A HIGHLY MINIATURIZED, BATTERY OPERATED, COMMANDABLE, DIGITAL WIRELESS CAMERA

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ABSTRACT

This paper discusses the design, development, testing, and demonstration of a highly miniaturized, battery operated, digital wireless camera. The miniature wireless camera receives commands transmitted from a remote base station requesting it to take one or more frames of data, and broadcasts the digital image data to the base station receiver for display. The camera uses a complementary metal-oxide-semiconductor (CMOS) active pixel image sensor (APS) that achieves noise performance comparable to a charge-coupled device (CCD) with orders of magnitude better power consumption performance. The image sensor is integrated with a wireless communications transceiver, antennas and batteries into a stand alone miniature package. The results of a three year development effort are described. The miniature wireless camera will be delivered to the Defense Advanced Research Projects Agency (DARPA) in July 1998.

INTRODUCTION

The objective of this effort is to develop and demonstrate a small wireless digital camera based on JPL's CMOS active pixel sensor (APS) technology with 1 km range, 2.5 Mbps image transmission rate, and a long battery life. This effort was motivated by the invention of the APS imaging technology, coupled with the proliferation of miniature, low power wireless communications integrated circuits. The highly integrated APS with its ultra low power consumption lends itself to miniature battery operated designs that are impractical for CCD based imagers. Applications of the miniature wireless camera include surveillance in military (e.g., shell launched and hand placed) and civilian settings, perimeter monitoring, micro unmanned aerial vehicles, and remote baby monitoring. [1]

The novel capabilities of the miniature wireless camera become apparent when compared to commercial wireless cameras that are on the market today. Table 1 provides a comparison of the DARPA/JPL wireless camera capabilities to two representative commercial wireless cameras. [2,3] The commercial cameras are typically used in applications where they are manually turned on, hand placed, and transmit continuously until the battery is completely discharged or they are manually turned off. The DARPA/JPL wireless camera differs from these cameras in that it has a command link that permits remote control. Additionally, it has sleep, receive, and transmit modes that are managed to conserve power. As is shown in this paper the wireless camera can have a lifetime of many days or weeks vs. hours for these commercial cameras. In addition to possessing "smart" camera capabilities the DARPA/JPL camera differs from commercial wireless cameras in that it is snap-shot oriented rather than video, uses digital vs. analog transmission, includes an APS vs. a CCD, and includes low profile, conformal antennas vs. non-conformal antennas. These features combine to provide a capability to the Department of Defense (DoD) that is not available with current wireless cameras.

Camera	Resolution	Remote Control	Range (feet)	Size (in^3)	Power (mW) [sleep/rx /tx]
DARPA/ JPL	256x256	Yes	3280	4.2	0.6 / 9 /1000
VID001	420x420	No	2000	2.5	no/ no / 1125
MvCm Tx528	380x350	No	300	29	no/ no / 3600

Table 1 Comparison of Wireless Cameras

SYSTEM DESIGN

The high level requirements established at the outset of this effort were as follows:

- 2.5 Mbps image data rate
- low data rate command link
- range ≥ 1 km
- spread spectrum transmission
- low profile antenna
- 256 pixel x 256 pixel x 10 bit imaging array
- minimize power consumption
- low power standby mode
- camera volumetric goal: 1”x1”x1”

The block diagram of the system designed to meet the requirements is shown in Figure 1. The user interface is built around a standard PC with a graphical user interface for controlling and configuring the camera and displaying images received from the camera. The base station transceiver was necessarily a custom design, but extensive use was made of commercial components where possible (e.g., antennas).

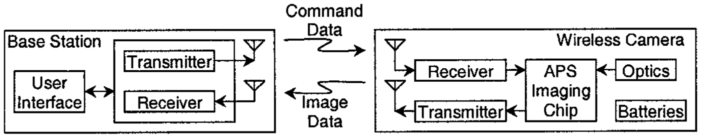


Figure 1. System Block Diagram

The miniature wireless camera design approach to meeting the requirements was to custom design the CMOS APS ‘camera-on-a-chip’ integrated circuit, and integrate this with a miniature transceiver design that leveraged off of highly integrated commercial integrated circuits, and combined them with a custom digital application specific integrated circuit (ASIC). The lens and high energy density batteries are off-the-shelf items.

Unstated in these requirements is that the design approach was to minimize the complexity in the camera in an effort to reduce the power consumption and volume, at the expense of increased processing complexity, larger size and less power efficiency at the base station. Following the same line of thinking, resources were concentrated on miniaturizing the packaging of the camera and minimal effort was expended to package the base station.

Upon completion of the detailed design, the system was built up into a ‘bench-top’ system for use in laboratory and field testing. The bench-top design made no attempt at miniaturization, yet utilized all the parts of the final system, and allowed for verification of the system performance and optimization prior to final miniaturization of camera end of the link.

MINIATURE CAMERA

The miniature wireless camera is shown in Figure 2. As can be seen in this figure the two conformal antennas are on top of the package and the lens is on one side. Not shown in the figure are the internal electronics which consist of a communication system, imaging system, and a power system.

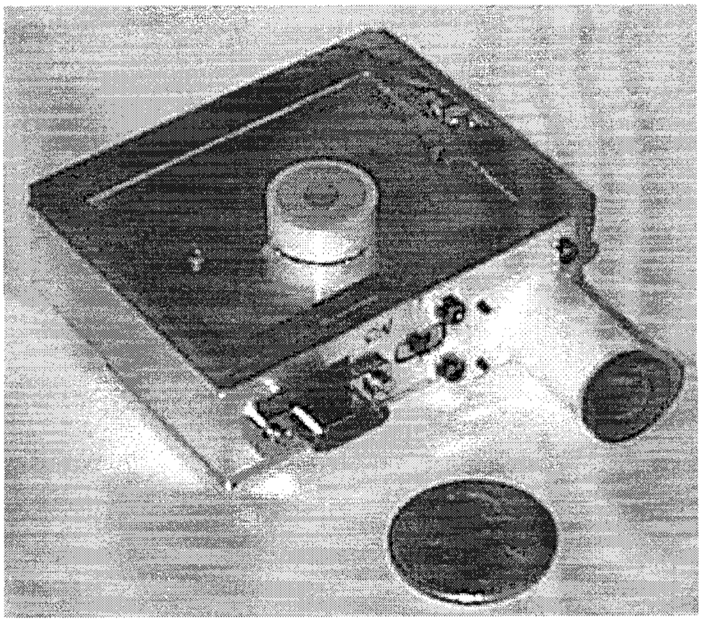


Figure 2 Miniature Wireless Camera

COMMUNICATION SYSTEM

The communication system operates over a one kilometer range with a UHF command link operating at 1.024 kbps and a spread spectrum S-band (Industrial, Scientific and Medical-ISM band) digital image data link operating at 2.455 Mbps.

The selection of the transmission frequencies was driven by two factors: 1) frequency spectrum regulatory constraints and 2) availability of miniature, low power transceiver components. The 2.4 GHz ISM band has the benefit of being an unlicensed band as long as the transceiver is compliant with FCC Part 15 regulations. Due to the commercial potential of this unlicensed band there is a wide selection of commercially available RF parts. This band has 83.5 MHz of spectrum which is almost fully utilized by our spread, high data rate image signal. The down side of utilizing the ISM band is that the receiver must contend with a multitude of other devices operating at the same frequencies.

The 418 MHz command link frequency was selected to capitalize on the availability of a low power, low data rate telemetry receiver that helps minimize the power consumption and size of the camera. The command link frequency requires regulatory approval prior to operation.

The low data rate nature of the command link lends itself to the use of inefficient modulations that permit the implementation of low power receiver designs. Amplitude shift keyed (ASK) modulation was selected. In order to keep the camera receiver simple, no error correction coding is used on the command link. Manchester encoding of the data is utilized to aid in clock recovery in the camera.

The 418 MHz ASK command receiver is a single-chip device which accepts the antenna signal input and produces baseband CMOS-compatible detected data bits at its output. This commercial device provides an RF sensitivity of approximately -100 dBm.

The low rate 418 MHz command link allows the use of a miniature loop antenna that has a minimum gain of -20dBi. The link margin is sufficient to accommodate this gain and thus, the antenna provides the required 360° coverage in azimuth.

The 2421.6 MHz image data link is designed to maximize the throughput of the link while keeping the camera transmitter simple and thus low power. Coherently detected QPSK modulation with a rate one-half, constraint length seven convolutional code was selected. To conform to the FCC Part 15 requirements the camera transmit signal utilizes direct sequence spreading with a processing gain of 11 dB. The programmable pseudo noise (PN) code is generated by a 16 bit shift register.

The communication link protocol is half duplex in order to eliminate the possibility of the transmitter interfering with the receiver which is extremely close by. Use of a half duplex transmission scheme also eliminates the need for a diplexer which would be prohibitively large. The protocol command packet is 64 bits long and allows for the addressing of up to 255 cameras from a single base station. The baseline operational scenario calls for a single image to be transmitted per command, but it is possible to transmit multiple images sequentially when required.

The baseband circuitry of the camera was initially implemented in a field programmable gate array (FPGA) design and was then converted into an ASIC to conserve power and size. This chip performs a number of functions. For the command link a matched filter, a clock recovery digital phase lock loop, a unique word detector, a parity checker, an address decoder, and a command word re-formatter were developed. For the image link a differential encoder, a convolutional encoder, and a digital quadra-phase spreader were implemented. Finally, a state-machine controlling the sleep/receive/transmit states was developed.

The RF portion of the camera's 2421.6 MHz spread spectrum transmitter consists of three sections: the local oscillator circuit, the quadrature phase shift keyed (QPSK) modulator and the power amplifier. The local oscillator circuit consists of a 403.55 MHz SAW stabilized Colpitts oscillator/multiplier whose collector circuit is tuned to the sixth harmonic. This sixth harmonic signal is amplified and filtered to produce the required local oscillator (LO) signal at 2421.6 MHz. The single-chip modulator accepts the LO signal plus baseband in-phase and quadrature digital signals and produces the QPSK modulated output. This modulated signal is amplified by the power amplifier and bandpass filtered to produce the 100 mW signal which is fed to the transmitting antenna. The S-band antenna provides 360° coverage on the horizon with a minimum gain of -1.5 dBi.

APS IMAGING CHIP

The imaging sensor included in the system is the first demonstration of a complete digital camera system on a single chip. The chip, described in detail in reference [4], utilizes a CMOS Active Pixel Sensor array, an image sensor that offers similar imaging performance to the more familiar CCD's, but uses roughly 100 times less power (10-20 mW as opposed to 1-2 W). Since this type of sensor is implemented in CMOS, circuitry can be included on the sensor itself to perform a variety of operations, such as, image processing or encryption, allowing compact monolithic image sensor systems.

The imager, shown in Figure 3, contains a 256 x 256 photogate array with 20.4 μm pixel pitch, and features 256 on-chip analog-to-digital converters (ADC's) in addition to full timing and control.

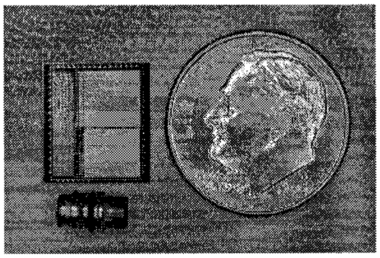
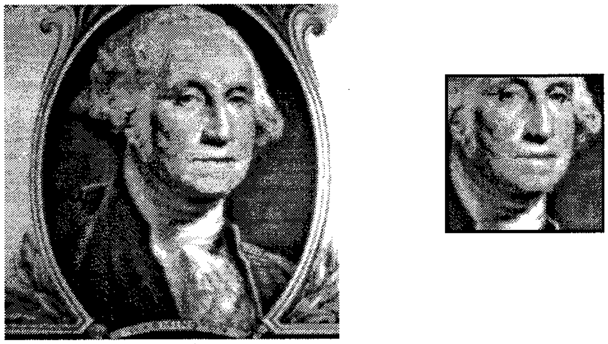
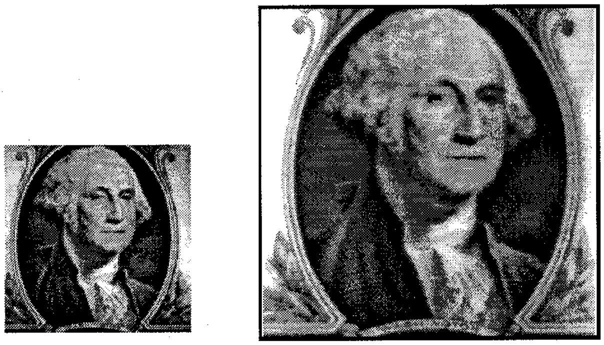


Figure 3 Low power (20 mW) complete digital camera-on-a-chip implemented in HP 1.2μ, 5V process through MOSIS. The 9.3mm x 11.2mm chip contains a 256 x 256 APS array and 256 on-chip analog-to-digital converters.

The imager requires only five digital lines for operation and uses 20 mW of power. All analog references required for proper imaging and digitization are generated on-chip and can be adjusted with four digital-to-analog converters (DAC's). Thus the camera has a complete digital interface. It can be programmed to support a variety of imaging operations; including a fully programmable exposure time ideal for remote sensing applications. It also has fully programmable windowing and subsampling as illustrated in Figure 4. These programmable on-chip data reduction options, when enabled, allow for accelerated image output and can be used to increase battery lifetime.



Original a) Windowed



b) Sub-Sampled c) Low Light

Figure 4 The imager can be programmed to support a variety of imaging operations such as a) windowing and b) subsampling. It also has a fully programmable exposure time as well as good low light operation c) image taken in a dark room with 8 sec exposure

To ease integration requirements, the camera chip can be programmed to accommodate a number of interfaces. For example, it can produce serial or parallel output with a variety of data formats; it can support full or half duplex protocols, generate vertical and horizontal frame syncs, perform serial input clock recovery and can handle various system data rates. While the imager can take images continuously, for this application it is programmed to take digital stills. After acquiring a digital still image, it automatically enters a low power (40 μW) idle mode, implemented by turning off analog circuitry.

POWER AND BATTERIES

The wireless camera will be powered by two lithium CR-2 camera batteries placed in series. These batteries provide 3.0 V each with a capacity of 800 mA-H. They are 27 mm long and have a diameter of 15.6 mm.

In an effort to extend battery life, three logical states have been incorporated into the camera design. These are a sleep state (minimum power mode, <600 μW), a receiving state (to see if commands are being sent to the camera, <9 mW), and a transmit state (largest power requirement, ~1 W). The duration of these modes can be set by utilizing a configuration module that is plugged into the camera during initial setup.

Estimates on the battery lifetime have been performed, based on power supply current measurements in the lab. Table 2 shows the results for several operational scenarios. The transmit frequency is the percentage of awake cycles during which a picture is returned. For example, the third line of the table specifies that the wireless camera will sleep for 64 seconds and then awaken to receive for a maximum of 2 seconds. If a command to transmit is received in this time (a case that will occur 1% of the time according to the table) then the camera will transmit one image. The 256x256 image transmission lasts 0.937 seconds. The camera then returns to sleep. In this case, the projected battery lifetime is approximately 190 days.

Sleep Time (s)	Transmit Time (s)	Picture Size (pixels)	Transmit Frequency	Pictures Returned	Battery Life (days)
64	0.937	256x256	100%	16009	12.40
64	0.937	256x256	10%	10661	82.60
64	0.937	256x256	1%	2456	190.29
64	0.560	64x64	100%	25819	19.89
64	0.560	64x64	10%	14273	109.95
64	0.560	64x64	1%	2608	200.93
512	0.937	256x256	100%	12649	75.39
512	0.560	64x64	100%	18076	107.65

Table 2: Battery Lifetime Projections[1]

One other mode of operation would be to send pictures continuously. The cycle for this mode is then 0.25 seconds of receive for every 1 second of transmit. This results in an operational lifetime of approximately 5 hours

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[1] a) Non-ideal environments in the field may affect these lifetime projections.

b) All projections assume a receive time of 2 seconds.

of operation. Assuming a return rate of 1 picture every 1.25 second, this translates to about 14,400 full resolution pictures.

PACKAGING

There are two primary components to the wireless camera packaging: the RF enclosure and the tiny camera enclosure. The RF enclosure houses the communications board and the batteries. The communications board is a 6 layer printed circuit with components on both sides. The printed circuit includes all circuitry for RF transmit, RF receive, digital transmit, digital receive, power conditioning systems, digital oscillators, and control circuitry.

The tiny camera enclosure houses the optics (f/2 lens, FOV ~23°), the APS die, and the analog power conditioning required for the APS die.

One of the primary goals of the wireless camera project has been to minimize the overall size of the camera package. The RF package dimensions are 2.025" x 0.725" x 2.5" for a total volume of approximately 3.67 in^3. The tiny camera enclosure is 0.6" in diameter by 1.16" long for a volume of 0.329 in^3. Small additional volumes are consumed by a low profile, top mounted, 418 MHz antenna, a small, top mounted, 2.4 GHz antenna, a small side mounted power switch, and a side mounted mini-DB15 connector (for configuration). The overall total volume is approximately 4.2 in^3.

The total weight of the wireless camera is 4.1 oz.

BASE STATION

There were no specified size or power constraints for the base station. Thus, size was not of primary concern. This allowed resources to be concentrated on minimizing the camera module. The base station hardware consists of a 5.25" rack mountable drawer and a portable personal computer with an RS-422 compliant communications board.

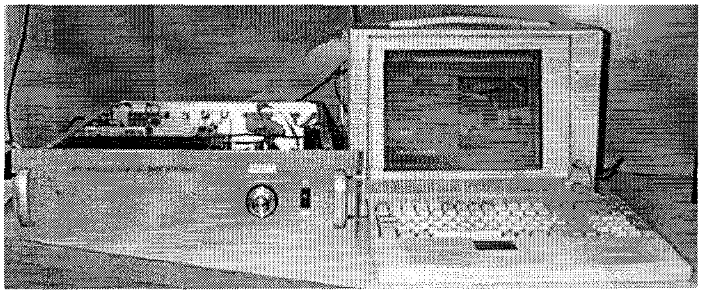

Figure 5 Base Station Without Antennas

The drawer contains an ASK modulator, a 5W power amplifier, up and down conversion circuitry, a spread spectrum demodulator, and required power supplies. Both the 418 MHz and 2.4 GHz base station antennas are Yagi's with gains of 12 dB and 16 dB respectively.

The user interface software on the base station was developed with Lab View. It allows the user to remotely control the operation of the camera. It also allows the user to set operational parameters like exposure time, windowing functions and image subsampling functions.

FIELD TESTING RESULTS

The wireless camera has been laboratory and field tested. The communication links were proven over the required 1 km range for both a "free space" link and a true terrestrial link (i.e., wireless camera placed on the ground and the base station antennas on a tripod placed on the ground). Both free space and terrestrial bit error rate (BER) test curves were generated. Figures 6 and 7 show the BER curves for the command link and data link respectively. These figures were compared to the predicted theoretical performance. Fairly close agreement between theory and experimental measurements was found. Images were transmitted reliably over these links. Additionally, it was found that by decreasing the transmit power to increase the bit error rate to 10^{-4}, images could still be transmitted without noticeable degradation.

The bit error rate curves for Figure 6 were generated by varying the transmit power at the base station and recording the result at the camera which was placed on the ground. For these tests, the camera was oriented such that the gain of the 418 MHz antenna was –5dBi (which is 15 dB above the –20 dBi minimum gain point of the antenna). The results show that with 37 dBm of transmit power, at the minimum gain point of the antenna, there is 25 dB of link margin for the free space link and 4 dB of link margin for the terrestrial link.

Link budget analysis for the geometry of this particular test environment predicted a link margin of 30 dB for the free space link and -5 dB for the terrestrial link. The differences between the measured and theoretical values are reasonable give the fact that our "free space" includes some terrestrial characteristics and thus the channel loss should be greater than true free space. Additionally, the statistical nature of the terrestrial path loss and the potential for signal gain due to ground wave propagation account for the difference between measured and theoretical results.

The BER curves of Figure 7 were generated by inserting an attenuator behind the receive antenna at the base station and varying the receive power. This method was necessary because the small size of the wireless camera makes it impractical to vary the transmit power. Thus, the

Figure 8 curves show the differences in available link margin in the image data link for various placements of the wireless camera. In generating curves 2 through 5, the base station was stationary while the camera was shifted to different positions, both laterally and vertically, at the same site (range = 1km).

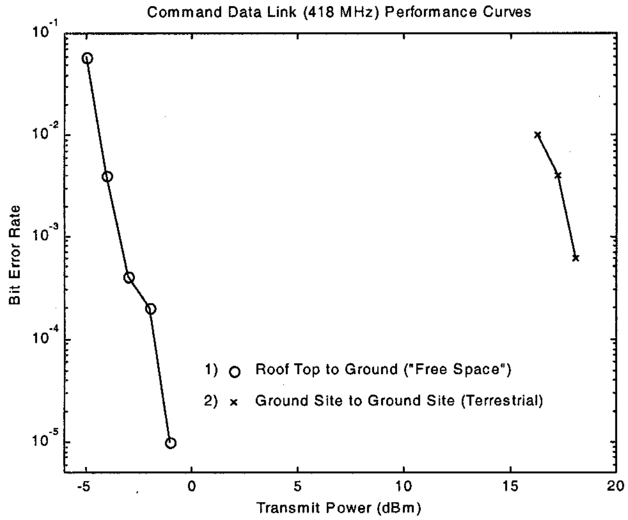

Figure 6 Command Link Performance (Range = 1 km)

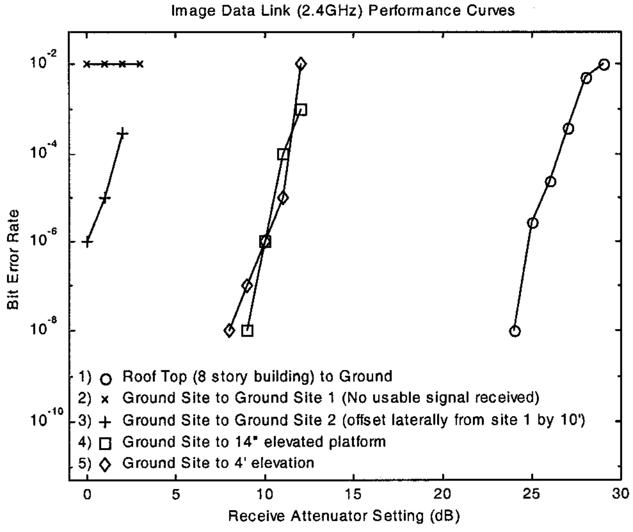

Figure 7 Image Data Link Performance (Range = 1 km)

These results indicate that with 20 dBm of camera transmit power, there is 25 dB of link margin for the free space link and almost no margin for the terrestrial link. The margin for the terrestrial link can be improved by 10 dB by elevating the camera a small distance (~14 inches) above the ground. Note that both the "free space" and the terrestrial links are subject to multipath fading. Curves 2 and 3 show the results of this effect. Curve 2 shows an inoperable link while curve 3, representing a lateral offset from the curve 2 position by approximately 10 feet, shows a link that will operate, but with minimal margin.

Link budget analysis predicted a link margin of 28 dB for the free space link and 8 dB for the terrestrial link. Again, these differences can be attributed to the non-ideal free space channel and the statistical nature of the terrestrial path.

FUTURE DEVELOPMENT

The wireless camera is scheduled to be field tested in July 1998 with the United States Marine Corps. A variety of DoD and other government agencies have expressed interest in the technology for surveillance, monitoring, and tactical applications. Extensions of the technology developed under this effort may include the development of higher resolution day/night imaging sensors, inclusion of on chip image compression, and further miniaturization and power reduction of the communication system, all of which could ultimately lead to a millimeter scale wireless video camera. In addition the miniature communication system could be interfaced to future multi-sensor systems.

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[3] http://www.interlog.com/~microvid

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