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Final Report for LDRD Project 02-FS-009 Gigapixel Surveillance Camera

R. E. Marrs, C. L. Bennett

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Disclaimer

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Introduction

The threats of terrorism and proliferation of weapons of mass destruction add urgency to the development of new techniques for surveillance and intelligence collection. For example, the United States faces a serious and growing threat from adversaries who locate key facilities underground, hide them within other facilities, or otherwise conceal their location and function. Reconnaissance photographs are one of the most important tools for uncovering the capabilities of adversaries. However, current imaging technology provides only infrequent static images of a large area, or occasional video of a small area. We are attempting to add a new dimension to reconnaissance by introducing a capability for large area video surveillance. This capability would enable tracking of all vehicle movements within a very large area.

The goal of our project is the development of a gigapixel video surveillance camera for high altitude aircraft or balloon platforms. From very high altitude platforms (20 – 40 km altitude) it would be possible to track every moving vehicle within an area of roughly 100 km × 100 km, about the size of the San Francisco Bay region, with a gigapixel camera. Reliable tracking of vehicles requires a ground sampling distance (GSD) of 0.5 to 1 m and a framing rate of approximately two frames per second (fps). For a 100 km × 100 km area the corresponding pixel count is 10 gigapixels for a 1-m GSD and 40 gigapixels for a 0.5-m GSD. This is an order of magnitude beyond the 1 gigapixel camera envisioned in our LDRD proposal. We have determined that an instrument of this capacity is feasible.

Parameters for a multi-gigapixel camera

We adopted a goal of 0.5-m ground resolution and 2 fps for the design of our instrument. From aircraft platforms, unlike satellites, this resolution can be achieved with apertures a few cm in diameter. Our design uses commercial camera lenses with focal lengths between 150 and 1000 mm, depending on the range, and f / numbers corresponding to an aperture size of about 5 cm. Large format CMOS focal plane arrays with fast readout rates are being developed elsewhere for use in digital cinematography and photography. CMOS sensors with up to 16 megapixels are now available. The pixel size for these sensors is in the range of 6 to 8 μm, so the 6-cm focal plane of the medium format series of commercial camera lenses (e.g., Hasselblad) could accommodate a CMOS sensor with 64-megapixels. Although such a large format sensor is not available at present and is unlikely to have a commercial market, it could be fabricated as a custom item. To reach 10 gigapixels would require an array of 156 64-megapixel sensors and lenses.

Multiplexing

We devised a multiplexing technique that allows each sensor to view 16 different fields of view so that the number of sensors and lenses required is reduced by a factor of 16. Multiplexing makes sense because the exposure time for each frame is 5 milliseconds or less, while the time between frames is 500 milliseconds, corresponding to a duty cycle of 1%. Our design uses an array of 16 flat tip-tilt mirrors to multiplex 16 different fields of view into the same sensor. This increases the sensor duty cycle to 16% and the total framing rate to 32 fps.

The development of the multiplexing technique is one of the major technical accomplishments of our project.

After considering several possible arrangements for tip-tilt mirrors, as well as other multiplexing schemes, we selected a constant-speed rotating mirror wheel as the most promising arrangement. In this approach, the 16 tip-tilt mirrors are mounted on the perimeter of a single rotating wheel. They are each tilted out of the plane of the wheel by different angles ranging up to about three degrees. Up to 16 (stationary) lenses and sensors are mounted around the rotating wheel, and each sensor takes an exposure when a tip-tilt mirror passes in front of it.

Even though the tip-tilt mirrors move very little during the brief exposure time, the rotational component of their motion is sufficient to blur the image if they are fixed to the rotating wheel. (Translational motion of flat mirrors makes a negligible contribution to image blurring for distant objects.) Our design avoids image blurring by mounting each of the tip-tilt mirrors on a counter rotating bearing that rotates with the same angular velocity, but in the opposite direction from the main wheel. This removes the rotational component of the mirror motion.

Design details

The gigapixel camera design is flexible so that parameters such as the field of view and GSD can be set for each mission and for the chosen focal plane sensor by adjusting mirror angles and lens focal length. Our feasibility study focused on a specific set of parameters (which we refer to as a "reference design") near the extremes of probable mission requirements. If our design can meet these requirements, then we can be confident that it will accommodate the full range of probable missions. In our reference design the corners of the total field of view are 40° from the axis of the instrument (i.e., 40° from nadir if the instrument is pointed straight down), the lens aperture is 5-cm in diameter, the exposure time is 5 ms, and the wheel rotation rate (i.e., the revisit time for each field of view) is 2 Hz. Estimates of expected signal level indicate that a 5-ms exposure time is more than sufficient for daylight scenes.

With our reference design parameters, each of the 16 sub-fields of view for one sensor subtends an angle of 4.3°. With these parameters, a GSD of 0.5 m occurs at a range of approximately 20 km for an 8-megapixel square format sensor and 50 km for a 64-megapixel square format sensor. If the instrument is mounted on a moving aircraft then it will need to be gimbaled to point at a fixed spot on the ground as the aircraft moves. This will eliminate motion blurring at nadir. However it is not possible to eliminate motion blurring over the entire field of view at the same time. For example, for typical aircraft speeds and altitudes, a camera that tracks a fixed point at nadir will see an apparent ground movement of roughly 50 cm in 5 ms at 30° forward and behind nadir.

We used optical ray tracing to select a mirror size and spatial arrangement for the optical components that would accommodate our reference design parameters (fields of view and aperture size) without vignetting. We chose 4-inch diameter circular tip-tilt mirrors located on a 24-inch diameter circle, along with a 4-inch diameter turning mirror close to each lens. The different pointing directions for the cameras are obtained by varying their position and angle with respect to the tip-tilt mirror wheel.

One of the biggest challenges in the design of the multiplexed gigapixel camera is to make sure that the mirror motion does not degrade camera resolution. If 64-megapixel sensors with a 6 × 6 cm square format are used in our reference design, then the total number of pixels is 16 gigapixels, the field of view for each pixel is 10 μrad, and the angular diameter of the diffraction disk (for the chosen 5-cm aperture) is about 20 μrad. If we limit camera motion to less than 5 μrad during a 5-ms exposure then it will not be a significant contributor to resolution, and we adopt that as our tolerance goal.

A complete analysis of the vibration modes of our instrument is not justified at this point, so we assumed that any movement of the optical components would be a harmonic motion at the 2 Hz rotational frequency of the mirror wheel. To achieve 5-μrad stability during the exposure time, the total magnitude or run out for the movement of the optical component must be less than 40 μrad at 2 Hz. We have identified light-weight commercial air bearings for the mirror wheel and tip-tilt mirror mounts that meet this requirement.

In addition to the vibration tolerances, the counter rotation of the tip-tilt mirror mounts must closely track the rotation of the main mirror wheel. This tolerance is more forgiving because the tip-tilt mirrors are almost in the same plane as the mirror wheel rotation, so the run out of the counter rotation angle can be as large as 0.5 mrad. This tolerance still presents a challenge, and at the end of our feasibility study we were evaluating several possible techniques for driving the counter rotation motion.

Development of motion detection algorithms

The amount of image data obtained by a gigapixel camera is so large that computer processing is required to locate and track moving vehicles. (A one gigapixel image would require approximately 1000 standard computer monitors to display all of the pixels.) We have developed a motion detection algorithm and tested it with available video of a freeway intersection obtained at about the same spatial resolution expected for our gigapixel camera (but covering a much smaller area). The algorithm works by comparing the intensity of each pixel in each frame to the running average of the intensity at the same location in preceding and following frames. Vehicle-sized clusters of pixels that deviate from the average intensity are then flagged as moving objects. This algorithm was able to find all visibly moving vehicles on the freeway interchange and discriminate against artifacts, such as those generated by slowly changing camera angle.

Summary

We have determined that it is feasible to construct a camera having more than 10 gigapixels that is capable of acquiring surveillance and vehicle tracking data for an area of roughly 100 × 100 km from a high altitude platform. We devised a powerful multiplexing technique that increases the effective number of pixels in an individual sensor by a factor of 16. We developed a specific design for 256 multiplexed fields of view, and carried it as far as optical ray tracing and mechanical layout. We also wrote and tested motion detection algorithms that successfully recognized and tracked moving vehicles in a complex scene.