Camera Body Incorporating a Movable Focal Plane Array

Preliminary Design

1. Requirements

The goal of this project is to design a camera body incorporating a movable focal plane array (FPA). The following requirements must be met.

- The body must include a mounting feature that is compatible with commercial, off-the-shelf (COTS) lenses. The class of lenses chosen (e.g. C-mount, F-mount, four-thirds) must include a focal length of at least 400 mm, with a speed of f/5.6 or faster.
- The sensor platform must be large enough to mount so-called full frame (35 mm) format FPA's.
- A specific FPA must be chosen as an example. This FPA need not be a full frame FPA.
- The FPA chosen must be part of a system that can be interfaced to a computer without a lot of electrical system design. For example, it could be part of a system with an IEEE-1394 (Firewire) interface. It could be part of a system that interfaced with a commercial frame grabber.
- The specific FPA and associated lenses should operate in the visible spectrum. This will keep development and test costs low. The design should not preclude other spectra, particularly in the infrared.
- The FPA should have a minimum frame rate of 15 frames per second.
- The FPA should have at least VGA resolution. There is no pixel pitch requirement per se, but smaller pitches are preferred for evaluation purposes.
- The sensor platform mechanism must allow for two translational degrees-of-freedom (DOF). No rotational DOF is required.
- The range of motion of the platform mechanism should correspond to a 1 mrad change of line-of-sight (LOS) at a focal length of 400 mm.
- The operational temperature range is 0—40 C.
- The focus and tilt of the focal plane need to be controlled and/or adjustable.
- The system needs to survive a 20 G shock

Additionally, the following analysis is required:

- Must come up with an actuator force requirement to accelerate the platform at 10 G.

2. Overview of design

Assembly drawings illustrating the complete system are shown in Figure 1, Figure 2, and Figure 3. The components of the system are

1. F-mount subassembly, consisting of a COTS, Thorlabs F-mount adapter and two simple custom parts
2. Three shim washers made of TBD stainless steel, which are for focus and tilt adjustment

3. FPA mechanism subassembly, which includes a camera headboard and a two degree-of-freedom (DOF) flexural mechanism
4. Three 1/4-20 $\times$ 0.75” socket-head cap screws, which attach the FPA mechanism to the F-mount subassembly and are part of the focus and tilt adjustment scheme

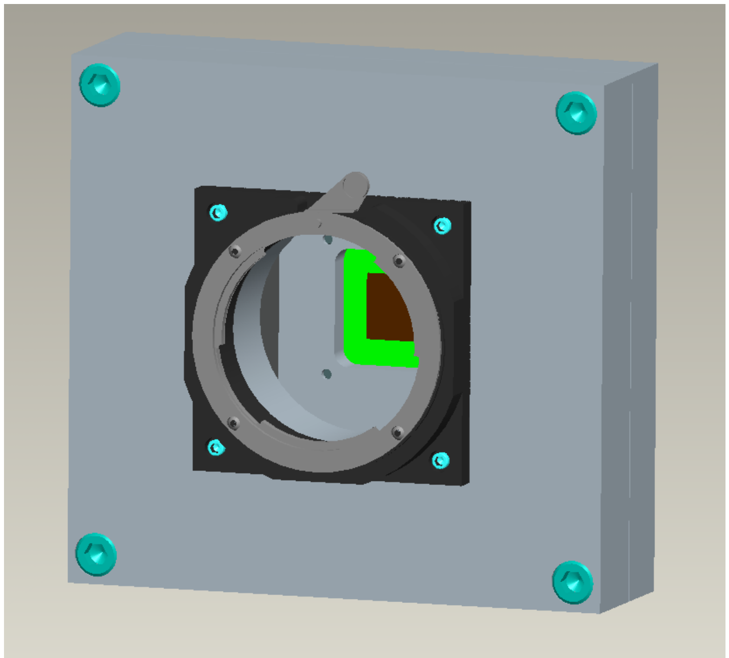

Figure 1: Assembly drawing of camera body (front)

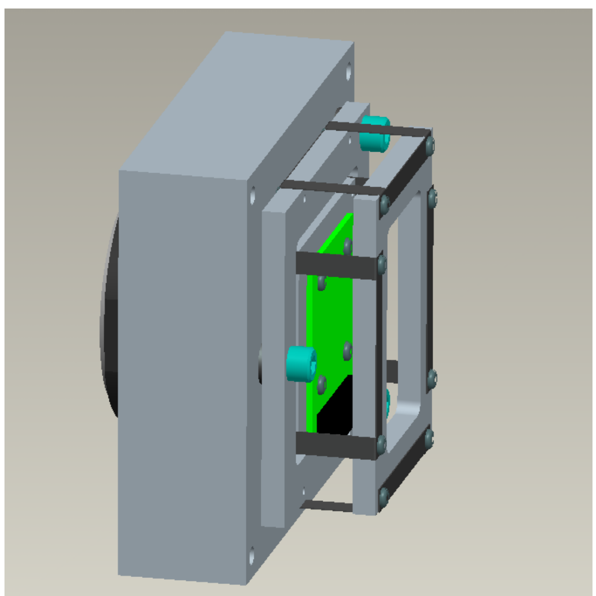

Figure 2: Assembly drawing of camera body (back)

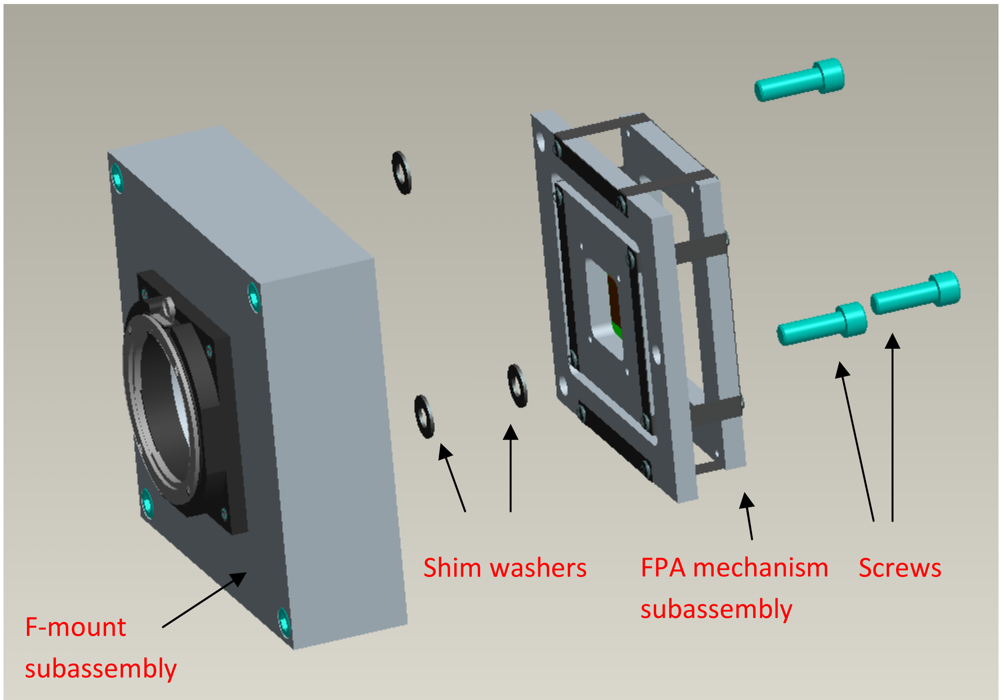

Figure 3: Assembly drawing of camera body (exploded)

Details of the F-mount subassembly are shown in Figure 4. The components of the subassembly are

1. Thorlabs model NFM1LC1 F-mount adapter
2. Mounting plate made of 6061-T6 aluminum
3. Mounting spacer made of 6061-T6 aluminum, which together with the nominal shim washers determines the nominal distance from the F-mount flange to the back of the focal plane array device
4. Screws
    a. Four 2-56 $\times$ 0.5 socket-head cap screws, which attach the F-mount adapter to the mounting plate
    b. Four 1/4-20 $\times$ 0.75 socket-head cap screws, which attach the mounting plate to the mounting spacer

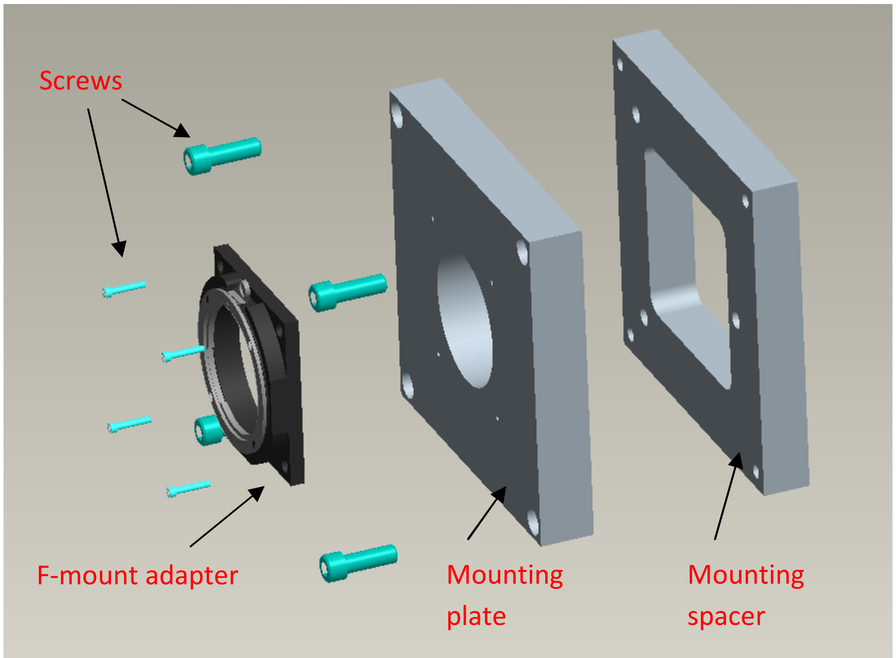

Figure 4: Exploded view of F-mount subassembly

The FPA mechanism is based on the design of a Ricoh patent application (Kitazawa, et al., 2002)[1]. Details of the FPA mechanism subassembly are shown in Figure 5, Figure 6, and Figure 7. The components of the subassembly are

1. Base platform made of 6061-T6 aluminum, which is attached rigidly to the F-mount subassembly
2. Kodak model KAC-9618 camera headboard, which is a subassembly including
    a. KAC-9618 CCD array sensor
    b. Printed circuit board
    c. Electronic components
    d. Electronic connector
3. FPA platform made of 6061-T6 aluminum, which is the mechanism link attached to the camera headboard
4. Intermediate platform made of 6061-T6 aluminum, which is the link between the base and FPA platform links
5. Four sheet metal flexures made of TBD stainless steel
6. Twenty 4-40 $\times$ 0.25 button-head cap screws

[1] The author is primarily interested in the academic study of this device and has no intention of building one. As such, we don't have to worry about intellectual property issues.

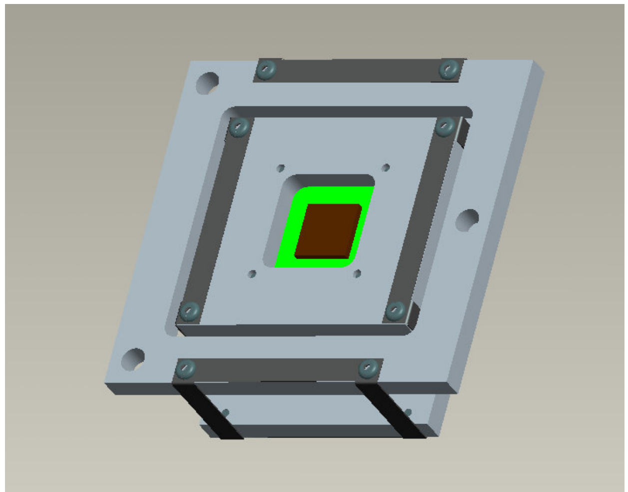

Figure 5: Assembly view of FPA mechanism (front)

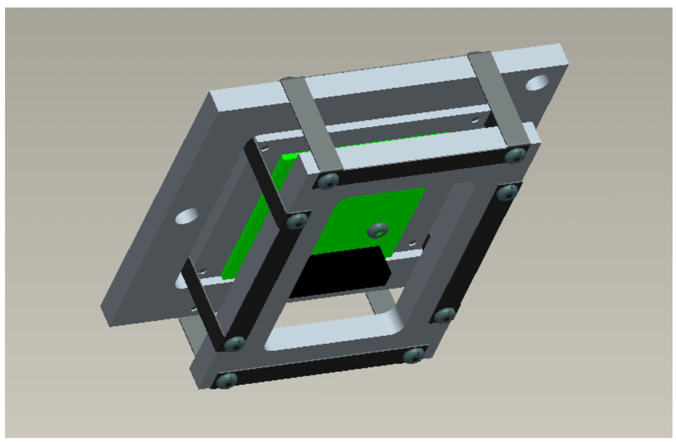

Figure 6: Assembly view of FPA mechanism (back)

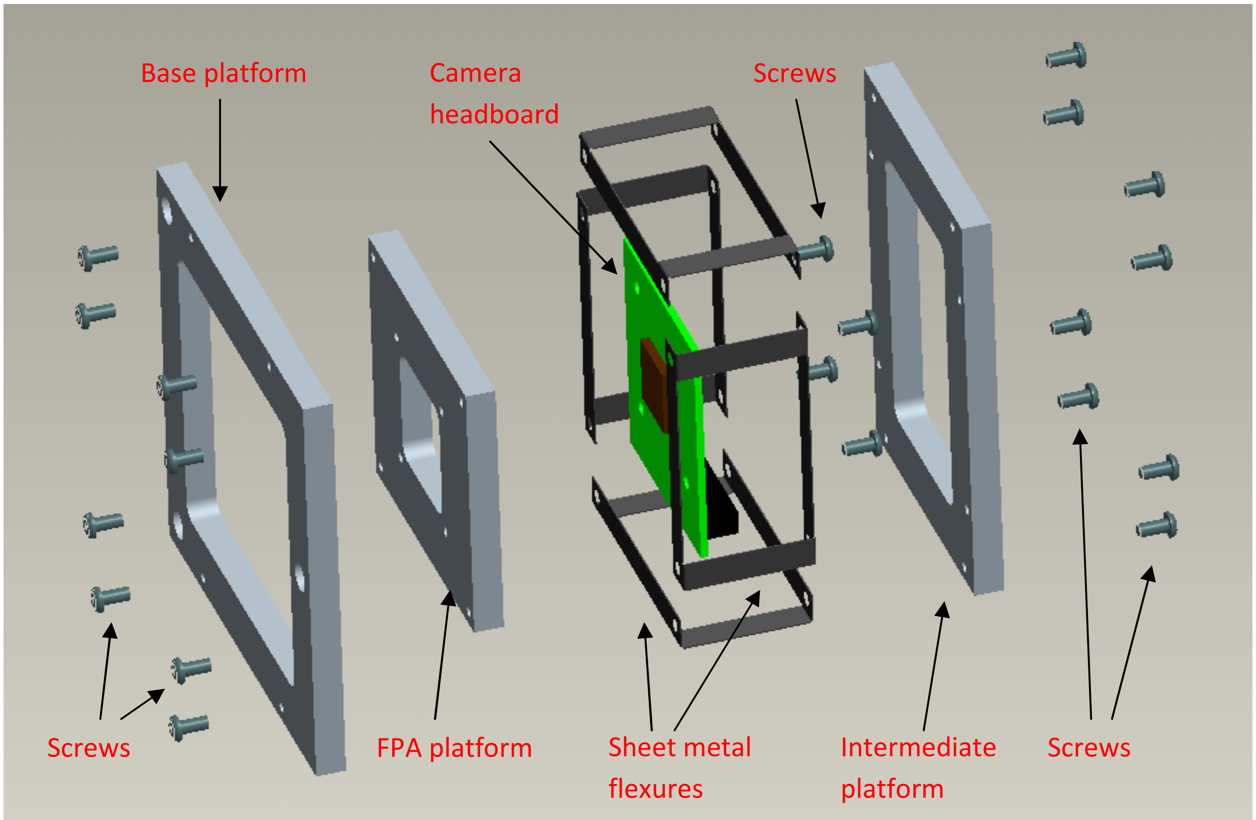

Figure 7: Assembly view of FPA mechanism (exploded)

3. Preliminary assembly plan

Make sure that all machining and bonding operations are performed at 20 ±1 C.

1) Assemble the FPA mechanism.
   a) Attach the camera headboard to the FPA platform using four 4-40 x 0.25 button-head cap screws.
   b) Attach the four sheet metal flexures to the intermediate platform using eight 4-40 x 0.25 button-head cap screws.
   c) Attach the FPA platform subassembly to the two corresponding sheet metal flexures using four 4-40 x 0.25 button-head cap screws.
   d) Attach the base platform subassembly to the two corresponding sheet metal flexures using four 4-40 x 0.25 button-head cap screws.
2) Assemble the F-mount subassembly.
   a) Attach the F-mount adapter to the mounting plate using four 2-56 $\times$ 0.5 socket-head cap screws.
   b) Attach the mounting plate to the mounting spacer using four 1/4-20 $\times$ 0.75 socket-head cap screws.
3) Determine the configuration of best focus and tilt.

a) Temporarily mount the F-mount and FPA mechanism subassemblies to the focusing and tilt test equipment[2].
b) Using an iterative procedure, determine the configuration of best focus and tilt[3].
c) Measure the gaps at the three shim washer locations using feeler gauges.
d) Select combinations (stacks) of shim washers and lap as necessary to get the required thicknesses.
e) Attach FPA mechanism to the F-mount subassembly using the shim washer stacks and three 1/4-20 $\times$ 0.75” socket-head cap screws.
f) Verify that the optical performance is as expected.

4. Requirements verification

4.1. COTS lens mount compatibility

The body must include a mounting feature that is compatible with COTS lenses. Quite a lot of effort was spent researching this particular requirement. For a long list of COTS lens mount types, see (Wikipedia, 2009).

Lens mounts that were given particular intention include

- C-mount
- Nikon F-mount
- M42
- T-mount
- Four-thirds

The four-thirds mount was eliminated because although it is purportedly an open standard, in fact it is not. According to the Four Thirds organization:

> *Details of the Four Thirds System standard are available to camera equipment manufacturers and industry organizations on an NDA basis. Full specifications cannot be provided to individuals or other educational/research entities.* (Four Thirds, 2009)

M42 and T-mount were eliminated because there are relatively few lenses available for these mounts.

This leaves C-mount and F-mount. C-mount would be preferred because it is so simple. However, there are not many C-mount lenses in the 400 mm and longer focal length range. There are C-mount adapters for such lenses.

---

[2] Custom focusing test equipments needs to be designed for this subsystem. Design of that test equipment is important but outside the scope of this project.

[3] What I envision is first optimizing on-axis focus by translating the FPA with respect to the lens mount while measuring the modulation transfer function (MTF) or some other performance measure. Keeping the on-axis distance fixed, MTF at off-axis fields would be measured. Tilt would be chosen so that the MTF was radially symmetric.

F-mount was ultimately chosen for three reasons

- Good availability of adapters
- Large number of lenses available in the 100 to 400 mm and longer focal length range.
- Flange-to-focal-plane distance of 46.5 mm gives plenty of design room.

Regarding the flange-to-focal-plane distance, the C-mount specifies only 17.5 mm, which creates packaging problems for this particular project.

Figure 8 shows a zoom lens made by Sigma that could be used for testing the camera body. The particular lens shown has a focal length range that varies from 80 to 400 mm, with corresponding speeds of f/4.5 to f/5.6. This lens costs less than $1500. Lenses with much longer focal lengths are available, at greater cost. Faster lenses in this focal length range are available as well, again at greater cost.

Figure 8: Example lens that could be used (Sigma 80—400 mm, f/4.5—5.6 zoom)

4.2. Sensor platform size

The sensor platform must be large enough to mount so-called full frame (35 mm) format FPA's.

Two examples of full-frame FPA's are shown in Figure 9. At left is a Fairchild CCD 3041 2k $\times$ 2k multiport scientific CCD, which has 15 µm pixels and a 37 $\times$ 46 mm package. At right is a Kodak KAF 4320 2084 $\times$ 2085 full frame image sensor, which has 24 µm pixels and a 50 $\times$ 50 mm package. So the sensor platform needs to have at least a 2 $\times$ 2" area free for the sensor.

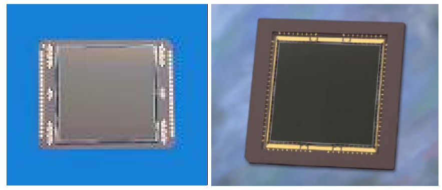

Figure 9: Two full-frame, visible arrays

Dimensions of the sensor platform for the preliminary design are shown in Figure 10. The platform size is 2.25×2.5". The area that would be available for the sensor is at most 1.75×2". This is a little too small, so I'll probably increase the dimensions of the platform to be 3×3" in a second iteration.

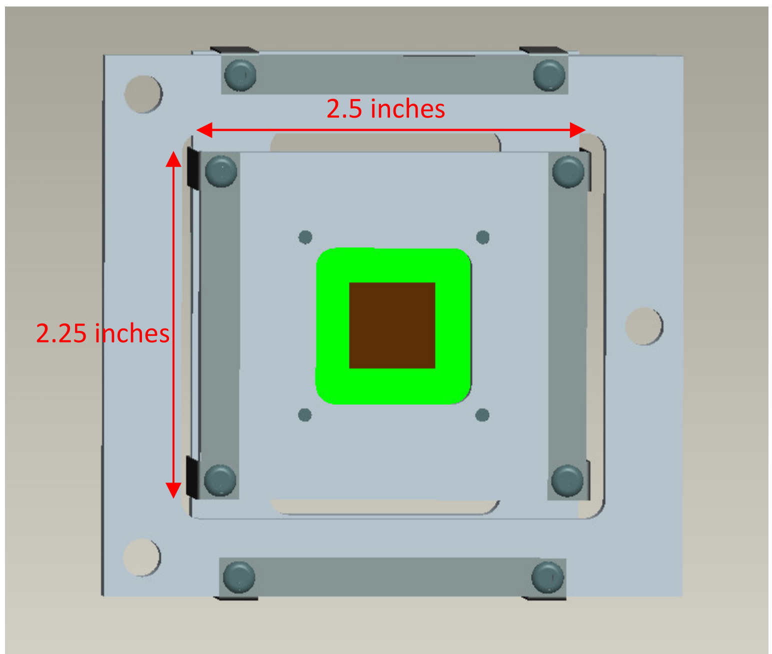

Figure 10: Dimensions of sensor platform

4.3. Specific FPA choice

For test purposes, a specific FPA must be chosen as an example. This FPA need not be a full frame FPA. Indeed, for test purposes it is more desirable to have a smaller FPA that is part of an electronics system with a suitable interface. The specific sensor that was chosen is the Kodak KAC-9618 sensor, which is a VGA resolution (648×488) CMOS sensor with 7.5 µm pixels[4]. A drawing of the sensor package is shown in Figure 11. This sensor was chosen primarily for system reasons, as elaborated in the next section.

[4] As of very recently, this product is being discontinued.

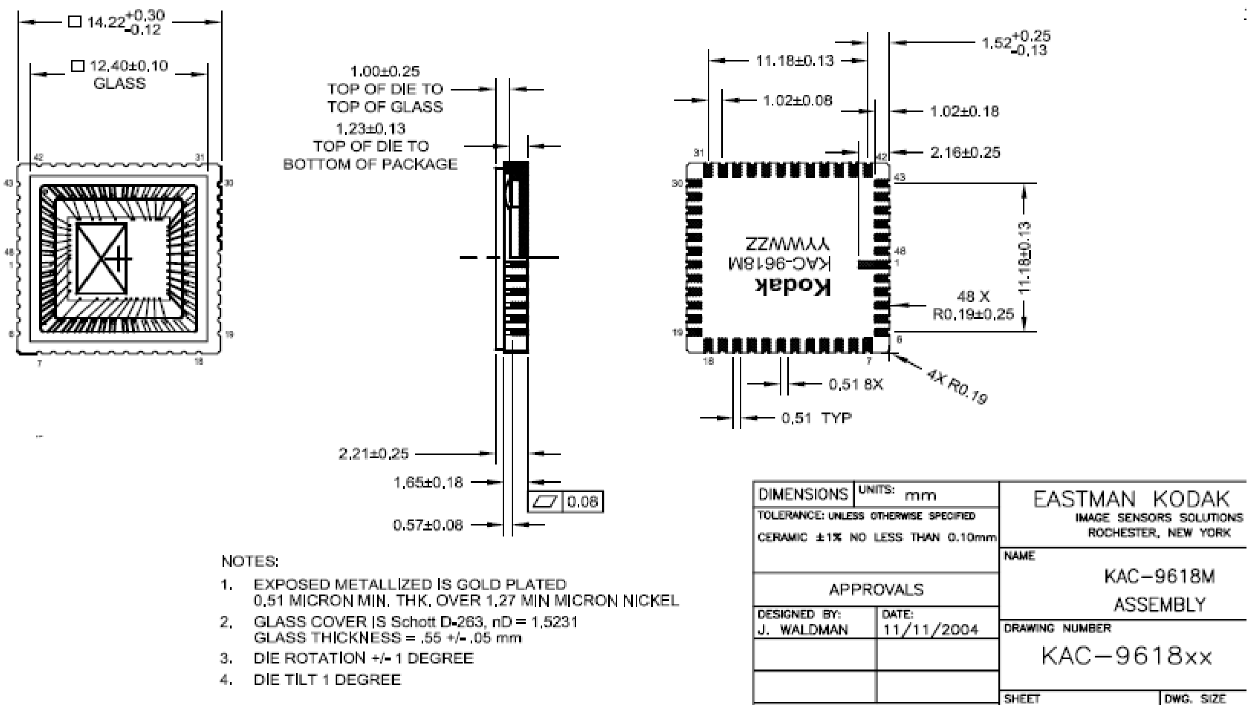

Figure 11: Drawing of Kodak KAC-9618 sensor (Kodak Image Sensor Solutions, 2009b)

4.4. Chosen FPA must be part of a system

The FPA chosen must be part of a system that can be interfaced to a computer without a lot of electrical system design. For example, it could be part of a system with an IEEE-1394 (Firewire) interface. It could be part of a system that interfaced with a commercial frame grabber.

Quite a bit of effort went into researching this topic. This camera is meant to be a testbed for image stabilization, not an electronics project. So the FPA needs to be mounted to an electronics board. But the board must be small enough that it can be mounted to the sensor platform.

There are a number of companies that make original equipment manufacturer (OEM) board camera. One example is the Dragonfly 2 camera made by Point Grey Research shown in Figure 12. This particular system is larger than desired.

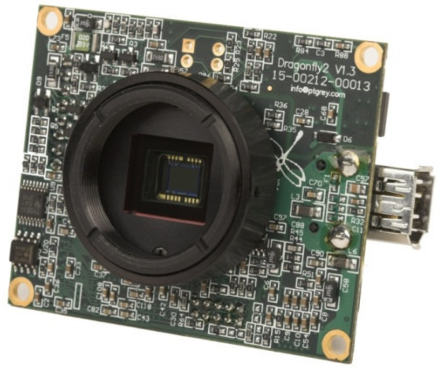

Figure 12: Dragonfly 2 OEM camera board (Point Grey Research, Inc., 2009)

Another camera board that was considered very seriously is the Unibrain Fire-i™Digital Board Camera Remote CCD, which is shown in Figure 13. This camera board has a firewire interface and is based on a Sony CCD array. It is very small and inexpensive.

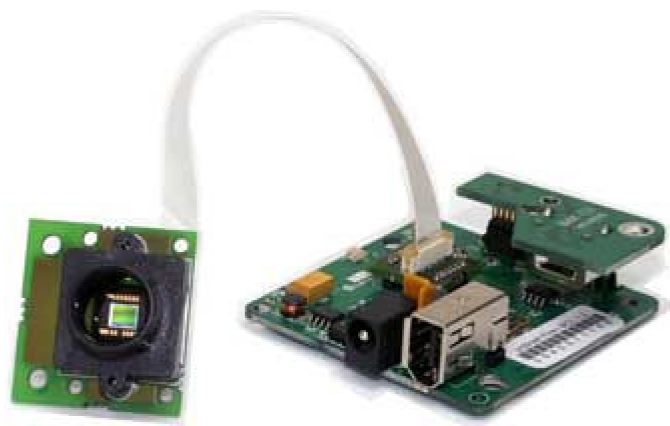

Figure 13: Digital board camera with remote CCD (Unibrain, 2009)

The system that was chosen is the Kodak KAC-9618 evaluation kit, which is illustrated in Figure 14 and Figure 15. The headboard has a removable C-mount interface. The headboard is small enough to mount easily to the sensor platform. Images are acquired via a separate frame grabber.

Figure 14: KAC-9618 evaluation kit headboard (Kodak Image Sensor Solutions, 2009a)

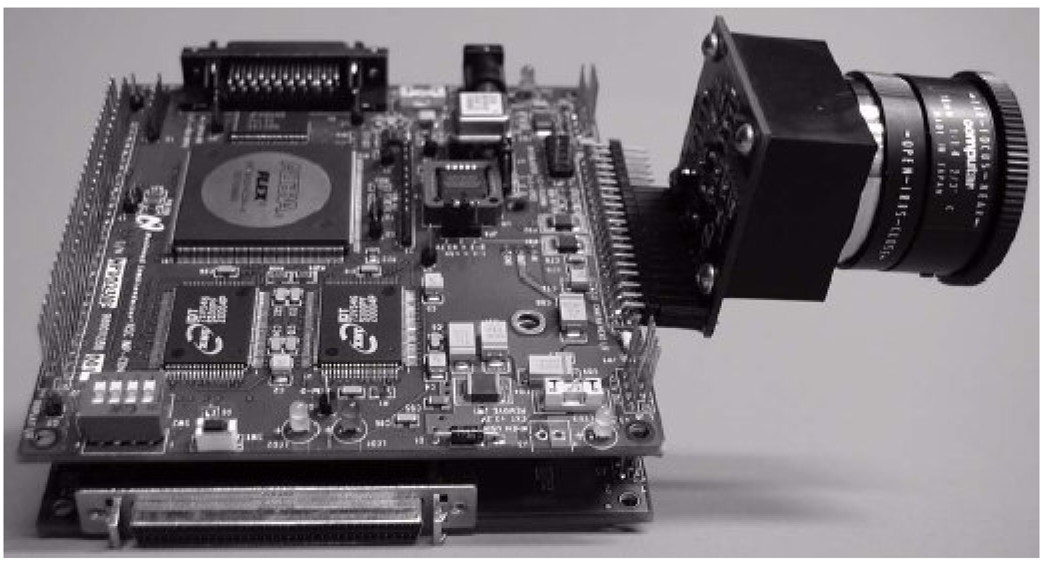

Figure 15: KAC-9618 evaluation kit system (Kodak Image Sensor Solutions, 2009a)

The main reasons for choosing the Kodak evaluation kit over the Unibrain system were

- Extensive documentation of Kodak system
- Kodak makes an entire family of sensors, including full-frame sensors

Given that the KAC-9618 has recently been discontinued, it may make more sense to go with the Unibrain system. The Unibrain system is extremely small and cheap, and has pretty good documentation.

4.5. Chosen FPA must operate in the visible spectrum

The specific FPA and associated lenses should operate in the visible spectrum. This will keep development and test costs low. The design should not preclude other spectra, particularly in the infrared.

The KAC-9618 sensor operates in the visible spectrum. There is nothing about the focal plane array mechanism or F-mount system design that precludes other spectra. In particular, there is no window that might block longer wavelengths.

4.6. Minimum FPA frame rate

The chosen FPA should have a minimum frame rate of 15 frames per second.

The KAC-9618 has a frame rate of 30 frames per second and thus meets the requirement.

4.7. FPA resolution

The FPA should have at least VGA resolution. There is no pixel pitch requirement per se, but smaller pitches are preferred for evaluation purposes.

The KAC-9618 has a resolution of 648×488 pixels, which is slightly greater than the required VGA resolution (640×480). In general, sensors tend to have pixel pitches between 2 µm and 30 µm. For a given focal length, a camera with smaller pixels is going to be more sensitive to image motion than a camera with larger pixels. Thus for evaluation purposes, small pixels are preferred to large pixels. The KAC-9618 sensor has square pixels with a 7.5 µm pitch.

4.8. Mechanism degrees of freedom

The sensor platform mechanism must allow for two translational DOF. No rotational DOF is required.

The preliminary design meets this requirement by inspection.

4.9. Mechanism range of motion

The range of motion of the platform mechanism should correspond to a 1 mrad change of line-of-sight (LOS) at a focal length of 400 mm.

This corresponds to a focal plane displacement of 400 µm, which corresponds to a displacement of 53 pixels for the chosen sensor.

Satisfaction of this requirement has yet to be verified.

4.10. Operational temperature range

The operational temperature range is 0—40 C.

Satisfaction of this requirement has yet to be verified.

4.11. Focus and tilt adjustment

The focus and tilt of the focal plane need to be controlled and/or adjustable.

A simple means of focus and tilt adjustment is provided via the three screws with shim washers that attach the base platform of the FPA mechanism to the F-mount subassembly. We need to be careful that sufficient range is provided, especially for focus.

4.11.1. Focus

The distance from the F-mount flange to the focal plane is dictated by the F-mount specification to be 46.5 mm.

$$t_{\text{flange-to-FP}} = 46.5 \text{ mm} \tag{1}$$

Let's look closely at the sensor drawing of Figure 11. The glass cover thickness is

$$t_{\text{glass}} = 0.55 \pm 0.05 \text{ mm} \tag{2}$$

The cover is made of Schott D-263 glass, with index $n_D = 1.5231$. The optical thickness of the glass is thus

$$t_{\text{glass,optical}} = \frac{t_{\text{glass}}}{n_{\text{D}}} = 0.3611 \pm 0.0328 \text{ mm} \tag{3}$$

The glass cover is effectively foreshortened by a distance

$$\Delta t_{\text{glass}} = t_{\text{glass}} - t_{\text{glass,optical}} = \frac{(n_{\text{D}}-1)t_{\text{glass}}}{n_{\text{D}}} = 0.1889 \pm 0.0172 \text{ mm} \tag{4}$$

The distance from the focal plane (top of the die) to the base of the package is

$$t_{\text{FP-to-base}} = 1.23 \pm 0.13 \text{ mm} \tag{5}$$

The effective optical thickness of the sensor is then

$$t_{\text{sensor,eff}} = t_{\text{FP-to-base}} + \Delta t_{\text{glass}} = 1.42 \pm 0.15 \text{ mm}^{5} \tag{6}$$

The required distance from sensor base to the F-mount flange is then

$$t_{\text{flange-to-base}} = t_{\text{flange-to-FP}} + t_{\text{sensor,eff}} = 47.92 \pm 0.15 \text{ mm} \tag{7}$$

The F-mount adapter thickness (flange to adapter base) is specified to be

$$t_{\text{adapter}} = 11 \pm 0.254 \text{ mm} \tag{8}$$

---

[5] Note that this is not the expected distance given dimensions of the C-mount adapter supplied with the headboard kit. The distance from the flange to the base of the adapter is 19.5 mm. The C-mount specification dictates that the flange to focal plane distance is 17.5 mm. So we expect the effective optical thickness of the sensor to be 2 mm, not 1.42 mm. This analysis would need to be reviewed if the system were to be built.

The mounting plate thickness is

$$t_{\text{mounting plate}} = 19.05 \pm 0.254 \text{ mm} \tag{9}$$

Let t_{spacer} be the spacer thickness and t_{shim} the nominal shim washer thickness. Then

$$t_{\text{adapter}} + t_{\text{mounting plate}} + t_{\text{spacer}} + t_{\text{shim}} = t_{\text{flange-to-base}} = 47.92 \pm 0.15 \text{ mm} \tag{10}$$

$$t_{\text{spacer}} + t_{\text{shim}} = 17.87 \pm 0.66 \text{ mm} \tag{11}$$

Choose the spacer thickness to be

$$t_{\text{spacer}} = 15.87 \pm 0.254 \text{ mm} \tag{12}$$

The required shim washer thickness is then

$$t_{\text{shim}} = 2.00 \pm 0.91 \text{ mm} \tag{13}$$

So the nominal shim washer thickness is 2 mm. The required focus range is ±0.9 mm.

4.11.2. Tilt

The tilt of the die is less than ±1 deg. At this preliminary design phase it is reasonable to assume that the total system tilt will be less than ±2 deg. This amount of tilt can easily be compensated for by the crude shim washer arrangement.

4.12. Shock survivability

The system needs to survive a 20 G shock.

Satisfaction of this requirement has yet to be verified.

4.13. Required analysis

Analysis must be performed to determine the actuator force requirement to accelerate the platform at 10 G.

This analysis has yet to be performed.

5. Bibliography

Four Thirds. (2009). *About Four Thirds*. Retrieved April 12, 2009, from http://www.four-thirds.org/en/about/benefit.html

Kitazawa, T., Kitaguchi, T., Shimizu, H., Katoh, M., Sato, Y., Sasaki, S., et al. (2002). *Patent No. US 2002/0163581 A1.* USA.

Kodak Image Sensor Solutions. (2009a). *Evaluation kit for Kodak KAC-9618 CMOS image sensor.*

Kodak Image Sensor Solutions. (2009b). *Kodak KAC-9618 CMOS image sensor device performance specification.*

Point Grey Research, Inc. (2009). *Imaging Products -- Dragonfly 2*. Retrieved April 12, 2009, from Point Grey Research, Inc.: http://www.ptgrey.com/products/dragonfly2/index.asp

Unibrain. (2009). *Fire-i Digital Board Camera, Remote CCD*. Retrieved April 12, 2009, from http://www.unibrain.com/Products/VisionImg/Fire_i_BC_remoteCCD.htm

Wikipedia. (2009). *Lens Mount*. Retrieved April 12, 2009, from http://en.wikipedia.org/wiki/Lens_mount