Design Considerations Of CCD Optical Sights For Tracking Long Range Objects In Real Time Suitable To Micro Air Vehicles (MAVs)

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ABSTRACT: A Novel CCD Optical Sight was designed and developed to track movement of objects in real time. The concept of introducing this specific CCD Optical Sight on a weapon simulator has been realized. Rigorous field trials at different ranges have proved the robustness and efficacy of the system. Few numbers of these items were fabricated, integrated into the weapon simulators and delivered to the user. Apart from this specific application, present development enabled to carryout innovative research and development of new devices to capture real time trajectory of a long range weapons (~ 4000 m). The paper accounts the importance of the selective features of Charge Coupled Device (CCD) sensors and its advantages over film-based imaging. The purpose and features of a CCD Optical Sights for Micro Air Vehicles (MAVs) are accounted. Design considerations of well corrected optical systems and types of configurations suitable to such environments are reported. The basic idea is to develop a knowledge based design centre to cater to the design and development requirements of long range object Detection, Recognition and Identification and adaptation of a well-corrected optical system matching the imaging properties of CCD sensors, display devices. These details are explained with illustrations from the work carried out for a specific task. Few details on the Engineering design; development, description and functioning of the systems for military applications are provided. The same philosophy is extended to address the developmental needs of optical systems for Micro Air Vehicles for different applications.

Keywords: Charge Coupled Device (CCD), Optical Sight, Weapon Simulator, Micro Air Vehicles, Visible Sensors, Infra Red Sensors, Infra Red Focal Plane Array, Aberrations and Optical Design Parameters.

I. CHARGE COUPLED DEVICE (CCD) IMAGING

Scientific imaging applications are expanding in to different domains [1]. Image observation through eyepiece based instruments is cumbersome and strenuous. The observation cannot be made for longer periods. Later, the imaging units were clubbed with a film for recording the image. These delivered sharp, clear pictures with plenty of details and good contrast. The hard copy print was a result of the photographic’s efforts. Nevertheless, there were many drawbacks in the use of the film. The wait to see a picture was a lengthy process. It was difficult to get a film image into a computer. Storage of film based pictures consumed a lot of space, the files were difficult and time consuming to retrieve, and they degraded over time. Finally, some of the characteristics of film, such as its dynamic range, linearity at different light levels and consistency left a lot to be improved upon. Solid State Technology helped to overcome the difficulty experienced in using the film based imaging. This technology has given, Charge Coupled Devices (CCDs). These devices have become the image-capturing platform of choice for scientific imaging, because of their ability to image in real time and ensured the accuracy of focus and exposure. This type of imaging is called CCD Imaging. Solid-state technology enabled the image on a screen as soon as it is exposed. This screen is either a Television Monitor or Computer Monitor. Storing images on standard computer media is highly efficient and there is no danger of degradation. There is no chemical processing. Solid-state imaging delivers consistent and repeatable results. Notable improvements in CCD image over a photographic image are: a) Low noise, b) Large dynamic range, c) High resolution and d) Higher quantum efficiency. Taking advantage of the better characteristics of the CCD sensors and contemporary Optical software and hardware tools, a novel CCD Optical Sight was conceived and it was developed to function as real time video capturing unit. Following paragraphs provides the design, development, integration, evaluation and application stages of the equipment.
II DESIRABLE FEATURES OF A LONG RANGE TARGET TRACKING SYSTEM

A Second Generation Anti-Tank Guided Weapon (ATGW) system consists of a Weapon and a Launcher. A pilot is required to swivel the Launcher Optical Device manually for surveillance and aiming purposes. Once a specified target is in the vicinity of attackable range, a pilot is expected to acquire the target, then launch the weapon and continue to track the target until the weapon hits it. This is a complex task for a pilot considering the technology, accuracy, short flight duration of 12 to 13 s for a range of 2000 m, cost of the weapon and expensive drills in outdoor environments. Therefore, a pilot needs training on a Simulator with the following desirable features:

- Actual Launcher or close to it used in battlefield conditions on actual targets in real terrain
- Immersion effect to the pilot in the battlefield environment
- Instant feedback during and after the exercise on aiming, tracking, launching, guiding the weapon, lead, lag, hit and miss information
- Measurement of improvements made from drills and
- Equipment which is easy to install, operate and rugged.

III. DESIGN ASPECTS OF CCD IMAGER

While developing a weapon simulator, necessity arose to capture the target movements in real time to enable the instructor to assess and improve the performance of the pilot. Therefore, a novel CCD Optical Sight was conceived and developed. Design of CCD Optical Sight started with an assessment of: a) Target Acquisition; b) Lens System; c) Image Sensor and d) Display Device parameters. Firstly application constraints, requirements and desired results are discussed. Later, the selection of the lens system, image sensor and display devices are discussed.

IV. TARGET ACQUISITION CONSTRAINTS, REQUIREMENTS AND DESIRED RESULTS

The criteria of target acquisition [2] is dependent on how much field of view supported by the optical sensor, its magnification and its ability to provide data that is meaningful for visual discrimination task. Target acquisition generally deals with Detection, Recognition and Identification of the point of interest. For a weapon simulator application, targets could be military vehicles or soldiers. The human eye has a resolving power of about one-minute of arc, which is equivalent to 291 µrad. Comparing this resolution with the required sensor’s field of view can provide an estimation of the magnification necessary for the required visual task. As per the Johnson’s criterion, there exists a relationship between observer’s ability to resolve bar targets through an imaging device and their ability to Detect, Recognize and Identify military vehicles. It was found that observers could detect a target when presented with “one cycle” of information, which in the case of a bar target is one black and one white bar. Table 1, provides the information about the “number of cycles” that is just resolvable across a target’s critical dimension for various discrimination tasks. Johnson’s criterion thus helped to calculate the sensor resolution necessary for any visual acquisition task at any range. With this criterion and other data shown in Table 2, it was possible to arrive at an appropriate sensor size, its field of view, resolution and other parameters. The design criteria mainly depend on capturing a target of 1.5 m x 1.5 m located at a distance of 1000 m to 1500 m with clarity and its image must display on a computer monitor. The displayed target image size on a computer screen must not be less than 10 x 10 pixels out of 220 x 144 pixels. It is then the dedicated software program can recognize, process the image, analyse and provide useful data.

V. LENS SYSTEM, IMAGE SENSOR AND DISPLAY DEVICES SELECTION

Lens System was the most basic optical component. It collects light from a target and refracts/reflects that light to form a usable image of the target. Basic lens system properties are: Effective Focal Length (EFL), Aperture, Field of View (FOV) and Image Format. Calculation revealed that the required field of view was 1º. Clear Aperture of the Optical System selected was 80 mm, so that this size caters to the light gathering power in the day environment from dawn to dusk. FOV is often determined by the size of a detector.
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Table 1: Target’s critical dimension data for three discrimination tasks

<table>
<thead>
<tr>
<th>Target</th>
<th>Detection (cycles)</th>
<th>Recognition (cycles)</th>
<th>Identification (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck</td>
<td>0.9</td>
<td>4.5</td>
<td>8</td>
</tr>
<tr>
<td>Jeep</td>
<td>1.2</td>
<td>4.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Commando Car</td>
<td>1.2</td>
<td>4.3</td>
<td>5.5</td>
</tr>
<tr>
<td>M-48 Tank</td>
<td>0.7</td>
<td>3.5</td>
<td>7</td>
</tr>
<tr>
<td>Soldier</td>
<td>1.5</td>
<td>3.8</td>
<td>8</td>
</tr>
<tr>
<td>105 Howitzer</td>
<td>1</td>
<td>4.8</td>
<td>6</td>
</tr>
<tr>
<td>Average</td>
<td>1.0</td>
<td>4.0</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>[-0.3 to +0.5]</td>
<td>[-0.5 to +0.8]</td>
<td>[-0.9 to +1.6]</td>
</tr>
</tbody>
</table>

The relation between FOV, image size and EFL is:

\[
\text{FOV} = 2 \tan^{-1} \left( \frac{\text{image height}}{\text{EFL}} \right) \tag{1}
\]

Since FOV value determined was 1°, to suit the picture format on the computer, a CCD sensor of 8.0 mm (diagonal size of ½ inch CCD camera) was selected. Using the Eq. (2), EFL of the optical system was calculated and the value was 458 mm. Lens System speed is a useful indicator of the brightness conditions under which the system functions. Lens system speed (F-No) is related to EFL and Entrance Pupil Diameter with the following relation:

\[
\text{F-No.} = \frac{\text{EFL}}{\text{Entrance Pupil Dia.}} \tag{2}
\]

Practically, Lens System’s F-No varies from F-1, which is very fast, to a slow F-22. Image brightness is inversely proportional to the square of F-No. In the present system, F-No varied from 5.7 to 305. An adjustable iris mechanism was used to work in varied brightness conditions. Lens system collects light from a point on the target and focuses to a corresponding point on the sensor. Ideally, the image of a point source formed by a perfect lens system would be an image of zero diameters. In the real world, even a perfect lens system gets affected from diffraction and the lens
system aperture causes diffraction pattern called the Airy pattern. The central spot in the pattern is called the Airy Disc. The diameter of the Airy Disc is directly proportional to the lens system F-No and the wavelength (\(\lambda\)) of the light. The relation between Airy Disc spot diameter, F-No., and \(\lambda\) is given by the equation:

\[
\text{Spot diameter} = 2.44 \times \lambda \times \text{F-No}
\]  

(3)

Using Eq. (3), value of the spot diameter is calculated and it is 8 \(\mu\)m. It is a known fact that 85% of the incident light power is focused by the lens system in to this spot. This spot size decides the individual pixel size of the sensor, as it is reasonable to match the blur size with pixel size. Therefore, the spot size assessment makes optical design calculations more meaningful. The inability of a lens system to form a perfect image is due to lens aberrations [3]. It is normal practice to choose a lens system with a small blur circle to give the required resolution. While choosing a lens system, the monochromatic aberrations such as - Spherical, Coma, Field curvature, Astigmatism, Distortion & polychromatic aberrations such as - Axial colour, Lateral colour are optimized. To arrive at an optimum lens system, design was carried out from the first order layout and optimized using Computer Aided Optical Design Software. Sensor was selected based on the required image size.

VI. SYSTEM DATA AND FABRICATION

Based on the design principles and governing equations; calculations are carried out to derive the system data (Table 3), based on the conceptual sketch of the imaging system layout given in Fig. 3 - keeping the image quality as prime concern. System data was used in fabricating the CCD Optical Sight (Fig. 1). Computer Aided Design (CAD) techniques are used to model the optical, mechanical, electrical and electronic subsystems. After thorough verification of the CAD modelling, drawings are generated. After finalisation they are released for fabrication of the items. Later the components and subsystems are integrated in the total system. Some of the work sequences are shown in the Fig. 4, Fig. 5, Fig. 6, and Fig. 7. Selection of the Computer System and Auxiliary Display Unit (ADU) plays a crucial role for supporting the total system design concept. ADU supports the display activity for visualizing the image by a batch of trainees, as well as helps the instructor in assessing the pilot’s performance. Care has been taken to have high resolution and image clarity.

Fig.1. Charge Coupled Device (CCD) Optical Sight

Computer System works as a Command & Control Station for the System and analysis tool to the Instructor. ADU functions as demonstrative tool to the co-pilots. CCD Optical Sight tracks a target situated in the range between 25 to 2000 m, in real time; sends analogue video image to Computer and ADU. Once the trigger is pressed, computer starts acquiring target images and continues the process till the end of weapon flight time. The analogue image from the CCD Optical Sight is converted into digital image by a frame grabber resident in the computer. The acquired image is processed and analysed for specific purpose using dedicated motion analysis algorithms using computer hardware. The resulting data, such as aiming, tracking, hit / miss indication and error etc., in graphic and text form, are displayed on the computer monitor. The instructor then provides a feedback to the pilot and reviews the sequence of performance of the pilot. Simultaneously, co-pilots are shown the video display on ADU. Initially few prototypes were fabricated. Rigorous field trials at different locations proved the robustness and efficacy of the system.
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![Diagram of Optical Imaging System Layout](image)

**Fig. 2 Optical imaging system layout**

![Diagram of Train of Optical System Layout](image)

**Fig. 3. Train of Optical System layout to couple Optical System with CCD sensor**

**Table 3: System Data**

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optical System</strong></td>
<td>Effective Focal length: 458 mm; Clear Aperture Diameter: 80 mm; FOV (H x V x D): 0.8° x 0.6° x 1°; Resolution: ~ 0.1 mil; Spot Size: 8 µm; Iris &amp; Focus: Manual Control; Working Range: 25–2000m; Day Time use</td>
</tr>
<tr>
<td><strong>CCD Sensor</strong></td>
<td>CCD format: ½ inch Colour; Area: 6.4 mm x 4.8 mm; Pixels (H x V): 9 µm x 9 µm; Res.:480 TVL; Sensitivity: 1.5 Lux (min.)</td>
</tr>
<tr>
<td><strong>Display Devices</strong></td>
<td>Computer: Display size:14”; Format:320x200 pixels; Power:230 VAC, 50 Hz</td>
</tr>
<tr>
<td></td>
<td>Auxiliary Display Unit (ADU): CRT diagonal size: 14 inch; Resolution:480 TVL(H); Scanning: PAL 625 TVL; Power:230 VAC, 50 Hz</td>
</tr>
</tbody>
</table>

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Fig. 4 CAD models of CCD Optical Sight

Fig. 5 Computer Aided Design (CAD) drawings of Mount for CCD Optical Sight

Fig. 6. Mounting arrangement of CCD Optical Sight on the Optical Device
VII. MICRO AIR VEHICLES

Micro Air Vehicles (MAVs) are a subset of Unmanned Aerial Vehicles (MAVs) characterized by their relatively small size. With wingspans in the fifteen-centimetre range, MAVs have a number of advantages such as the following:

• MAVs may be more amenable to a “faster, better, cheaper” approach to their development, procurement, and fielding
• It should be possible to design MAVs to have a small (even negligible) logistics footprint
• MAVs may afford a “commodity” approach to mission accomplishment either by enabling a variety of payloads to be manufactured for a single airframe or by proving flexible enough to permit payload variation in the field
• MAVs may prove a cost-effective augmentation to existing, low-density, high-demand systems
• MAVs may bring mission capabilities to smaller units that heretofore were not large enough to justify possession and operation of traditional systems providing such capabilities.

One example of the prominent requirement of possible MAVs is shown in Fig. 8.

Fig. 7 Photograph of Outdoor Simulator (ODS)

Fig. 8 Model of Lincoln Laboratory concept of the smallest possible MAV (7.4-cm Wingspan) with a visible imager for reconnaissance missions. The bottom view of the model shows the down looking camera port in the nose.
VIII. UAV CLASSIFICATIONS, CHARACTERISTICS, & EXAMPLES

The evolution of MAVs looks natural from the macro stage to micro stage. All the functional elements are same in aircrafts, UAVs and MAVs (Fig. 9). A Micro Air Vehicle is a system composed of constituent subsystems. It is at this subsystem level that many of the technology challenges present themselves. That said, it is very important to realize that unlike many other, larger systems, MAVs present a rather difficult systems engineering challenge. This is because for MAVs to be successful, they will require high degrees of system integration with unprecedented levels of multifunctionality, component integration, payload integration, and minimization of interfaces among functional elements. Additionally, extremely constrained weight and volume limits and high surface-to-volume ratios mean the traditional practice of “stuffing more” into the airframe shell will probably not suffice. Instead, each of the MAV’s components must perform as many functions as possible. An example of this could be antennas embedded in the surface skin of the MAV providing signal reception as well as bearing structural loads. Beyond the surface, weight, and volumetric concerns; close coupled, dynamic electromagnetic and thermal interactions will be even greater issues than they are for larger systems. Typical MAV performance goals of one particular user and its configuration are provided in table 4 and table 5 [7-8]. These parameters explain the technology status possible in these days.

Table 4. Typical baseline MAV Performance goals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airspeed</td>
<td>10 to 15 m/sec</td>
</tr>
<tr>
<td>Endurance</td>
<td>20 to 60 min</td>
</tr>
<tr>
<td>Downlink rate</td>
<td>2 Mb/sec</td>
</tr>
<tr>
<td>Communications</td>
<td>5 km range</td>
</tr>
<tr>
<td>Navigation method</td>
<td>Ground-station tracking (line of sight)</td>
</tr>
<tr>
<td>Visible sensor</td>
<td>1000 x 1000-pixel CCD; 40° x 40° FOV</td>
</tr>
</tbody>
</table>

Table 5. Typical baseline MAV Weight Distribution [7]

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight in grams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airframe</td>
<td>6</td>
</tr>
<tr>
<td>Propulsion</td>
<td>36</td>
</tr>
<tr>
<td>Flight Control</td>
<td>2</td>
</tr>
<tr>
<td>Communications</td>
<td>3</td>
</tr>
<tr>
<td>Visible Sensor</td>
<td>2</td>
</tr>
<tr>
<td>Total Weight</td>
<td>49</td>
</tr>
</tbody>
</table>
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IX. EVOLUTION OF IMAGING SENSORS

Even though a MAV is only a vehicle, it does not do many functions without the Visual Sensors or Cameras are attached to it. The camera systems shall have to carry out the basic functions such as Detection, Recognition and Identification of the objects of interest depending on the requirement. However, it does matter whether the targets in line of sight or off the line of sight. System configurations shall differ for different configurations. The intelligence, surveillance, and reconnaissance function is the leading driver going for the MAVs because of its strategic utility and the maturity of the supporting technologies. “Chip-on-Flex” technology is being employed to miniaturize payload electronics packaging significantly. Both tiny CCD array cameras and infrared sensors are supporting the applications for day/night imaging to sufficient quality to meet mission needs today. Miniaturization has advanced to the point that researchers at Oak Ridge National Laboratory have created a Camera Lens smaller than a Coat button. An off-the-shelf, one-inch long 300 x 240 pixel, black and white Video Camera weighing 2.2 grams and including a converter for standard National Television Systems Committee (NTSC) output, was flown. Literature survey indicates that a fifteen-gram colour camera with a 2.4 gigahertz downlink transmitter was also been demonstrated. In another program, a 512 x 512-pixel day/night camera was planned to take pictures at thirty frames per second or freeze frames once per second. This capability should prove particularly useful considering military experiences in handling the UAV operations. When a Predator UAV imaging was first made available, fighter aircrew were provided full-motion video in which the total delay between the real-time event and image presentation was only 1.5 seconds. However, after working with this capability, aircrew showed a preference for freeze-frame images updated every few seconds. This allowed them to better orient themselves on the target as they began their attacks and to obtain battle damage assessments within a few seconds of their weapons impact on or near the targets. This human factors consideration should allow “engineering and operational cleverness” to create significant reductions in imager power requirements through adjustment of video frame rates. Another example is the “Black Widow” MAV that is reported to have carried “the smallest video camera ever flown on a remotely piloted aircraft.” The Black Widow was equipped with a commercial low-resolution, “sugar-cube-sized” video camera that weighed two grams. The MAV’s builders were able to greatly reduce the camera’s size and weight by integrating the support logic with the camera’s lenses in contrast with traditional digital systems that consist of a CCD imager wired to four or five support chips. The near future could see a visible-light camera, occupying a volume of one cubic centimetre and weighing less than one gram. Such a camera has been designed by Lincoln Laboratory and would be based on a silicon CCD. It would have an aperture of approximately one-tenth of an inch across, contain 1,000 x 1,000 pixels, and produce an image every two seconds using as little as twenty-five milli watts power. By providing an angular resolution of 0.7 milliradian with a million pixels, this camera could produce high-definition television quality images that would enable viewers to tell the difference between a tank and a truck. The Jet Propulsion Laboratory (JPL) at the California Institute of Technology is also pushing the state of the art in miniature solid-state imaging sensors. JPL has developed ultra-low-power active pixel sensor technology that rests on the commercially available Complementary Metal-Oxide-Semiconductor (CMOS) device fabrication process. This process allows many components performing different functions to be integrated on a single chip thus producing cost savings and making possible reductions in system power consumption by a factor of anywhere from 100 to 1,000.

X. OPTICAL SENSORS

Without optical sensors, an MAV would be just a pocket-sized, high-tech model airplane, unsuitable for its intended operations. Like all MAV components, these sensors must meet small mass and power requirements: sensor mass must be under 2 g and power consumption under 100 mW. These parameters are one to several orders of magnitude smaller than for any commercial cameras available today. In addition, surveillance or reconnaissance missions require high-resolution sensors with the ability to see in the complete range of outdoor light levels, from noonday sunlight to overcast starlight. These optical sensors must have high resolution (approximately 1000 x 1000 pixels) for recognition of human figures at the mission altitude of 100 m. Other operational requirements are driven by two important environmental factors: movement of the aircraft, which could cause image blur, and relatively high operating temperature. To meet these requirements, Lincoln Laboratory has considered visible and infrared sensors. Visible sensors use an object’s reflected radiation to produce an image. The visible imager is sensitive to the visible spectrum (400 nm to 700 nm) and the near-infrared spectrum (700 nm to 1000 nm). The latter range is typically utilized in night-vision goggles. Although imaging capability at night is desirable for the MAV, current night-vision technology that uses high-voltage image intensifiers is too heavy to implement, has a limited dynamic range, and does not work well in daylight conditions. Current research efforts at Lincoln Laboratory focus on a supersensitive...
silicon imager that will be capable of responding to the full range of desired light levels. Infrared sensors use an object’s emitted radiation and, to a lesser degree, its reflected light to produce an image. Because the emitted radiation depends on an object’s temperature and emissivity, and not solar illumination, infrared sensors are sensitive during night conditions. One disadvantage to this technology is that sensitive infrared imagers operate at cryogenic temperatures and require a cooling unit that increases the MAV size and mass. Another disadvantage is that an infrared image requires more interpretation than a visible-band image. Warmer objects are prominent, but some terrains have low temperature contrast, which makes placing an object into context with its surroundings difficult. Researchers are addressing this problem by combining infrared and visible information to produce more easily interpreted images.

XI. VISIBLE SENSOR

A visible silicon imager should address noonday sunlight to partial moon illumination, which is most of the desired light-level range. Operation of the camera down to overcast-starlight night conditions is required for the MAV. Consequently, infrared imaging or a visible imager with larger optics would have to be used for these extremely low light-level conditions. Several important environmental factors influence the design of the optical sensor. The first of these is aircraft movement, which has two components: forward movement of approximately 15 m/sec and movement caused by turbulence. The degree of movement determines the maximum exposure time before image resolution is degraded. The high operational temperature of the device (ambient air temperature reaches up to 115 deg F) contributes to the generation of dark current in the visible imager. Dark current can increase noise in the image in addition to the read noise. Although cooling the visible sensor would enhance performance, the cooling unit would also exceed the MAV mass and power requirements.

For a given temperature, there is a trade-off between limiting the time to read out the device, therefore limiting the dark current, and conversely maximizing the time to read the device, and therefore limiting the bandwidth necessary for the output amplifier, thus also limiting the thermal read noise. The impact of temperature on the imaging device also affects the attempt to integrate all control and readout electronics on one imaging chip. Candidates for the visible imager have to be optimized. The CMOS imager does have the advantages of standard integrated-circuit fabrication techniques and low operating power requirements. The two back-illuminated CCD candidates have the best quantum efficiency, share the lowest read noise, and therefore are the most sensitive detectors for night application. Possible CCD sensor combinations are presented in Table 6.

Table 6: possible CCD sensor combinations:

<table>
<thead>
<tr>
<th>Types / Properties</th>
<th>CCD-1:Full frame No shutter</th>
<th>CCD-2:Full frame with shutter</th>
<th>CCD-3:interline transfer with frame store</th>
<th>CMOS with active pixel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution (pixels)</td>
<td>1000 x 1000</td>
<td>1000 x 1000</td>
<td>1000 x 1000</td>
<td>1000 x 1000</td>
</tr>
<tr>
<td>Pixel size (µm x µm)</td>
<td>5 x 5</td>
<td>5 x 5</td>
<td>5 x 5</td>
<td>&lt; 20 x &lt; 20</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>&gt; 85%</td>
<td>&gt; 85%</td>
<td>20% + lens let array</td>
<td>20 to 25 %</td>
</tr>
<tr>
<td>Read noise</td>
<td>&lt; 10 e⁻ at 1 MHz</td>
<td>&lt; 10 e⁻ at 1 MHz</td>
<td>&lt; 10 e⁻ at 1 MHz</td>
<td>&lt; 14 e⁻ at 1 MHz</td>
</tr>
<tr>
<td>Packet size</td>
<td>40,000 e⁻</td>
<td>30,000 e⁻</td>
<td>15,000 e⁻</td>
<td>64,000 e⁻</td>
</tr>
<tr>
<td>Dark current (pA/Cm²)</td>
<td>100</td>
<td>300</td>
<td>50</td>
<td>500</td>
</tr>
<tr>
<td>Shutter</td>
<td>Move to frame store</td>
<td>electronic</td>
<td>electronic</td>
<td>electronic</td>
</tr>
<tr>
<td>Frame store</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Noiseless binning</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Voltage levels (V)</td>
<td>11</td>
<td>21</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
Keeping the design considerations of detection, recognition and identification of military targets in mind, in order to have identifiable characteristic for the camera at longer ranges of 2 to 5 km, the FOV has to be of the order of 1°. Possible CCD visible camera system configurations for long range reconnaissance are provided in Fig. 10. The camera with a FOV of 1.2° is closely suitable to the task but the weight is 23 g and this factor has to be reduced considerably. However, the work projected by the Lincoln Laboratory, USA provides lot of insights in to weight reduction and simultaneously keeping the image clarity and resolution in good definition, which is accounted in this study.

A simulation study was carried out by Lincoln Laboratory, USA to assess whether the frame-shift shutter method caused unacceptable image degradation. The conclusion is that this method caused only minor degradation to an average aerial image, and therefore is not an important limitation. For the MAV, a remote frame store is needed to compensate for the light leakage associated with electronic shutters. In normal applications the exposure time is comparable to the time needed to read out the image. For the MAV imager, however, the readout time is approximately 1 sec, a factor of about 1000 larger than the exposure time. This longer readout time puts severe requirements on the shutter leakage and is the reason that all three CCD candidates are equipped with a frame-store region that is remote from the imaging region. However, the CMOS device is not readily able to be equipped with a remote frame-store region, and therefore image corruption by shutter leakage is a risk in this device. The pixel-readout binning function is planned for use in low-light-level conditions, to improve the signal-to-noise ratio and therefore the resolution at low light levels. The CMOS device is not equipped to bin photo charge in a noiseless way, because charge is converted to voltage (and therefore read noise is added) at every pixel site. Normal strategy for designing MAV imaging sensors is to reduce the pixel size of the focal-plane array, thus minimizing the size of the optics, and to incorporate additional functions, such as charge-to-digital conversion and clocking, on the same chip as the focal-plane array.

Figure 11 shows a concept that incorporated this approach by the Lincoln Laboratory. The visible sensor is based on a silicon CCD focal plane with a 1000 x 1000 array of 5-micron pixels. The optics has to be built to suit the requirements. The optics need to be built with micro fabrication techniques, resulting in overall camera dimensions of about one cubic centimetre, or the size of a dime. The mass of the complete camera has to be less than 1 g, and power requirements are under 25 mW. The 1000 x 1000 pixel array provides image resolutions equivalent to high-definition television. The simulated sample image shown in the fig. 11 (b) is derived from a photograph taken at an altitude, aspect angle, and width of field of view representative of conditions seen by an MAV CCD sensor. It was digitized to form an image representative of the number of pixels (in the horizontal dimension) and 4-bit gray scale envisioned for the CCD sensor. The resulting image provides sufficient detail to recognize the presence of vehicles and personnel on the ground. The image contains 4 Mb of data that must be stored or transmitted to the MAV operator. An update rate of 0.5 frame/sec should be adequate for flight speeds of 10 to 15 m/sec, which would require a communications link capability of 2 Mb/sec (assuming no image compression). Frame rates could be increased with a more capable communications system.
Camera parameters:

- Aperture: 0.26 cm
- Angular resolution: 0.7 mrad (7 cm at 100 m range)
- Pixel count: 1000 x 1000
- Frame rate: 0.5 frames/sec
- Mass: < 1 g
- Power: < 25 mW

Fig. 11 (a) Visible sensor for MAV. Advanced silicon CCD technology permits the packaging of 1000 x 1000 pixel imager and associated output electronics in a single chip resulting in the size of a cubic cm and weighing less than 1 g.

Fig. 11 (b) With the resolution comparable to that of high definition TV, the simulated image shows an example of the detail that could be obtained by mounting the visible-light camera on a MAV.
Design Considerations Of CCD Optical Sights For Tracking Long Range Objects In Real Time Suitable To Micro Air Vehicles (MAVs)

XII. INFRARED SENSOR

A candidate infrared-camera design was conceived with off-the-shelf technologies. Figure 12 shows a 3 to 5 micron band infrared camera based on a Platinum Silicide (PtSi) CCD focal-plane array with 512 x 485 pixels. Other infrared imager technologies with higher quantum efficiencies such as Indium Antimonide (InSb) and Mercury Cadmium Telluride (HgCdTe) could be considered, but the PtSi arrays have the smallest possible pixel sizes and lowest noise. The longer wavelength range necessitates larger and more complex optics than the visible camera, and 3 g of liquid nitrogen is required to cool the CCD for about one hour. (Liquid nitrogen could be generated in the field with a portable mechanical refrigerator.) The complete camera mass could be under 16 g with power under 150 mW from using small pixels and combining functions on the CCD chip. While this camera mass greatly exceeds the payload mass limit, second-generation MAVs with advanced propulsion systems could be capable of carrying such a sensor for extremely dark night-vision missions. The infrared image in Figure 12, while only 236 pixels wide, indicates the image quality from this infrared sensor. The view spans a parking lot and roads; automobiles and a pedestrian can be easily identified. A 2-Mb/sec communications link accommodates a rate of 2 frames/sec for the full 512 x 485-pixel array. The two cameras described here could be a possibility given the technology advancements paving way for the miniaturisation of UAVs leading to MAVs.

XIII. CONCLUSION

In order to acquire the design knowledge in the optical sensors as payloads in this new area of MAVs, effort has been made to study the operational requirements of the visible and infrared sensor cameras required for optical reconnaissance in the line of sight condition in the different terrains. This study is limited to sensors only and acquisition of additional knowledge on other design aspects of MAVs is required.

Camera parameters:
- Aperture: 0.77 cm
- Angular resolution: 1.3 mrad (13 cm at 100 m range)
- Pixel count: 512 x 485
- Frame rate: 2 frames / sec
- Mass: < 15.5 g
- Power: < 150 mW

Fig. 12 (a) Mid Wave Infra Red (3 to 5 µm) for day and night conditions. The camera based on PtSi CCD technology is larger than visible camera of Fig. 11 (a) because of larger optics and liquid nitrogen cooling of the focal plane.
Fig. 12 (b) A sample image from a day/night camera of a parking lot taken at a range of 200 m shows a pedestrian and automobiles.

References