Precision Pointing from a Mobile Robot

The Robotics Institute, Carnegie Mellon University
February 14, 1994

Submitted to: National Aeronautics and Space Administration
For the period: October 1, 1994 to September 30, 1997

Principal Investigators:
William Whittaker, Eric Krotkov

1. Objectives

Carnegie Mellon University proposes a three-year program to develop and demonstrate precision pointing to enable high data rate telemetry from roving ground platforms. In the first two years, we will focus on video telemetry (frame-rate stereo imagery for entertainment and science users) from a lunar rover that establishes a visual lock on Earth. In the third year, we will concentrate on a different high data rate communication scenario such as video telemetry from service vehicles to satellite systems for mobile surveying.

Traditional planetary telemetry either relays through landers or stores-and-forwards through orbiters. In the lander scenario, the relay limits the mission to the region within line-of-sight of the lander, a 3-4 km radius on the Moon, and requires substantial scars to the lander for power, thermal, comm, and other systems. In the orbiter scenario, the mission is confined to a narrow band on the planet, and is constrained by intermittent, short uplink windows. Both scenarios cost more, weigh more, and entail greater risk than a self-reliant rover.

The technical challenge in achieving rover self-reliance lies in achieving the high data rate (required for entertainment and valuable for science) while roving. Current mobile communication systems use low gain, omnidirectional antennas in order to ensure coverage while traveling. A fundamental problem with this approach is that the capacity of the communications link is limited, thus restricting the data rate. The data rate can be increased by boosting power or increasing antenna size, and this is effective for orbiting platforms and large ground vehicles such as tanks. However, the resulting escalations in power budget and component size are not feasible for small roving vehicles.

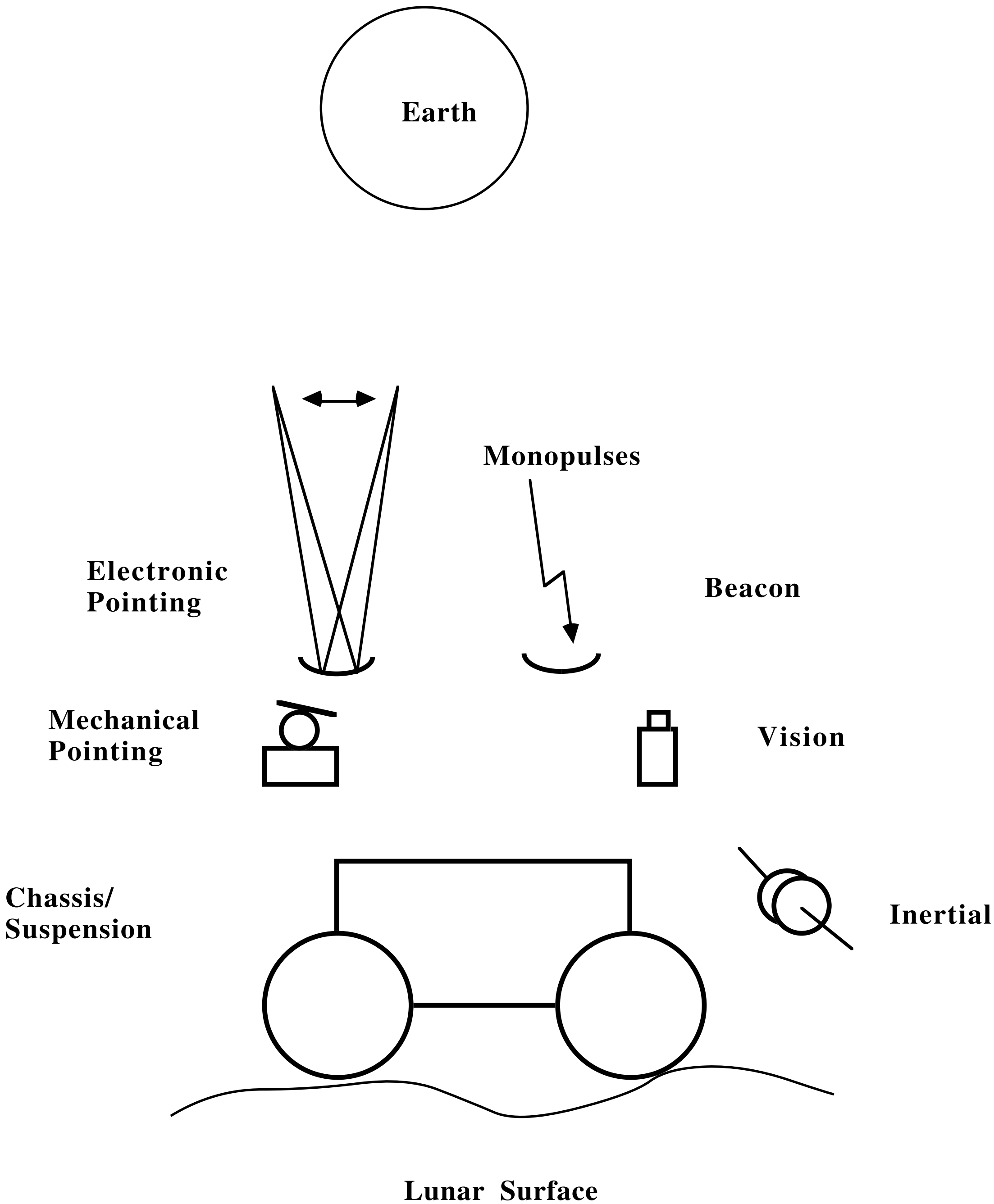
For a mobile communication systems to use a high gain antenna, it must track the target (the Earth for the lunar rover, satellites for terrestrial mobiles), following both vehicular and orbital motions. This is beyond the current state of the art. The need is to automate the orientation of devices using small, light, low-power components to enable high-bandwidth communications.

2. Justification

The capability for precision pointing from a moving platform using lightweight components is essential for direct video communication from a roving lunar robot. The capability also enables a wide variety of applications, including

- satellite communications, especially mobile satellite services, broadcast services, data relays, and secure communications
- mobile surveying
- precision navigation of mobile equipment such as tunnel boring machines
- designating targets and pointing weapons

The automation of precision mobile pointing will be relevant in all of these markets, as described in Section 6.



3. Approach

In Year 1, we will begin by performing a link analysis to derive the data rates, radiated power, carrier frequency, antenna size, bit error rate, and other link parameters. Next, we will determine the pointing system requirements in terms of articulation, slew rates, and motion compensation. Given these requirements, we will in parallel develop hardware and software. In hardware, we will configure, design, and build a breadboard model of the pointing system. In software, we will implement the controller and sensor modules. Finally, we will demonstrate fine pointing from a roll-pitch-yaw platform that simulates the three orientation freedoms of rover traveling over lunar terrain (pointing requires control of only two orientation freedoms).

In Year 2, we will refine and iterate the breadboard system to meet all pointing requirements. Next, we will design and build a fieldworthy pointing system. Then we will demonstrate precision pointing from a rover traversing lunar analog terrain.

In Year 3, we will customize the pointing system for a class of mobile equipment selected for its commercial viability, and demonstrate an application-specific task such as a mobile survey.

3.1 Link Analysis

For the proposed lunar mission, a number of quantities are already known, including the Earth/Moon distance, the size of the receiving antennas on the Earth and their positional accuracy, and the acceptable signal-to-noise ratio (decibel margin). In the following, we present preliminary considerations on the communications link.

The data rate follows from the mission requirement to transmit stereo images. At frame rate, this requires approximately 120Mbit/sec. Since the data is intended for use by humans, not computers, lossy data compression techniques that achieve 20:1 compression ratios may be used, resulting in a net data rate of 6 Mbit/sec.

The amount of power available for data transmission will also follow from the mission profile. However, international agreements place an upper limit on the downlink power flux so as to avoid interfering with existing terrestrial services. We will perform a power study to determine the trade-offs involved in pumping power into the antenna versus pumping it into the pointing system, while not exceeding the downlink limitations.

For the carrier frequency, we are considering four frequency bands: S, X, Ku, and Ka. Of particular interest are the S, X and Ka bands. The primary advantage of the S band is that there exists a large body of pre-existing hardware. The band has been used extensively in previous space missions, and is not greatly affected by absorption in the Earth's atmosphere. The drawback with S band is that larger equipment and antennas are required than for the other bands. X band has many of the same attributes as the S band, however, there is not as much existing hardware for this band, and it is used exclusively by the military. The Ka band's primary attribute is the small size of the telemetry hardware components and antennas. Its drawbacks are significant signal attenuation from the atmosphere and a small, but developing, base of hardware.

The antenna size required to produce a beam-width of two degrees (the angle subtended by the Earth as viewed from the Moon) depends on the carrier frequency. The sizes range from 4.2 m for S band to 0.6 m for Ka band.

The pointing angle error depends on the transmission beam-width. The smaller the beam-width, the greater the impact of pointing inaccuracy. For a high-speed vehicle, maintaining an accurate position lock is an extremely challenging task, thus indicating the possible desirability of wider beam-width to reduce the pointing requirements. Such a system will require greater transmitter power, but will be easier to control because the antenna is smaller.

The bit error rate can be derived from mission requirements. Since the proposed mission is supplying data for humans and not computers, the acceptable bit error rate is higher, which has the same affect as lowering the required signal-to-noise ratio at the receiving antenna.

Concerning atmospheric losses, S and X band suffer essentially no loss from atmospheric and rain attenuation. However, Ka band signals can experience losses of as high as 20 dB depending on the angle of the incoming signal and weather conditions at the receiving station.

Based on these preliminary considerations, two tentative options have emerged as low technology-risk candidates: S-band, and an existing optical satellite-to-satellite link.

3.2 Pointing Requirements Analysis

We will determine the requirements for the pointing system in the following form:

- Articulation range: azimuth and elevation (deg)
- Retargeting slew rates: azimuth and elevation (deg/sec), and settling time (sec)
- Target motion compensation: control (arcsec) and stability (arcsec/ms)

To determine the requirements we will analyze two primary constraints: rover/terrain dynamics, and observability of the Earth.

In rover/terrain dynamics, there are three key parameters that affect the angular excursions and vibrations of the vehicular antenna:

- Terrain morphology. As the rover traverses, we expect pitch and roll angles on the order of +/-50 deg. Independent of terrain, we expect yaw angles up to 360 deg. Terrain roughness will accelerate the rover and induce vibrations.
- Rover suspension. The suspension filters the vibrations induced by terrain irregularities. The dynamic behavior of the payload above the suspension obeys a set of well-understood differential equations, which we will solve to identify the rover chassis motions.
- Pointing platform. The same set of differential equations govern the platform that orients the antenna. The solutions will identify the antenna motions.

In observing the Earth, the issue is that the pointing angle varies with the regions traversed on the lunar surface. Missions at the poles require the antenna to be pointed at angles grazing the vehicle and terrain. Missions at the center of the near-side require the antenna to point nearly straight up from the vehicle. Since preliminary mission scenarios call for excursions starting from the center of the near-side, for the purposes of this study we will concentrate on the case of steering angles in a cone overhead the rover. For lunar applications, the results will be relevant to missions +/-40-50 deg from the center of the near-side. For terrestrial applications, the results will be viable for geostationary communications from the temperate latitudes.

3.3 Pointing System Configuration

The pointing system will consist of one subsystem for coarse pointing and another subsystem for fine pointing. In this decomposition, the fine pointing subsystem provides resolution and response greater than the coarse stages, but over a narrower range of orientations. Our preliminary analysis suggests that a mechanical system is most appropriate for the coarse stage, and that an electronic system is most appropriate for the fine stage. We expect the power study described in Section 3.1 to further elaborate this analysis.

3.3.1 Mechanical Pointing

The first candidate for the orienting platform is the pan/tilt mechanism commonly employed in oriented satellite antennas. For example, in work following ETS-VI, Toshiba has developed a (slow) pointing mechanism that provides 0.0057 deg resolution over a scan range of +/-180 deg azimuth and +/-120 deg elevation.

In addition, we are investigating the use of magnetic levitation using the Lorentz force to isolate the pointing mechanism from the rover chassis. This technology has been successfully reduced to practice in robotic applications, and holds promise for space viability. A leading practitioner, Ralph Hollis, has recently joined the Robotics Institute with several tractor-trailers of equipment.

3.3.2 Electronic Pointing

The first candidate for electronic pointing is a phased array antenna, because it provides high-speed scanning in a relatively small and lightweight package. A phased array antenna is an array of small antenna elements deployed over a large area and connected so that their received or transmitted signals are in the correct electrical relationship (phase) with each other. A phased array can be electrically scanned (pointed) by changing the phasing of its elements. The technology is relatively mature, and a base of flight-worthy microstrip antennas exists.

3.4 Sensors

Like the pointing system, the sensor suite will consist of a coarse-to-fine hierarchy. We envision an inertial system for vehicle-scale feedback, a vision-based system for mechanical pointing feedback, and a beacon-based system for electronic pointing feedback.

3.4.1 Inertial

We will employ an inertial instrument to provide vehicle attitude data. This data will play roles both in vehicle control and pointing control.

Based on preliminary analysis, a strapdown IMU (inertial measurement unit) based on ring-laser gyros will provide (at 20 Hz) static accuracies of 0.3 deg and dynamic accuracies of 2 percent. These devices are widely available. We will also evaluate fiber-optic gyro systems to determine their price, performance, and availability.

3.4.2 Vision

We will deploy one or more vision devices to provide coarse information about the direction of the Earth. (By "vision" we mean to include non-visible wavelengths.) These devices will be used for initial acquisition and for re-acquisition, and for establishing a visual lock. Preliminary analysis suggests using a CCD camera to find directions within 10 deg, and a horizon sensor to find directions within 1 deg. We will also continue to evaluate the use of sun sensors.

For the CCD camera, we will configure the lensing to have roughly a 40 deg by 40 deg field of view. We will develop two-dimensional processing to search the image for the projection of the Earth. The basic approach is to first segment out those pixels that belong to the projection of the Earth, and then to fit a model (ellipse) to those pixels. The segmentation and modeling approaches will succeed even if the Earth is only partially in the image. The computational complexity of each of the approaches is either constant or linear in the number of pixels. Thus, there will be no difficulty in implementing an efficient Earth-finder that can provide frame-rate (30 Hz) feedback for visually servoing. As necessary, we will account for second-order effects such as atmospheric refraction and parallax.

By "horizon sensor" we mean the sensor that is the principal means for directly determining the orientation of spacecraft with respect to the Earth. We expect to utilize a commercially available device that operates in the 14-16 mm CO_2 band in the infrared, because the position of the Earth's horizon is least ambiguous in that band. We anticipate using a body-mounted device (rather than momentum wheel-mounted) with a field-of-view of 2 deg x 2 deg, and an accuracy of 0.5 deg.

3.4.3 Beacons

We will exploit signals uplinked from the receiving stations on Earth to provide fine direction information for electronic pointing. The uplink signal will be received by a directional sensor attached to the orienting platform.

The measured quantity is signal strength. One alternative is for the signal to be a +/- monopulse pair. Another alternative is for the signal to be a laser beam, which would illuminate a footprint on the lunar surface of radius approximately 1 km. Significant further analysis of the technology options and their costs is required to establish the preferred beacon signal.

3.5 Controller

In the lunar rover scenario, the controller will control all motions in the actuator chain (vehicle plus orienting platform) and in addition control electronic endpointing. The pointing mechanisms and sensors have been selected to form a coarse-fine hierarchy. The controller must establish feedback loops at each level of the hierarchy in order to achieve pointing that is accurate and stable despite the disturbances excited by the terrain.

Significant effort has been devoted by roboticists to develop manipulator endpoint control using coarse-fine approaches. In a pointing simulation, we will evaluate at least three basic controller designs that have been adopted in robotics. The controllers will include a classical frequency domain (PID) design, a nonlinear dynamic compensator, and a state space filter. The controller that performs best in the simulations will be selected for a detailed design and practical implementation.

4. Participants

Carnegie Mellon University. Scope to include formulation, research, demonstration, and project management.

MIT. Scope to include analysis and collaboration. Prof. Dubowsky has submitted an option in the current cycle of TRIWG submissions.

Mitre, JPL, Martin Marietta/GE Aerospace, and/or Harris. Scope to include consulting on link analysis and antenna design.

Boeing. Scope to include consulting on phased-array antenna for Comanche.

5. Deliverables

FY95: Develop complete breadboard model of pointing system and demonstrate fine pointing (15 deg beam-width to 2 deg target) from a roll-pitch-yaw platform with a 2.5 deg/sec disturbance rate.

FY96: Develop fieldworthy pointing system and, from rover traveling on lunar analog terrain, demonstrate pointing with precision required for Moon/Earth video telemetry (until requirements analysis complete, anticipate at most 10 deg beam-width to 2 deg target, and at least 5 deg/sec disturbance).

FY97: Develop customized pointing system for heavy equipment and demonstrate mobile survey.

6. Commercialization Potential

The precision pointing technology has significant potential in a wide range of markets. Here we focus on the markets in communications, mobile surveying, precision navigation, and weapon systems.

COMMUNICATIONS. According to the 1993 NASA/NSF study on Satellite Communications Systems and Technology, in the decade ahead the satellite communications business (excluding military communications) will expand from approximately $15 billion to about $40 billion. The study predicts that the global market will expand very rapidly into personal communications and new mobile satellite services, expanding from under $1 billion in 1992 to $10 billion in 2002 (excluding equipment sales).

The study identifies the topic of this proposal as a critical technology: "With [1993] vehicular antenna technology, all proposed mobile satellite systems will be relatively starved for power, even with the largest foreseeable space antennas. Thus, the availability of cheap, high-gain, automatically tracking vehicular antennas would have a big impact on throughput and capacity." By enabling high gain vehicular antennas and human-portable (briefcase, backpack) antennas, the precision pointing technology developed in the proposed work can secure a significant market share of the $10 billion mobile services market.

The precision pointing technology has obvious potential in several other communications markets:

- Broadcast satellite services (projected growth from $0.5 billion in 1992 to $8 billion in 2002), including remote news and sports coverage
- Data relay services (projected growth from $0.1 billion to $0.3 billion), including field telephony
- Secure communications for the military, intelligence, and industrial communities

MOBILE SURVEYING. The precision pointing technology can revolutionize the surveying industry by minimizing the time and effort required to collect data. Current practice features total stations that permit textual annotation of measurements, and mobile GPS data acquisition. Precision pointing could virtually eliminate the need for field parties, replacing them with a single driver and a service vehicle. The vehicle will be capable of precisely targeting landmarks such as buildings, utility poles, and trees, and of streaming video and quantitative data back to stationary analysts at a geographic information system.

PRECISION NAVIGATION OF MOBILE EQUIPMENT. Precision navigation is critical for a number of enterprises with heavy equipment. For the construction industry, GPS fails to provide the millimeter precision required for building bridges, digging tunnels, and joining roadways. For the agriculture and automotive industries, similar arguments apply.

WEAPON SYSTEMS. The precision pointing technology has direct applicability to the tasks of designating targets and pointing weapons. One example application is in gun-turret systems for helicopters and tanks.

7. Funding

FY95: $250K (includes 50 equipment and 50 subcontract for link and antenna analysis)

FY96: $350K (includes 30 equipment and 50 subcontract for engineering services)

FY97 $250K (includes 10 equipment and 20 subcontract for technology transfer)

Total $850K

8. Facilities

This work will be performed primarily at the Field Robotics Center and the Vision and Autonomous Systems Center at the Robotics Institute, Carnegie Mellon University.

The Robotics Institute is a unique resource. Established in 1979 as the nation's first comprehensive robotics research center to conduct research in robotic technologies relevant to scientific, industrial, and governmental needs, the Institute has grown into a powerful, interdisciplinary research organization, which draws upon Carnegie Mellon's strengths in computer science, engineering, science, and industrial administration.

The Institute has a staff of over 120 personnel, over 50 graduate students enrolled in affiliated programs, and 60 graduate students enrolled in the Robotics Ph.D. program. The Institute is organized into thirteen dedicated research laboratories and three program centers, which cover the spectrum of robotic research initiatives and encompass a wealth of robotic expertise. The Institute pursues a comprehensive research agenda that culminates in competent, working robots.

9. Principal Investigators

William "Red" Whittaker, Field Robotics Center, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, tel 412-268-6559, fax 412-682-1793, red@frc2.frc.ri.cmu.edu

Eric Krotkov, Robotics Institute, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, tel 412-268-3058, fax 412-621-1970, epk@cs.cmu.edu