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, 2.455 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 would have been 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]

SYSTEM DESIGN

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

- 2.455 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).

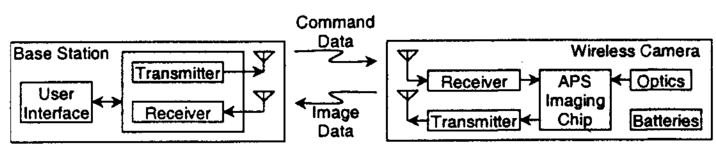

Figure 1. System Block Diagram

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 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.

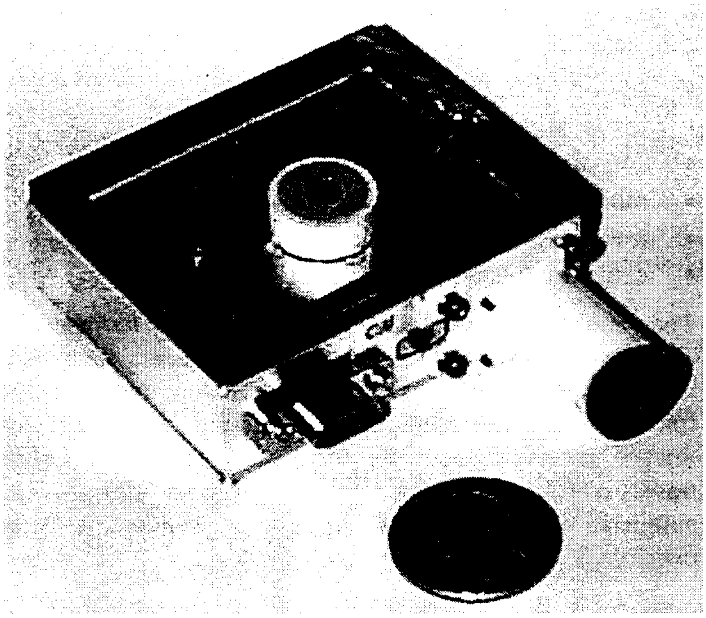

Figure 2 Miniature Wireless Camera

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 receive antenna that has a typical gain of -10dB with a single low gain point of -20dB. The link margin is sufficient to accommodate the low point 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 spectrum 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. The protocol command packet is 64 bits long and allows for the addressing of up to 254 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 application specific integrated circuit (ASIC) to conserve power and size. This chip performs a number of functions. For the command link a MFQ filter, digital phase lock loop for clock recovery, unique word detector, parity check, address decoder, and command word re-formatter were developed. For the image link a differential encoder, convolutional encoder, and 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 chain, the QPSK modulator and the power amplifier. The local oscillator chain 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. A 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 and bandpass filtered by the power amplifier 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 gain of minimum gain of -1.5 dB.

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 more detail in reference [2], utilizes a CMOS Active Pixel Sensor (APS) 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. It 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.

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.

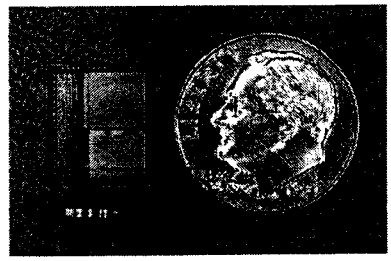

Figure 3 Low power (20 mW) complete digital camera-on-a-chip implemented in HP 1.2μ 5V. process through MOSIS. The 9.3mm x 11.2mm chip contains a 256 x 256 APS array and 256 on-chip analog-to-digital converters.

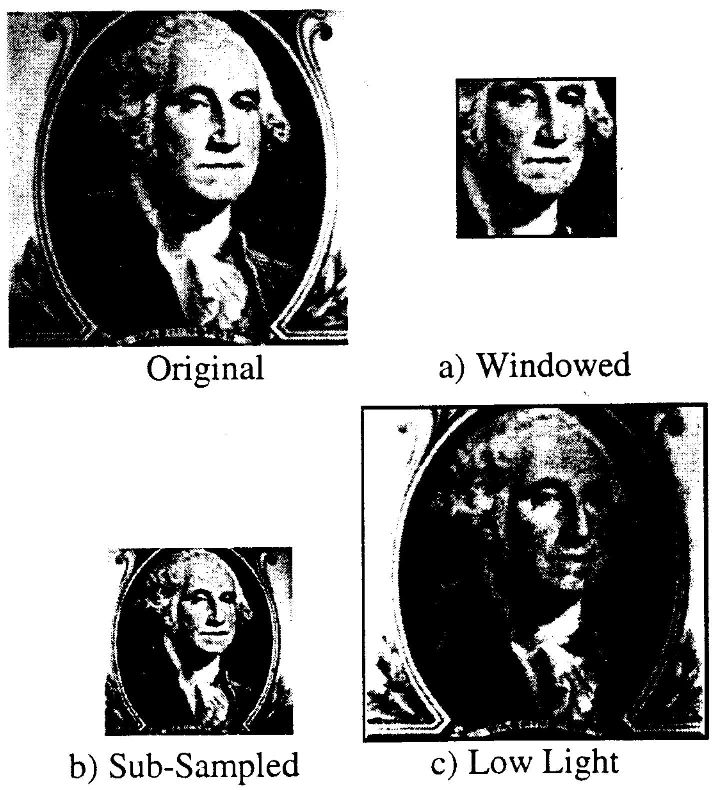

Figure 4 The imager can be programmed to support a variety of imaging operations such as a) windowing and b) subsampling. It also has a fully programmable exposure time as well as good low light operation c) image taken in a dark room with 8 sec exposure

POWER AND BATTERIES

The wireless camera will be powered by two lithium CR-2 camera batteries 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 current measurements in the lab. Table 1 shows the results for several operational scenarios. The transmit frequency is the percentage of awake cycles during which a picture is returned.

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

Table 1: 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 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.

BASESTATION

For the base station, there were no specified size or power constraints. 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 reduced size personal computer with an RS-422 compliant communications board.

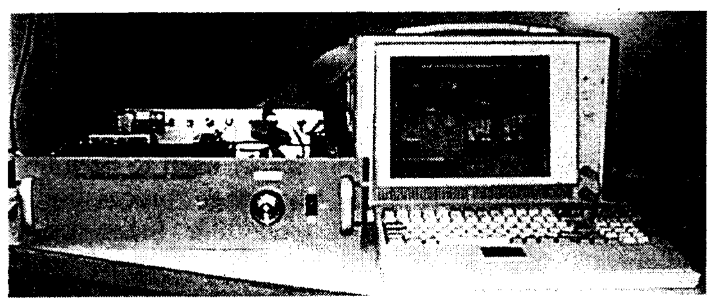

Figure 5 Base Station Without Antennas

The drawer contains an ASK modulator, a spread spectrum demodulator, up and down conversion circuitry, a 5W Power Amplifier 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 software on the base station was developed with Lab View. It allows the user to 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 a) These projections were made from current measurements in the lab. Factors such as increased temperatures or marginal communications environments will affect these lifetime projections.

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

1km range for both an essentially 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 and plotted. Figure 6 and Figure 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. Additionally, images were transmitted reliable over these links, and by decreasing the transmit power to increase the bit error rate to 10^{-4} images were transmitted without noticeable image degradation.

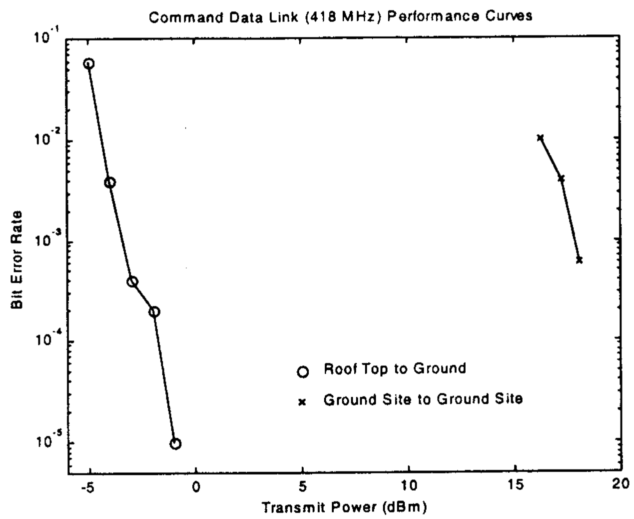

Figure 6 Command Link Performance (Range = 1 km)

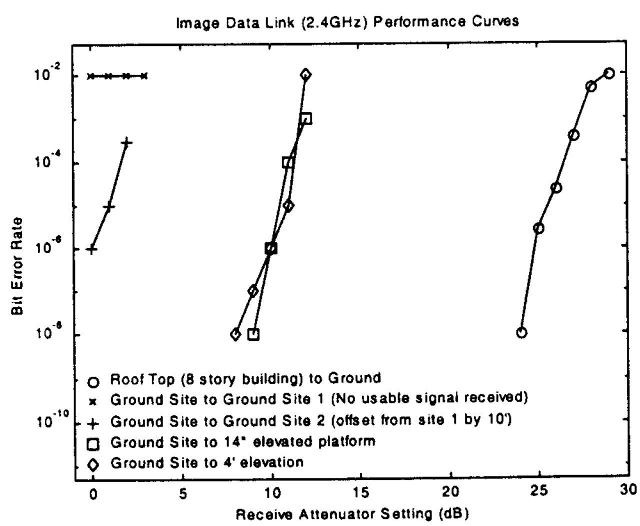

Figure 7 Image Data Link Performance (Range = 1 km)

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. 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. Thus, the Figure 7 curves are actually an indication of the differences in available link margins in the image data link for various placements of the Wireless Camera.

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 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.

REFERENCES

[1] M.J. Agan, E.R. Fossum, R.H. Nixon, B.H. Olson, B. Pain, C.R. Pasqualino, E.H. Satorius, T.J. Shaw, and G.L. Stevens, *Highly Miniaturized, Battery Operated, Digital Wireless Camera Using Programmable Single Chip Active Pixel Sensor (APS) Digital Camera Chip*, Patent Pending, NTR No. NPO-20331, December 9, 1997.

[2] B.H. Olson, T. Shaw, B. Pain, R. Paniccaci, B. Mansoorian, R. Nixon and E.R. Fossum, *A Single Chip CMOS APS Digital Camera*, IEEE CCD Workshop (1997).

Acknowledgments

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