Chapter 7

Communications

Traditional approaches to telemetry between the Earth and a mobile platform on the moon involves either relaying data through a stationary lander or storing information and transmitting it in bursts through an orbiter which then forwards the data to Earth. In the lander scenario, the need to relay limits excursions of the mobile platform to a region within line-of-sight of the lander, a 3-4 km radius on the Moon, and places substantial demands on the lander's power, thermal, communication, and other systems. In the orbiter scenario, the mission is confined to a narrow band on the moon, and is constrained by intermittent, short uplink time-windows. Both scenarios probably cost more, weigh more, and entail greater risk than a self-reliant rover which communicates directly with a station on the Earth.

The technical challenge is to achieve the high data rate required for entertainment, and valuable for science, while roving. It is notable that the significant data rates needed to support video for entertainment far outscale the low data rates motivated by traditional planetary science experiments. Current mobile communication systems use low gain, omnidirectional antennas in order to ensure uninterrupted coverage while traveling. The capacity of the communications link is limited and the data rate is severely restricted at reasonable power levels. With an omnidirectional link a high data-rate can be achieved only over a distance less than several kilometers. The data rate can be increased by boosting power or increasing the antenna size, and these strategies can be effective for orbiting platforms and large ground vehicles such as tanks. However, the resulting escalations in power budget and component size to achieve high data rate transmission over long propagation paths are not tolerable for small roving vehicles.

Much higher data transmission rates can be achieved for directional antennas (versus omnidirectional antennas) for given power and antenna size. Higher data transmission rate can be achieved by precision pointing. In this case the data transmission is proportional to the pointing accuracy, defined as the deviation of the antenna pointing vector from the desired line of sight. These considerations drove the decision to select a directional antenna for communicating directly with the earth and an omnidirectional link to provide the rover-to-rover communication. For this mission, the communication architecture is illustrated in Figure 7.1, and can be described as:

- Each rover is equipped with an omnidirectional antenna for dialoguing with its twin and a high gain parabolic-dish antenna for communicating with the Earth.

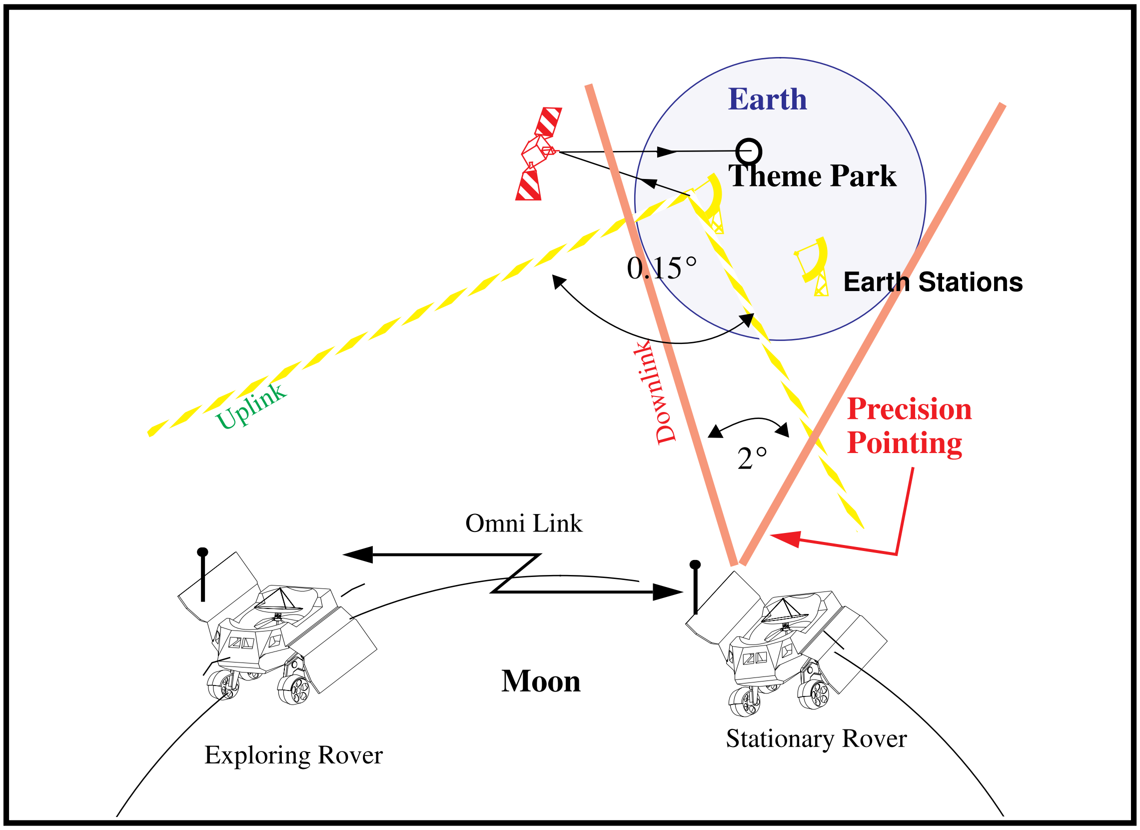

FIGURE 7.1 *Communications Scenario*

- The two rovers alternate between two operating modes: the first rover is stationary while the second rover explores the Moon in the vicinity of the first rover. The moving rover transmits data to the stationary rover which, in turns, relays the signal to the Earth.
- The stationary rover locks onto the line-of-sight to the earth using a precision pointing mechanism and it communicates directly with the earth stations.
- The Earth station then relays to a theme park via satellite links and high-bandwidth telecommunications lines.
- If one rover fails, the other can communicate directly with the Earth while moving, but at a reduced data rate.
- The Earth station then relays to the theme park via satellite links and high-bandwidth telecommunications lines.

An omnidirectional antenna is an understood technology and it will receive little attention in this document. On the other hand, significant attention is given to the direct communication link with the Earth and the precision pointing system needed to achieve reliable high-bandwidth transmission. First, the communication system requirements are discussed, followed by descriptions of the link parameters and antenna pointing system. The section concludes with a statement of open issues and future work.

7.1 Requirements

The communication system must maintain the link between the rovers and Earth at all times while the rovers are active. The requirements and constraints on the rover-to-Earth communication system are summarized in Table 7.1. In addition the hardware must be able to survive the temperatures, radiation and vacuum encountered on the moon.

TABLE 7.1 *Communication Requirements and Constraints for LRI*

Item	Value	Comments
Data Rate (Downlink)	12.0 Mb/sec	Stationary
	2.0 Mb/sec	Moving
Lifetime	2 yrs	Minimum
Power	100 W	Overall Comm[a]
Mass	20 kg	Overall Comm
Antenna Size	~ 1 m	
Cost	< $5 M	2 units

a. includes communication system and ancillary systems, like pointing mechanism.

7.2 Communication Link Design

This section deals with the links (downlink/uplink) between the stationary rover and an Earth station. Link requirements are summarized in Table 7.1:

- Power on the rover is limited to 100W or less for the communication link and pointing functions. Assuming a transponder efficiency of 15%, the radiated power will be on the order of 15 W.
- The antenna diameter will be of the order of 1 m or less, as determined by vehicle stability requirements and possible interferences with solar arrays and radiators.
- Data transmission capability is at least 2.0Mbps when moving and 12Mbps when stationary.
- Receiver dishes of the order of 10 m diameter have been assumed for Earth stations.

Table 7.2 summarizes various parameters of the downlink.

7.2.1 Communication link budgets

With the requirements of the communication system selected, a link budget can be performed. As mentioned, due to the limitation of power available on the rover, the radiated power is limited to near 15W (while moving).

Table 7.3 gives the results of the link analysis. A BPSK+R1/2 Viterbi coding scheme is assumed since it gives a large power reduction. Note that 18.5 W of power is needed while transmitting at 12.0 Mb/sec. Because the communication is done while the rover is stationary, the power savings from the locomotion system allow the extra power to be dedicated to communication.

TABLE 7.2 *Communication Link Parameters*

Parameter	Value and Rationale
Frequency	12.5 GHz (Ku-Band) - Reasonable sized antenna (~ 1m) for the desired beamwidth - Ku band devices (modem, transponders, etc.) tend to be small. - Ku band devices have a large consumer base - Low atmospheric attenuation
Antenna Type	Parabolic reflector (center feed) with 0.84m diameter - Simple, light- weight structure - High gain - Mature design
Transmitted Beamwidth	$2°$ - Illuminates the whole earth. - Smaller beamwidth will require larger antenna while larger bandwidth will require more power
Receiver Diameter	10 m - Available commercially - D > 10 m requires very high tracking accuracy - D < 10 m requires P > 10 W at the rover transmitter
Receiver Tracking Accuracy/ Resolution	$0.03°$ - Available commercially
Data Rate	2.0 Mb/sec (while moving) 12.0 Mb/sec (while stationary)
Transmitter Antenna Material	Kevlar coated with thin-film gold - Light weight - Excellent stiffness and thermal stability

7.3 Precision Pointing Mechanism

Pointing an antenna to the Earth from a stationary rover is relatively simple. However, tracking the earth from a moving rover requires an innovative pointing system to enable the robot to transmit while moving. In the case of a failed rover, this would allow the surviving rover to drive and communicate, although at lower data rates. The justification for precise pointing includes:

- the datarate decreases geometrically with increasing pointing offset.
- without precision pointing, higher power is needed to maintain the datarate, and power is limited.
- without an adequate pointing mechanism, communication with the Earth may be lost as a result of disturbances caused by the rover motion over irregular terrain.

TABLE 7.3 *Link Budget Results*

Item	Downlink (Stationary Rover)	Downlink (Moving Rover)	Uplink
Frequency	12.5 Ghz	12.5 GHz	14.5 GHz
Data Rate	12.0 Mb/sec	2.0 Mb/sec	0.5 Mb/sec
Power	18.5 W	4.6 W	0.8 W
Beamwidth	$2°$	$2°$	$0.15°$
Transmitter Dia.	0.84 m	0.84 m	10.0 m
Transmitter Gain	37.5 dB	37.5 dB	60.52 dB
Receiver Gain	59.4 dB	59.4 dB	59.4 dB
Pointing Accuracy	0.05 deg	0.5 deg	0.03 deg
Bandwidth	27.2 MHz	5.7 MHz	1 MHz
Link Margin	8 dB	8 dB	8 dB
EIRP[a]	49.9 dBW	43.1 dBW	58.2 dBW

a. Equivalent Isotropic Radiator Power

The challenge of achieving precise pointing from a rover moving over arbitrary lunar terrain is profound. Performance requirements can however, be relaxed by the following means:

- choosing an appropriate locomotion configuration so as to minimize the disturbances due to vehicle motion at the antenna.
- decoupling the antenna pointing system from the motion of the rover.
- placing constraints like maximum speed and the maximum obstacle size on locomotion.

Table 7.4 summarizes the pointing requirements for the mission obtained after relaxing the requirements using these means. They are higher than offered by existing mechanisms. For comparison, Table 7.5 lists key features of some existing pointing mechanisms. The first four systems are antenna pointing systems for satellites, while the last one is an optical mount.

TABLE 7.4 *Precision Pointing Requirements*

Item	Value
Azimuth	360 deg
Elevation	60 deg
Pointing Accuracy	0.5 deg
Slew Rate	20 deg/sec
Slew Acceleration	40 deg/sec^2
Temperature	-55 to 130 C
Vacuum	10^{-9} torr
Continuous Operation Interval	360 hrs

The slew rates (or the pointing rates) are an order of magnitude higher than typical for satellite RF communication systems. Satellites have slighter pointing challenges due to their smooth motion. Eutelsat is based on electronic beam tracking and has limited scan angles. All these mechanisms have masses 15kg or more. AOM-300-4 is a servo gimbal for terrestrial usage with capability close to lunar rover requirements in terms of accuracy and rates. The main problem is that it consumes more than 20W of power and its mass is 18kg.

TABLE 7.5 *Precision Pointing Mechanisms*

Name	Range (deg)	Slew Rate (deg/sec)	Accuracy (deg)
Toshiba APM-1[2]	+/- 15 both axes	0.31	0.0029
Toshiba APM-2[2]	+/- 180Az +/- 120 El	3	0.0057
HST STAPS[a]	+/- 110 both axes	0.5	0.6
Eutelsat [1]	+/- 6 deg both axes	3.8	-
AOM-300-4 [b]	360 Az 360 El	30	0.05

a. Honeywell- HST Antenna System

b. Aerotech, Inc., Pittsburgh.

Based on the existing mechanisms and preliminary survey, the main requirements in designing a pointing system for the mission are precision pointing (achieving 0.5 deg is easy from a stationary platform, but quite difficult from a moving platform), high angular rates and accelerations, mass/power limitations and the harsh lunar environment (e.g. temperature, dust, vacuum and radiation). In the following subsections, a preliminary concept for the pointing mechanism is presented.

7.3.1 Pointing mechanism

A two stage pointing could isolate gross vehicle rotations using one mechanism (for example, a pendulum) and perform finer rotations with another mechanism (for example, a gimbal). The pendulum could compensate for large angular motions of vehicle and servo-gimbal can fine tune for pendulum oscillations and orbital motions. Figure 7.2 shows the concept for a 2-Stage pointing mechanism with the Stage-1 possessing a suspended weight (a pendulum). The weight hangs in a 2-Axis cradle. The second stage consists of a servo-controlled 2-axis platform.

The main advantages of 2-Stage pointing might be:

- A pendulum with low damping would align the platform approximately to the gravity vector. This helps in isolating the antenna from large rotations (pitch and roll) of the rover.
- A 2-Axis servo-controlled platform (on which the antenna is mounted) could fine tune the pointing direction. Due to first stage isolation, the pointing requirements from Stage-2 are reduced in terms of required envelope of motion, slew rate and acceleration and hence fine tuning is relatively easy.

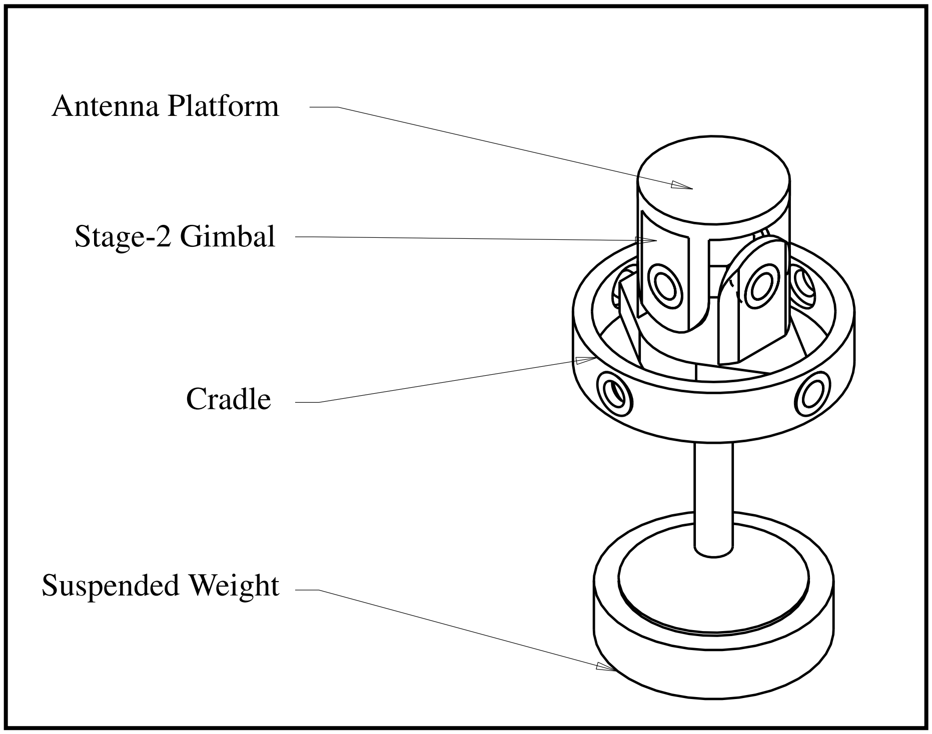

FIGURE 7.2 *Two-Stage Pointing Mechanism*

Preliminary analysis suggests that the 2-Stage pointing mechanism will be suitable for high-precision applications for mobile robots. It is being modelled and simulated. Some of the open issues, which will be addressed, include position of the center of gravity, damping, and position of the actuators.

Stage-1 (pendulum) can acquire gyroscopic stabilization by replacing the counter-weight with a rotating wheel. It may provide better isolation of vehicle motion, but precession induced by disturbance torques may be problematic. The merits of the concept will be assessed.

Initial analysis shows that a 2-stage design is possible and practical within the given mass and power limits (5 kg and 5 W respectively), and ensures a backup operational capability of 2.0 Mbps data rate for the communication system.

7.4 Sensors

The ability to dynamically point an antenna must be directed by a sense of where to point. The following sensors are considered for the precision pointing:

1. An inertial system for vehicle-pose feedback. Available IMUs can measure disturbances (excursions, rates, and accelerations) with an accuracy of 0.02 deg at 400 Hz, and with drift less than 1deg/hr. Furthermore, integrating the IMU output yields the location of the platform with respect to an inertial reference, which is useful for servo control of the fine pointing stage.

2. An encoder system for antenna-scale feedback. The system could consist of encoders mounted on both axes of the pointing mechanism. The encoder readings determine the antenna attitude with respect to the platform on which the antenna is mounted, and hence with respect to the inertial reference provided by the IMU.
3. An image-based system for celestial fixing. This could consist of a wide field-of-view star-tracker, which provides an inertial reference by matching a star field to an on-board star map. The star-tracker will determine the rover attitude in an inertial reference, and hence its angular coordinates with respect to the Earth, and hence the requisite pointing direction.
4. An image-based system for pointing feedback. This could consist of a CCD camera and image analysis software to search the image for the Earth. That search might proceed by first segmenting out those pixels that belong to the projection of the Earth, and then fitting a model (ellipse) to those pixels.
5. A beacon-based system for fine pointing feedback. This could consist of some variant of a beacon signal tracking system typically used in satellite communications, including monopulse track, lobing track, and program track systems.

These sensors have to be evaluated based on bandwidth, cost, accuracy, reliability, power and component availability for eventual application to determine the technical viability and cost-effectiveness of any proposed mix.

7.5 Controller

Various control strategies are being considered to close feedback loops around cameras, a beacon tracker, or other sensors. The coarse stabilization stage isolates the effect of rover motion from the fine pointing stage. Uncompensated motion will appear as disturbances to the fine pointing system. Figure 7.3 illustrates a preliminary concept for the control system to compensate for those disturbances. The controller generates commands for the actuators by comparing the signal from an IMU, which measures the attitude of the fine pointing platform, with a reference signal. The controller then servos the actuators to the commanded levels using the encoder output as feedback.

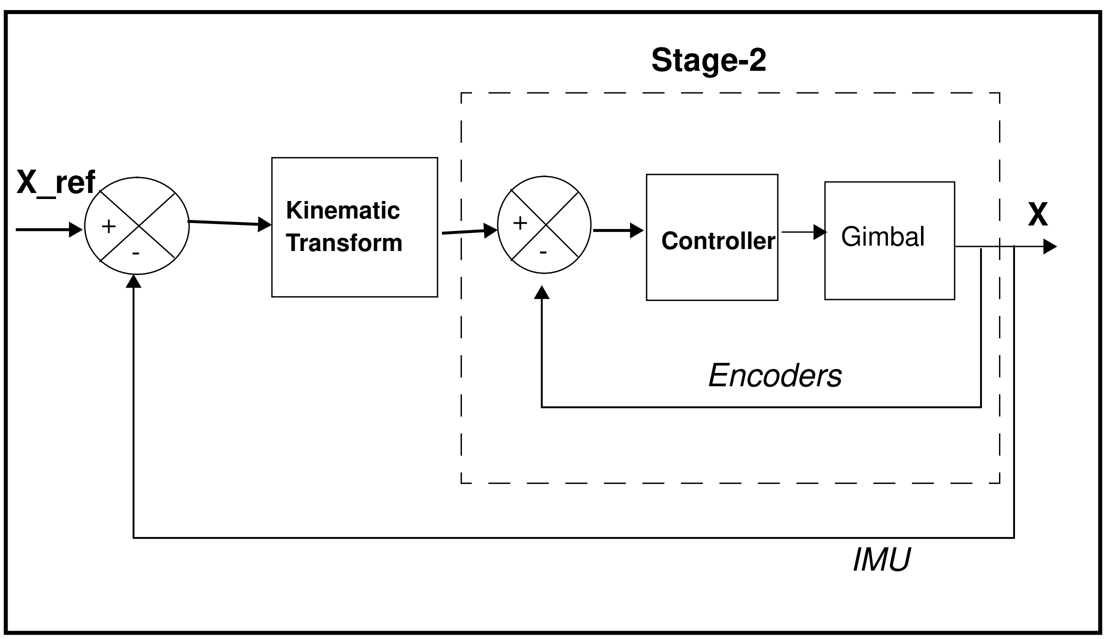

FIGURE 7.3 *Control of Pointing Mechanism*

7.6 Risks and Future Work

A conceptual design for a precision pointing system has been offered in this chapter, but detailed modelling and simulation are incomplete. Analyses will be performed which take into account the motion of the rover over diverse lunar terrains. A parallel inquiry will consider other concepts such as phased arrays. Other important issues which will be addressed are:

- Efficient coding schemes: BPSK Plus R-1/2 Viterbi coding, though it has excellent BER performance and is not susceptible to the phase disturbances, has very poor use of spectrum (hence high bandwidth is required).
- Efficient compression algorithms: An efficient compression algorithm would decrease the necessary data transmission rate and relax the requirements of communication link and the pointing mechanism.

Other concerns for implementing the proposed communication link include determining component specifications, locating established vendors for key components and obtaining a frequency license.