA should provide research into novel techniques for implementing potentially low cost A/D converters of adequate accuracy and conversion rate for aerospace applications. References pertaining to this section are 114 through 138.

The work done during this preliminary study has indicated that a more detailed study should be conducted to establish the need for mini-RPA's in the civilian applications environment. A flow chart of such a mission-oriented trade-off study is shown in Fig. 5.1. It is recommended that starting with the various user communities, those leading to an early use of RPA's be identified. Then system requirements should be generated on the basis of selected mission characteristics/scenarios, taking into account the impact of various regulatory agencies. Finally, the recommended study should clearly identify areas where further NASA research and development funds should be spent and formulate promising market introduction strategies. In conclusion, it is believed that mini-RPA's in civil applications may well be the next major technological benefit of NASA research activities.

TABLE 5.2 - KEY TECHNOLOGY AREAS AND NASA SUPPORT

SUBSYSTEM	TECHNOLOGY	COMMENTS
LLL RV	CCD-MIS	Sensor System
IR	CCD-MIS*	Sensor System
μ C	IIL-MOS	Processor System
INTEGRATED MICROWAVE POWER SOURCES	MIC	Communication System
PHASED ARRAYS LIGHT WEIGHT MATERIALS	MIC*	Communication System
LOW NOISE AMPLIFIERS	MIC	Communication System
A/D CONVERTERS	MOS*	Sensor Interface
D/A CONVERTERS	MOS	Communication Interface
AUTOMATED IMAGE PROCESSING	Transform Coding Theory*	Real Time Mission Data Assessment
FEATURE EXTRACTION	Information Theory*	Real Time Mission Data Assessment
LIGHT WEIGHT POWER SOURCE	Alternator Battery*	Real Time Mission Data Assessment

* Areas for NASA (technology Development) Support

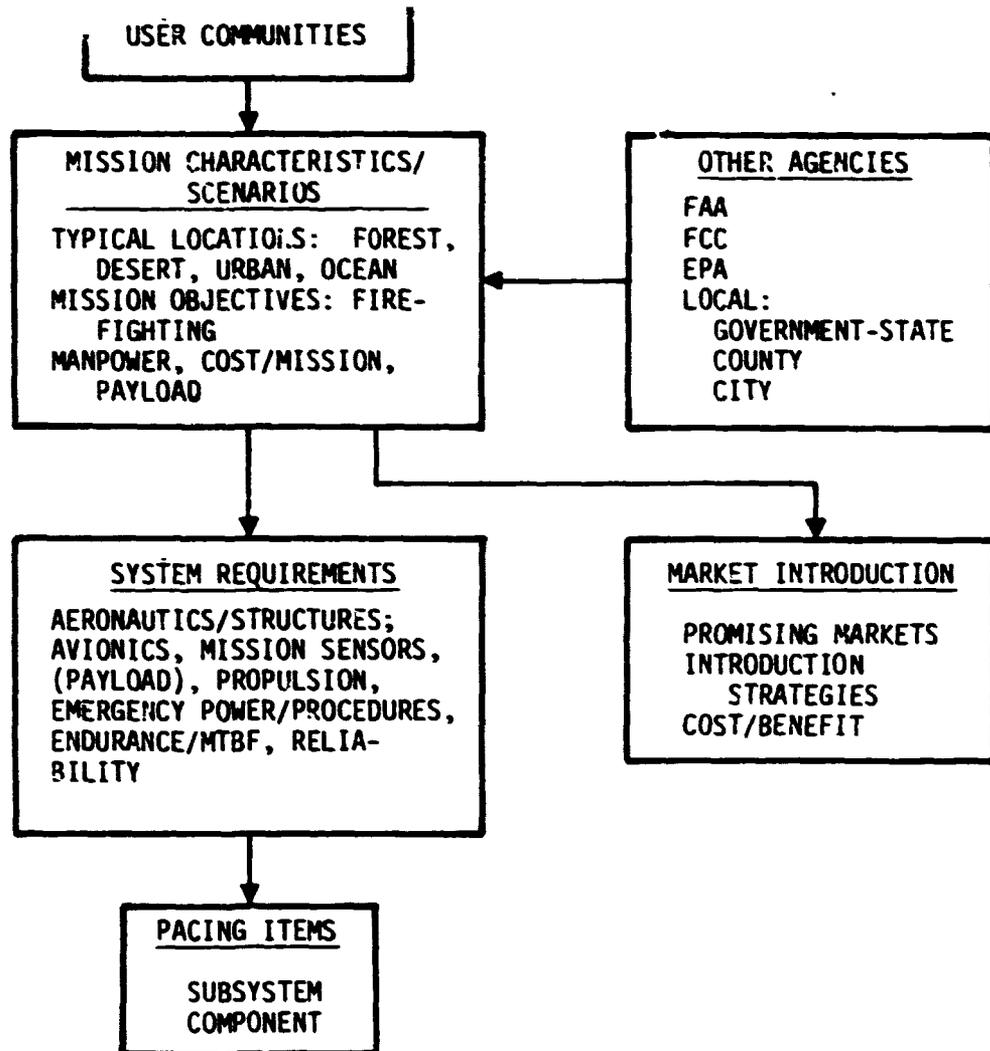


FIGURE 5.1 - CIVILIAN MISSION ORIENTED SYSTEM TRADEOFF STUDY

**APPENDIX A
TV COVERAGE/RESOLUTION CALCULATIONS**

It is of interest to calculate the optical system parameters and ground resolution for the mini-RPA mission. Based upon the nomenclature of Table A.1, certain useful quantities are computed:

$$\text{Scale factor } S = \frac{F}{LKr} = \frac{13 \times 10^{-3}}{10^3 \times .7 \times .25} \sim 7 \times 10^{-5}$$

$$\text{Focal length } f = SH = 7 \times 10^{-5} \times 0.6 \times 10^{-6} \sim 42 \text{ nm}$$

$$\text{Field of view (FOV)} = 2\phi \times 2\phi$$

where

$$\begin{aligned} \phi &= \tan^{-1} \left(\frac{rL}{2H} \right) = \tan^{-1} \left(\frac{0.25 \times 1000 \times 10^{-3}}{2 \times 0.6} \right) \sim \tan^{-1}(0.2) \\ &= 11.3^\circ \end{aligned}$$

TABLE A.1 - NOMENCLATURE

r	- Resolvable length $\sim 0.25 \text{ m}$
F	- Image target format size (edge) $\sim (0.5 \text{ in})^2 \sim (13 \text{ mm})^2$
L	- TV lines $\sim 1000^2$
G	- Ground resolution element $\sim (0.25 \text{ m})^2$
K	- Kell factor ~ 0.7
S	- Scale factor
f	- Focal length
H	- Altitude $\sim 2000 \text{ ft} \sim 0.3 \text{ km} \sim 0.6 \text{ km}$
E	- Exposure time/frame
R	- Readout time/frame
FOV	- Field of view ($2\phi \times 2\phi$)
f#	- Optics aperture stop
V	- Aircraft speed $\sim 250 \text{ ft/sec} \sim 85 \text{ m/sec}$
n	- Bits/element

Thus, f-stop (f#) is given by

$$1 \leq f\# \leq \frac{f \tan \phi}{1.83 \times 10^{-4} \times L} \sim \frac{42 (0.2)}{1.83 \times 10^{-4} \times 10^3} \sim 2.2$$

Let f# = 2. Then,

$$\text{Optical Diameter } D = \frac{f}{f\#} = \frac{42 \text{ mm}}{2} \sim 21 \text{ mm} < 1 \text{ in}$$

$$\text{Object size/frame} = Lr^2 = 250 \text{ m}^2$$

$$\text{Time/frame} = 250/85 \sim 3 \text{ seconds}$$

$$\text{Time/line} = 3 \text{ msec}$$

$$\text{Max exposure} = \frac{3 \text{ msec}}{4} \sim 750/\text{msec}$$

Actual exposure time is determined by the intensity of incident radiation and saturation exposure level.

Let

$$t_e = 100 \text{ ms (i.e., smear distance } \sim 100 \times 10^{-6} \times 85 \times 10^3 \sim 8.5 \text{ nm)}$$

Then the allowable yaw rate is

$$\psi = \frac{r}{3Ht_e} = \frac{0.25}{0.6 \times 10^3 \times 100 \times 10^{-6}} \sim 1 \text{ rad/sec}$$

and the allowable roll rate is

$$\dot{\phi} = \frac{r}{6Ht_e} > 0.5 \text{ rad/sec}$$

Thus,

$$\text{Bits/frame} = nL^2 = 8 \text{ mega bits/frame}$$

It is recommended that frame differential pulse code modulation be used (3 bits/PEL); in this case,

$$\text{bits/frame} = 3L^2 = 3\text{Mb/frame.}$$

Because the time per frame is 3 seconds, it is recommended that a new frame be generated and transmitted only once per second. This, the required data rate is 1Mb/sec. At the ground facility, each frame is repeated 30 times/sec to provide a visual flicker-free display. If automatic feature extraction algorithms are to be employed, this frame rate is quite adequate; frame-to-frame data redundancy is 33%. A number of applications require a multi-spectral scanner; assuming 8 channels of data, the data rate would be 8Mb/sec. A similar analysis can be performed for CCD infrared sensors, currently under development by Hughes and other companies. For further information concerning sensor systems, see Refs. 35-54.

APPENDIX B IMAGE PROCESSING

This appendix summarizes the current state of development of image processing theory, based on the references (particularly Ref. 114).

Figure B.1 shows the configuration of a typical picture communication system. The ideal image of an object, $g(x,y)$, is converted to an actual image, $f(x,y)$, by an imaging system (e.g., return beam vidicon) and sampled and quantized to give a digital image, $f(i,j)$, defined here as a matrix of numbers. This digital image $f(i,j)$ is suitably encoded and transmitted across an appropriate channel. At the receiver end, the received picture signals are decoded to yield the received digital image $\hat{f}(i,j)$. The restoration filter performs an operation opposite to that of the imaging system to give a restored ideal image $\hat{g}(i,j)$ which is further passed through an enhancement filter and displayed to the human observer. The purpose of the enhancement filter is to modify the restored image $\hat{g}(i,j)$ to match human psychovisual characteristics and as a result produce an image that is more pleasing and acceptable to the human eye.

Image Coding

The objective of image coding is to minimize the number of code bits required to reconstruct an image so that: (a) the channel bandwidth can be reduced, (b) the image can be transmitted at the faster rate, or (c) the communication transmitter power can be reduced.

Approaches

	<u>BITS/PEL</u>
1. Pulse Code Modulation (PCM)	8
2. Statistical Coding	3,4
3. Predictive Coding	
(a) Differential Pulse Code Modulation (DPCM)	3
(b) Delta Modulation (DM)	2
4. Interpolation Coding	1
5. Contour Coding	--
6. Transform Coding	2

Coding can be intraframe and/or interframe.

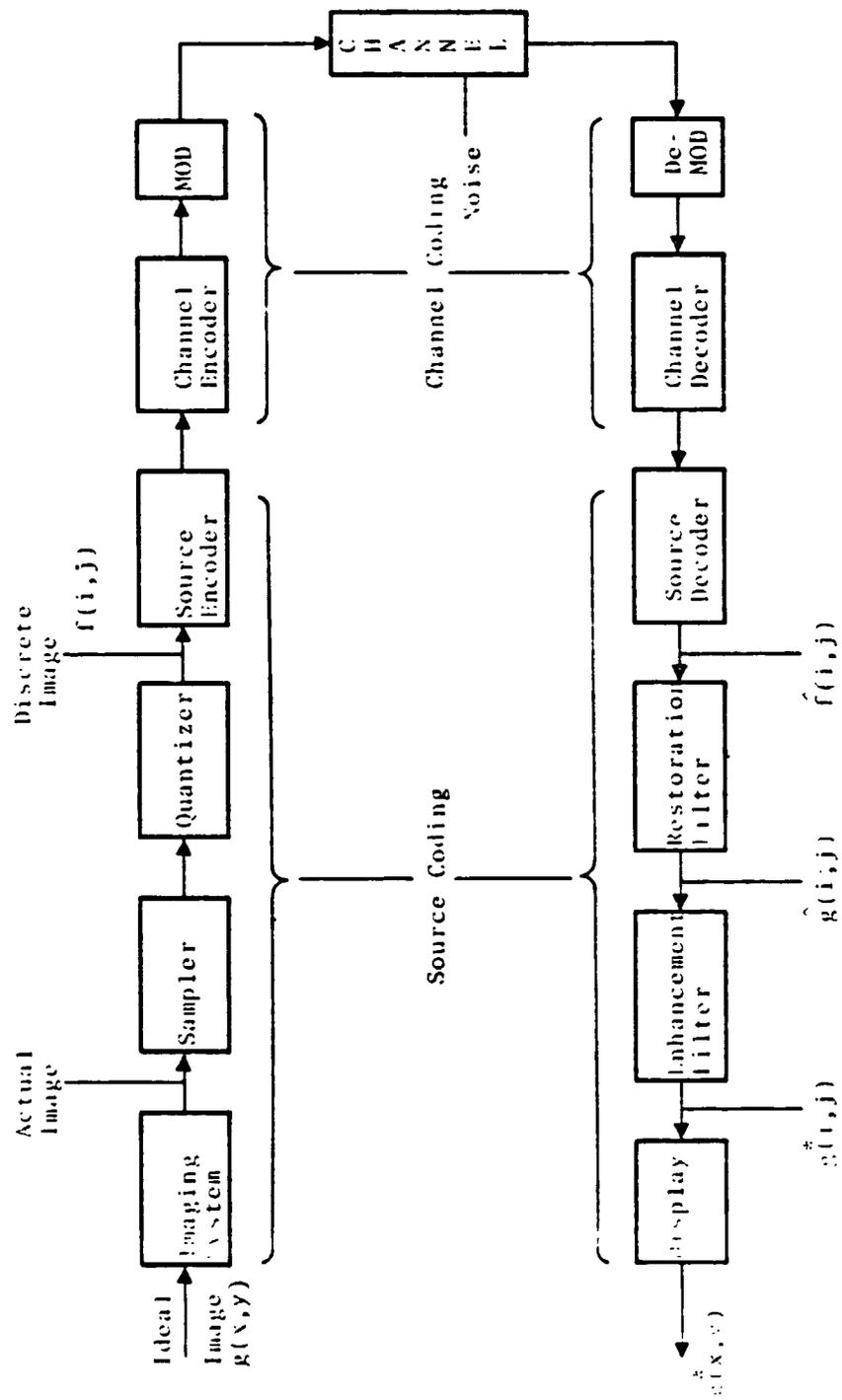


FIGURE B.1 - CONFIGURATION OF A TYPICAL PICTURE COMMUNICATION SYSTEM

Transform Coding

Figure B.2 shows a block diagram of a generalized transform image coding system. An original digital image, denoted by $f(j,k)$, is defined here as an array of samples of a continuous two-dimensional intensity pattern of light. The samples of this image under-go a two-dimensional transformation over the entire image or some subsections of the image called blocks. The resultant transform samples, denoted by $F(u,v)$, are then operated on by a sample selector, $S(u,v)$, that decides which samples are to be transmitted on the basis of magnitude or geometrical location in the plane. A bandwidth reduction can be achieved by this selector simply by not transmitting all of the transform domain samples. Those samples that are to be transmitted are then quantized and coded. At the receiver, the samples are decoded and inversely transformed to form the reconstructed image $\hat{f}(j,k)$.

General Representation

Mathematically, a two-dimensional transform maps a two-dimensional image array of dimension* $N \times N$ into a two-dimensional array of the same dimension by

$$F(u,v) = \sum_{j=0}^{N-1} \sum_{k=0}^{N-1} f(j,k) a(j,k,u,v) \quad u,v = 0,1,\dots,N-1$$

where $a(j,k,u,v)$ is the forward transform kernel. A reverse transform is defined by

$$f(j,k) = \sum_{u=0}^{N-1} \sum_{v=0}^{N-1} f(u,v) b(j,k,u,v) \quad j,k = 0,1,\dots,N-1$$

where $b(j,k,u,v)$ is the reverse transform kernel. When the function $f(j,k)$ is equivalent to the original image $f(j,k)$, the reverse transform is called an inverse transform.

* For simplicity, assume all arrays to be square

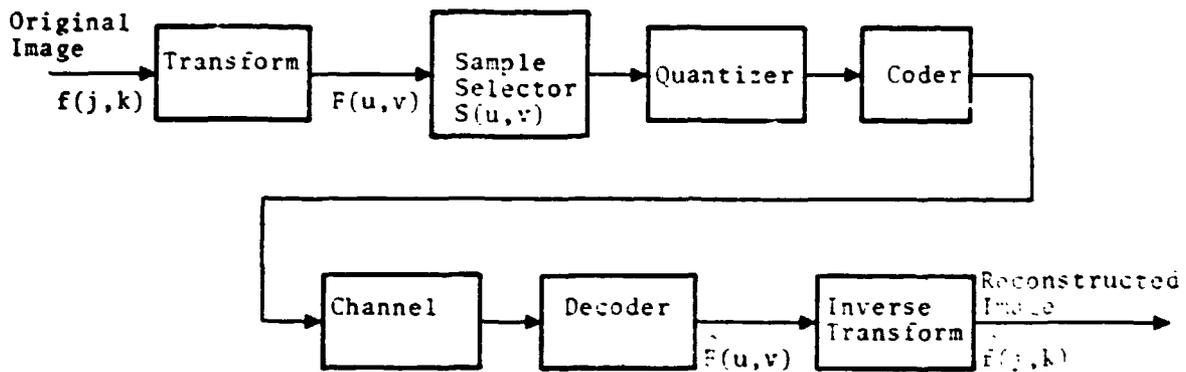


FIGURE A.2 - TRANSFORM IMAGE CODING SYSTEM

A forward (or reverse) transform kernel is said to be separable if it can be written as

$$a(j,k,u,v) = a_j(j,u) a_k(k,v)$$

A separable two-dimensional transform can be computed in two steps: a one dimensional transform along each row of the image $f(j,k)$;

$$F(u,k) = \sum_{j=0}^{N-1} f(j,k) a_j(j,u)$$

and then a one-dimensional transform along each column of $F(u,k)$,

$$F(u,v) = \sum_{k=0}^{N-1} F(u,k) a_k(k,v)$$

It is often useful to express two-dimensional transforms in matrix form if the transform kernel is separable. Let $[f]$ be an image matrix representation of the array $f(j,k)$ and $[F]$ be a transformed image matrix representation of $F(u,v)$, then a two dimensional transform can be written as

$$[F] = [a_j][f][a_k]$$

where $[a_j]$ and $[a_k]$ are one-dimensional transform matrices along rows and columns of an image. If $[a_j]$ and $[a_k]$ have inverses, then a two-dimensional inverse transform can be written as

$$[f] = [a_j]^{-1}[F][a_k]^{-1}$$

Hadamard Transform

The Hadamard transform is based on the Hadamard matrix which is a square array of plus or minus ones. The lowest order Hadamard matrix can be written as

$$[H_2] = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

and the construction of a Hadamard matrix of order N can be written by the following recursive relation:

$$[H_N] = \frac{1}{\sqrt{2}} \begin{bmatrix} H_N & H_N \\ H_N & -H_N \end{bmatrix} [P]$$

where $N=2^n$ and n is an integer. The matrix $[P]$ is a permutation matrix which permutes the rows of H_N such that the number of sign changes of each row increases with the row index. This is the sequency ordered Hadamard matrix.

The Hadamard matrix is real, symmetrical, and orthonormal. Therefore, the forward transform can be written as

$$[F] = [X]^{-1}[f]^{-1}[X]$$

and the inverse transform becomes

$$[f] = [X]^{-1}[F]^{-1}[X]$$

Figure B.3 contains a sketch of the Hadamard transform waveforms of order 16. The sequency property and a constant basis vector can be easily seen in the waveforms.

Fast transform algorithm.- Computation of the transform $F(u,v)$ is performed in two steps. First, a one-dimensional H-transform is taken along each row of the array $f(j,k)$. Then a second, one-dimensional H-transform is taken along each column of the array $f(j,k)$. Computation of the one-dimensional H-transform by brute force methods required N^2 operation ($N \equiv 2^n =$ dimensions of the square array) where an operation is an addition or subtraction. A fast H-transform in one dimension takes $N \log_2 N$ operations.

$$\text{Total No. of operations} = N^2 \log_2 N^2$$

$$\text{Storage required} = N^2 + 2[2^n - 1]$$

Image restoration and enhancement.- Image restoration is defined as the reconstruction of an image to compensate for degradation in the image formation. Typical image restoration applications include: correction of image blurr caused by defocus or image motion during exposure, geometric distortion compensation and sensor noise compensation. Image enhancement, on the other hand, entails operations that improve the appearance of an image to a human viewer or simplify the display format for human analysis.

Image restoration.- Image degradation in picture communication may be caused by a variety of factors. In image restoration, the degrading system is mathematically modeled as some linear or nonlinear operation on an ideal distortion free image. Image restoration implies the use of methods to recover the ideal image from the distorted image. A block diagram of the image restoration process is shown in Fig. B.4. In many cases of practical interest, the degrading system may be modeled by a general linear space variant system as follows:

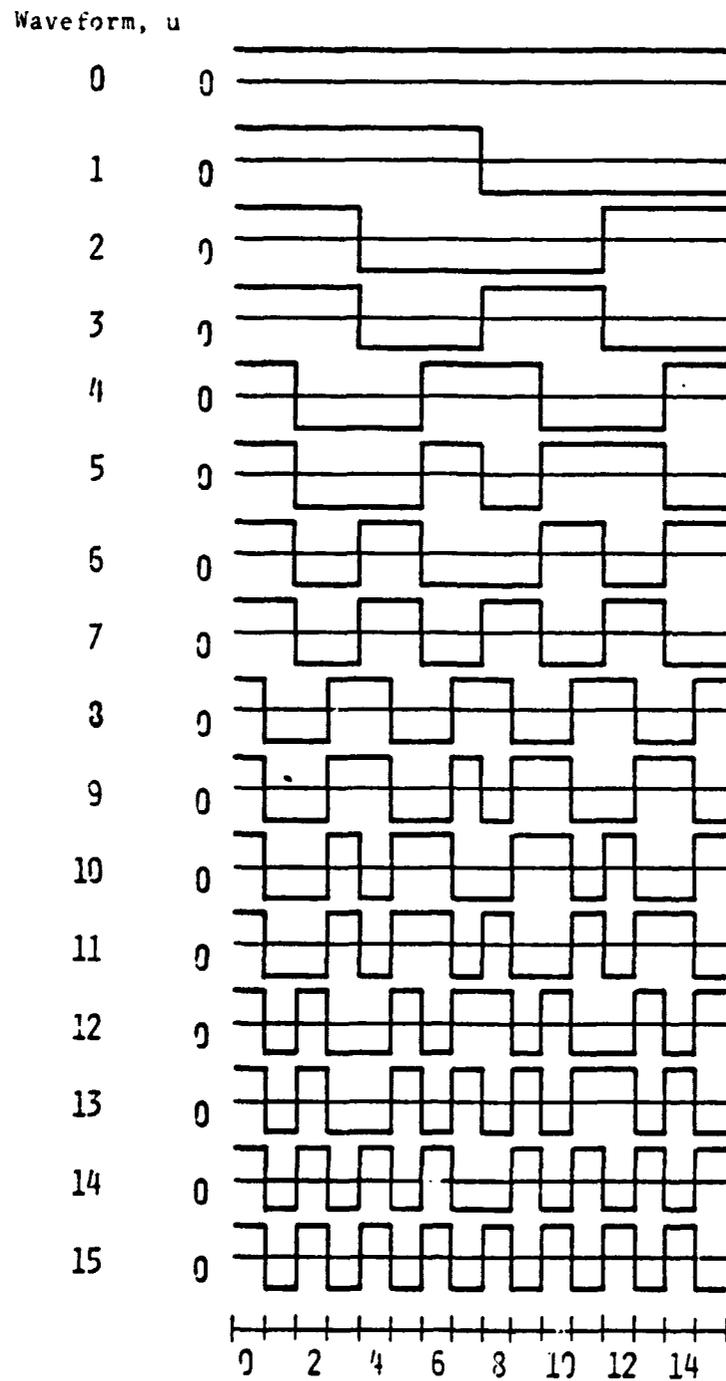


FIGURE B.3 - HADAMARD TRANSFORM

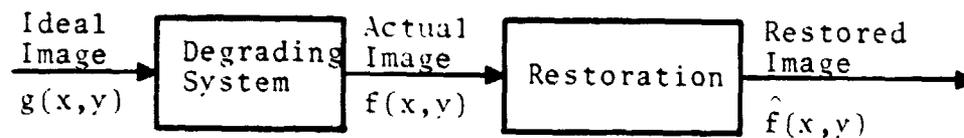


FIGURE B.4 - IMAGE RESTORATION

$$f(\underline{x}) = \int_{-\infty}^{\infty} h(\underline{x}, \underline{z}) g(\underline{z}) dz$$

where

$$f(\underline{x}) \equiv f(x,y)$$

$$g(\underline{x}) \equiv g(x,y)$$

and $h(\underline{x}, \underline{z})$ is the SVPSR (Space-Variant Point Spread Function) of the degrading system.

Ma. SVPSF's can be further decomposed as shown in Fig. B.5. The image restoration scheme for the degrading system of Fig. B.5 is shown in Fig. B.6. The space-invariant filter $\hat{h}^{-1}(z)$ is chosen to be an inverse filter of $h(z)$ or as a two-dimensional Wiener filter.

Computations.-

2 Geometrical Distortions: T_1^{-1} and T_2

$$\begin{aligned} f(w_1, w_2) &= f(z_1, z_2) \\ f(\underline{w}) d\underline{w} &= f(\underline{z}) d\underline{z} \\ f(z) &= f[T_2^{-1}(z)] \frac{\partial w}{\partial z} . \end{aligned}$$

1 2-dimensional linear convolution.



FIGURE B.5

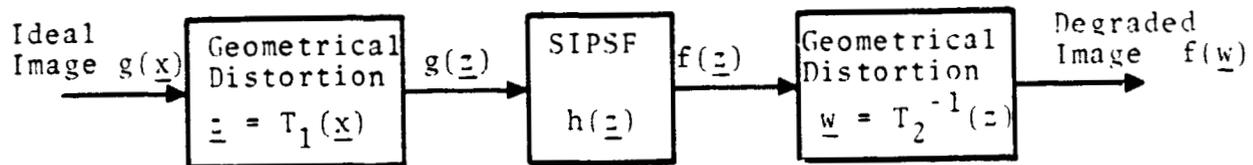


FIGURE B.6 - GENERAL SPACE-VARIANT DECOMPOSITION OF THE DEGRADING SYSTEM

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