High Resolution Large Format Tile-Scan Camera

Design and implementation

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Camera website: http://www.dgcam.org

Since this document was written, the camera was significantly redesigned.
For more information please contact the author.

DISCLAIMER

This tutorial describes the research work of the authors. The method described in it has not been tested in commercial environment. The construction description contained in this tutorial is given AS IS for educational purposes only. The author provides no warranty (explicitly or implied) of any kind and disclaims any and all potential liabilities in relation to your use of this tutorial.

NO GUARANTEE IS GIVEN REGARDING THE SAFETY OF THE PROCEDURES DESCRIBED IN THIS DOCUMENT FOR THE CONSTRUCTION AND/OR USAGE OF THE CAMERA.

Readers should be aware that:

1. A camera is a delicate device that requires utmost accuracy to work properly.
2. A camera includes expensive parts that can be damaged easily.
3. Your camera may not work as expected even you have followed the construction instructions strictly.
4. Following the instructions described in this tutorial will VOID the warranty for some of the components of the camera.
5. Operating machinery and constructing and handling electrical devices IS DANGEROUS without proper knowledge and training.

By following any of the procedures in this tutorial, you acknowledge that you are fully qualified to evaluate and perform the procedure safely.

This document might contain errors and/or omissions. Comments and error corrections (via email to authors) will be greatly appreciated.

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For any inquiry regarding the camera and its use, please contact the author by email:
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1 Scope

This document describes how the dgCam was built, and to some extent, why certain decisions were taken. This document neither describes how the camera *works* nor *how it should be used*. These parts are described in the ‘relevant document that are available at the camera web site: http://www.dgcam.org.

2 Before you start

Yes, a digital gigapixel camera can be built, by a single person, in just a few months. You do not need to be an engineer, and no complex machinery is needed. However, having a certain level of optical, mechanical, electrical and software understanding is required.

The camera does not come cheap either. To have high quality results one must use high quality ingredients, in particular the lens and main sensor. The cost of a complete camera can reach $25K (2009 prices). This is significantly more expensive than a consumer level SLR camera. The good news is that this cost is considerably lower than the cost of professional phonographic equipment such as Seize, or Hasselblad that can easily reach $40K or more.

Before you begin, read this document as well as the information given at the camera site (http://www.dgcam.org) thoroughly. Make sure you understand the advantages as well as the disadvantages of a large format digital camera. In particular, consider if using image mosaic is an alternative choice depending on your needs.

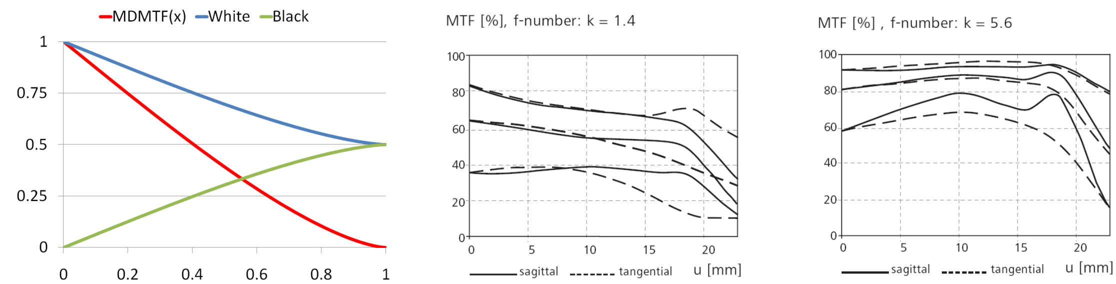
Above all - don’t rush; things will go wrong, make sure you fully understand what went wrong, and consider multiple options before you take irreversible actions. Good Luck!.

3 Critical decisions

This section describes the main design and consideration related to the camera. It is recommended for readers who wish to explore different alternative and to better understand why we choose this particular setup. It can be safely skipped by reader who primarily wishes to build a replica of our camera. To get a more complete view of the technical consideration, please read the technical paper as well.

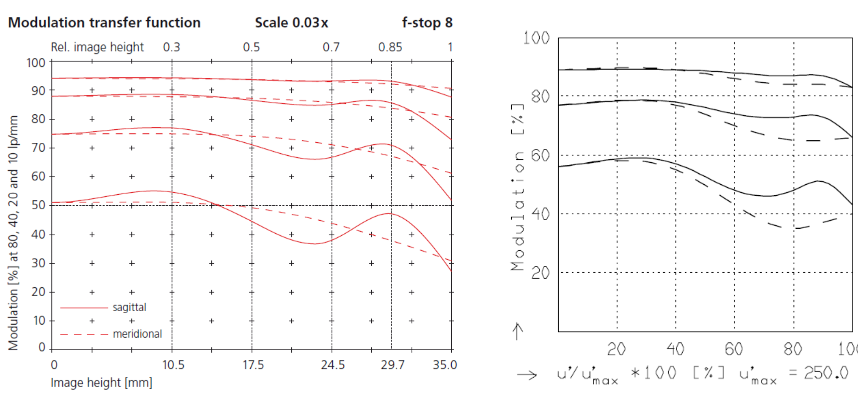
3.1 Selecting the lens

The lens is the most important part of the camera; information that is lost by the lens cannot be later recovered. It is therefore important not only to select the right lens, but also to make sure not to degrade the image by adding unnecessary or low quality



(a) (b) (c)

Figure 1: (a) Monochromatic diffraction limited MDMTF for a circular aperture X:normalized frequency, Y:Transmitance. (b),(c) MTF of the Carl Zeiss Planar T* 1.4/50 standard lens for f-no 1.4 and 5.6 respectively Source: manufacturer web-site . Unaltered, faithful to original (b,c).



(a) (b)

Figure 2: Modulation transfer function for the Rodenstock's HR Digaron-S 5.6/60 (a), and the Schneider Optics' APO SYMMAR 8.4/480 (b). The graphs show the MTF for spatial resolution of 10 20 40 80 lp/mm for the Rodenstock, and 5, 10, 20 for the Schneider's. Source: manufacturers web-site . Unaltered, faithful to original.

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elements in the optical path. There is very little use in purchasing thousands of dollars worth of lens and then degrade the image by applying a low quality filter or by introducing motion blur to the image.

3.1.1 Lens format and sharpness

The first thing to notice when selecting a lens is that there is no such thing as *the* sharpness of the lens, for example "a sharpness of 100lp/mm". Even for theoretical perfect conditions (diffraction limited monochromatic) the contrast of the image will drop gradually as the details become finer, until the image is no longer resolved. This is expressed by a function called *The modulation Transfer Function*, which is a function of the aperture and of the spatial frequency (level of details). A normalized graph of this function is shown in Figure 1(a). The red line shows the transmittance as a function of the spatial frequency, and the blue and the green line show the transmitted value of white and black for this frequency respectively. As can be seen, the contrast between black and write drops until there is no contrast at all - or gray color. To be able to resolve the differences between a black and white line, the MTF value should be approximately 9% or better (Rayleigh criterion).

The story becomes more complicated where real lenses are considered. The MTF of a real lens changes with: location relative to the center of the image, lens aperture (due to diffraction and abberations), distance from the object and the orientation of the pattern. This is too much information to display in a single graph, so the lens manufacturer usually provide several graphs that provide part of the information. For example, figure 1(b),(c) show the MTF of a Zeiss standard lens at f-numbers 1.4 and 5.6 as a function of distance from the center of the image. The different lines show the MTF for 10,20 and 40 lp/mm in two pattern orientations.

The MTF alone is not sufficient, we also need to consider the *size* of the optical image. For example, Figure 2 compares the MTF of the Rodenstock's HR Digaron-S 5.6/60 with this of the Schneider Optics' APO SYMMAR 8.4/480. Both have similar field of view (60^o for the Rodenstock and 56^o for the Schneider's). Clearly, the Rodenstock lens is much sharper and capable of resolving 80lp/mm at 40% MTF over (almost) its entire field of view, where as the Schneider lens can only resolve 20lp/mm. The reason is that the Rodenstock lens was designed for use with a medium format digital sensor where as the Schneider's was designed for use with large format film. However, if we compute the number of pixels at the image circle that are obtainable at 40% MTF as $\pi r^2 * 4(lp/mm)^2$ (pixels at Nyquist frequency), we get that the Rodenstock lens can obtain 98 mega-pixels, whereas the Schneider's can obtain 314 mega-pixel at the same quality. This is over 3 time more. If we estimate that at 10% MTF (barley resolve) is three times the density of 40% MTF, we get values of 886 mega-pixels for the Rodenstock and 2.8 giga-pixels for the Schneider. Of course, a rectangular image will only use part of this.

The Schneider's lens has another advantage: due to a lower spatial resolution it can work in a smaller aperture which means a better depth of field can be obtained.

Finally, lens distortion and light transmittance (vignetting) should also be considered, however, usually these are very good for large format lenses.

3.1.2 Selecting lens type

After reviewing the format and sharpness issue comes the time to choose which lens to use. In particular selecting the type and aperture of the lens.

The aperture of the lens determines the speed in which an image can be taken. Speed is of utmost importance for sport and nature photography, however due to the scanning operation of the digital back (see below), speed is definitely not a quality of this camera, as image capture can take anything from a few minutes to a few hours. Moreover, since the sensor only sees a small part of the FOV at any given time, there is little use of having a large aperture in order to blur the background - this can be done later on. Having a small aperture is important for increasing the depth of field, however an aperture that is too small will degrade the sharpness of the image due to diffraction (see table in the pixels size discussion).

The type of lens will probably be either a standard lens, a telephoto lens, wide angle lens or a macro lens. Each of these is designed to work best at different distances from the object, different fields of view and different magnifications. For example, a telephoto lens may not be able to focus at all at a close range, whereas a macro lens is optimized to work only at close range. For most applications, a standard (50^o) lens and a somewhat wider field of view (100^o) lens will likely be sufficient.

3.2 Selecting the main sensor

The next step after selecting the lens is to select a sensor for this lens. Unfortunately most digital sensors are *not* designed to work with large format lenses such as the Schneider's lens we use. There are two reasons for this. The first reason is that a large format *film* lens focuses the Red, Green and Blue at slightly different distances to match the film layered structure. This does not match most digital sensors (except, perhaps, the Fovion sensor). The second reason is that most digital lenses that have microlenses on the sensor require a telecentric lens at the sensor size to match the field of vide of the microlenses. This problem is illustrated by Figure 3. To overcome these problems, the sensor must have the largest possible pixel size for the lens and no microlenses.

3.2.1 Which sensor type to use?

As seen above, we must select a sensor without microlenses. This practically rules out CMOS sensors because they are simply not made without microlenses, as this will severely degrade its fill factor (much more than CCD sensors). Even for CCD sensors there is a large selection to choose from and we describe each one and discuss its advantages and disadvantages.

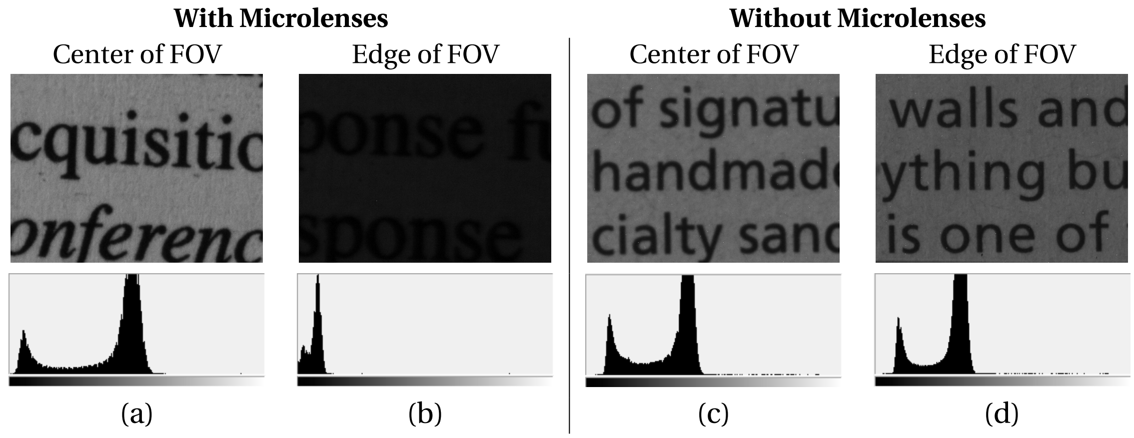

Figure 3: Microlenses are harmful for large format imaging. (a) and (b) are images (with their histogram shown below) taken by a senor with microlens at the center and the edge of the field of view, whereas (c) and (d) are images taken by a sensor without microlenses. We can see that the image taken with microlenses is severely degraded at the edge of the FOV because sensors with microlenses are not designed to work with large format lenses.

Linear CCD array

Linear CCD arrays (LCA) are sensors usually having a single column of pixels. LCAs can be read very fast and are usually used in scanners, where the sensor moves relative to the scanned object. Having 3 separate columns for RGB allow LCAs to capture a color image without Bayer interpolation, which is an advantage. However, LCAs have a few significant disadvantages that make them less than ideal for our purpose. The first is that LCAs must be moved very accurately to prevent image distortion. In principle they can be moved pixel by pixel by a very accurate step motion (piezo-electric motor) however, for simplicity they are usually moved with constant continuous motion (as scanners do).

If moved in such continous motion this leads to a second disadvantage: in order to avoid motion blur, a very slow motion or very strong light (as used in scanners) is needed. For example, if the light is sufficient for $\frac{1}{100}$ of a second exposure time, and we wish the blur to be less than 10 microns in size, then the maximal speed would be $\frac{1mm}{sec}$. Scanning a single line of a 500mm image plane would then require 8.3 minutes. Lets further assume that we use cascaded multiple LCAs so only 1D scan is needed. Now, consider the case that due to low light an exposure time of 10 seconds is needed (close shutter for larger depth of field and cross light polarization cam easily lead to 10 second or more exposure time) - this will take nearly a week(!) to capture the same image, which is clearly impractical.

A third disadvantage of LCAs is that they require movement to get an image - making functions like through the lens focusing very hard. Finally, a defective pixel in an LCA will result with a defective line in the image with no redundancy to overcome it.

Time delay integration CCD array

Time delay integration CCD arrays (TDI) are very clever sensors designed to overcome some of the shortcomings of LCAs. A TDI sensor consists of several columns of pixels, and like LCAs it needs a scanning motion to produce an image. However, unlike LCAs, TDIs are clocked in such a way the the electronic image (the charge) is moved across the CCD at the same speed and opposite direction to the the mechanical motion. The results is that nearly all motion blur is eliminated. Additionally a single defective pixel will only affect the brightness of a line (that can be compensated for later) and not destroy the entire line. However, TDI sensor requires very accurate synchronization and mechanical alignment. Also, changing the exposure time requires a change of the mechanical scanning speed, and finally These are not trivially obtained. Additionally TDI sensors are not very suitable for color filter array and therefore RGB is obtained by using 3 CCD configuration which is more complex. Finally, a TDI sensor is even less comfortable for functions like through the lens focusing since in the absence of motion it will not generate even a single column of data.

Full frame CCD

Full frame (FF) CCDs are the most commonly used in SLR cameras and digital backs. FF CCDs are very efficient sensors and can achieve nearly 100% fill factors without microlenses. In many ways they are the ideal choice to use with a large format camera. However, FF CCDs have one major disadvantage: they require a physical shutter in addition to any electronic shutter that they may have. The reason is that an electronic shutter of a FF CCD will not prevent image smearing during image readout. Large format cameras usually have a manual shutter embedded in the lens. Replacing this shutter with an electro-mechanical one that is fast, reliable enough and does not alter the optical structure of the lens in any way will provide a good solution. However, at the time of writing, only size 0 and 1 shutters are available (by Rollei). Attaching a solenoid actuator to an otherwise manually operated shutter, could work, but may not be a good choice as the shutter was not designed to operate this way. The alternative is to use a sensor side shutter which is large enough not to block light at the edges of the image. Finding such shutter turned out to be a difficult task. Furthermore, a mechanical shutter have a limited fail-free operation estimated at approximately 100K[1]. With bracketing and/or photometric stereo (see below), a single image an easily exceed 500

[1] (As reported by different manufacturers, though some individuals reported up to 1M .)

exposures, which means that the mechanical shutter expected life is just 200 such images. This is not acceptable.

An electronic (ferroelectric) shutter may be an easier choice, however it will not block light completely when closed and will attenuate and possibly affect the spatial resolution when open. For these reasons we chose not to use FF CCD.

Frame transfer CCD

A frame transfer (FT) CCD uses double chip size to provide a light shielded area of the same size as the sensing area. A FT CCD quickly transfers the image from the sensing area to the light protected area from which it is read out line by line like a FF CCD. The quick transfer causes less smear than FF CCD, but does not eliminate it completely. The (relative) amount of smear depends on the exposure and the size of the CCD, and the clocking of the CCD. Transfer times between several hundreds micro-seconds to few mili-seconds are reported by manufacturers. A typical applications of FT-CCD is astronomical sensors (which are cooled and have long exposure time) and fast video camera, where the sensors are relatively small and the transfer to the shielded area is fast. With large size (10M or more)[2] and short exposure times (approximately 100 mili seconds) FT-CCD solution become more problematic.

Moreover, is that due to their higher cost FT CCDs are quite uncommon. At the time of writing, I am a not aware of a single commercial large (10 mega-pixel or more) Color FF CCD to date, not to mention a camera that uses one and is suitable for our needs (see below). Though potentially FF CCD can be a good solution, however it is not currently practical.

Interline CCD

Interline CCDs are widely used in video camera, surveillance camera and web-cams (though CMOS sensors are replacing CCD in many applications due to simpler production, lower cost and lower energy consumption). The pixels of an interline CCD have a light shielded part in which the data is stored and can be read without smearing. However, having an interline CCD without microlenses is usually *not* a good idea, as the fill factor drops to 50% (or slightly less). This clearly reduces the amount of available light by half, and may also miss some of the data (causing aliasing).

The aliasing problem can be reduced by slightly super-sampling the image plane (this also helps with demosacing of the Bayer pattern). The fill factor problem has no simple solution and we either need to open the lens one stop more, or double the exposure

[2] A small CCD will result with unacceptable number of mechanical operations per image.

time.

This however is a small price to pay compared to the advantages of an interline CCD. No mechanical shutter is needed, there is no smear during image reading, and a wide selection of commercially available CCDs and cameras exist.

3.2.2 Which sensor size to use?

The trade off here is fairly simple - small form factor and low resolution sensors are usually cheaper and have a higher frame rate than large form factor and high resolution sensors. However, having s small form factor and low resolution will require a significantly larger number of mechanical motions, that will significantly increase the acquisition time. Here a compromise is probably the best policy and we have chosen a 35mm, 11megapixel sensor.

3.2.3 Which pixel size to use?

Having small pixels will increase the image size (up to several giga-pixels), but these will only be empty pixels due to the limited resolution of the lens. Moreover they will be noisier and the overall quality will degrade. Larger pixels are more sensitive, have less noise and have better dynamic range. However, pixels should not be much larger than the lens resolution (if no computational super-resolution is used).

Pixel size should therefore be set to the largest size that still slightly over-samples the lens resolution. The pixels should not be smaller than than the pixel size set by the diffraction limit for the most common working aperture. Few values are given in the table below:

λ	**f-no**	**Airy Disk**	**Pixel Size**	**Comment**
550	2.8	1.87	0.94	Not very practical
550	4	2.68	1.34	Cell phone quality
550	5.6	3.75	1.87	
550	8	5.36	2.68	Point and shoot quality
550	11	7.38	3.69	
550	16	10.73	5.36	SLR quality
550	22	14.76	7.38	
550	32	21.47	10.73	Scientific quality
550	45	30.19	15.0	High-End Telescope quality
550	64	42.9	21.4	

Note that due to lens aberrations, it is unlikely that a commercial lens will be diffraction limited at f-numbers that are smaller than 11 (whereas most high quality lenses will be diffraction limited at f-no 32), therefore the sweet spot for pixel size would be somewhere between 4 to 10 microns. We have chosen a sensor with a 9 micron pixel size.

3.2.4 Which camera and interface to use?

A sensor cannot work by itself, it requires support circuitry, clocking, amplification, analog to digital conversion and an interface to the computer.

In principle, there are thee options for obtaining a camera. The best option is to find an OEM camera; these cameras usually come as one or more bare boards that are fully functional but contain no enclosures. The second option is to use a development board - these boards are designed for the testing, evaluation and development of prototypes, they are usually larger and often very basic and not very comfortable to work with. The third option is to get an assembled camera and take it apart, **which will void warrantee**.

There are also several interface options including: FireWire, USB, Ethernet, CameraLink, and dedicated (usually flat) cables used in development boards. *It is important that the interface will be long enough, light-weight enough and flexible enough to allow free movement of the sensor on the translation stages.* With this respect the FireWire, USB and Ethernet have a clear advantage.

Unfortunately, the market for s special camera that has a sensor fitting our requirement is small, and therefore the margins are much higher than in the consumer market. Finding the right camera was a long and sometimes frustrating experience. We have eventually selected a USB camera that also has an advantage of having a common interface that can work with any computer and does not require an expensive capture card. (for details see the main sensor description below).

3.3 Thermal considerations

Unlike a large film format camera that can work at a relatively high temperature range (depending on the film used) from few degrees above freezing to 40-50 degrees Celsius (perhaps even wider range), a digital camera works best at low temperature that reduces the noise generated by the sensor and electronics. Unfortunately, the sensor itself is a strong source of heat. In our camera the sensor alone (large CCD) produces 18W of heat. The translation stages also produce some heat. The sensor is moving and it needs to be in a light-tight enclosure which creates a problem dissipating the heat from the sensor. Using a cooled sensor will not solve the problem as the heat in the enclosure will rise until the cooling system fails. The following alternatives are possible:

3.3.1 Cooling fans

A cooling fan replaces the hot air inside the enclosure with cooler ambient air. It is the most common method of cooling electronic devices. However, in our case cooling fans have several disadvantages:

Light tight - Cooling fans must not allow light to enter the enclosure, building light traps in the way of the air is possible, but it complicates the system and reduces its efficiency.

Humidity and dust - Cooling fans enter the ambient air into the camera, if the ambient air is humid or dusty (and in particular if an active cooling component is used inside the camera) this may cause water condensation and dust deposit on the sensor or the lens, which can severely affect the performance and even damage the camera (a quick look at a desktop PC can easily show just how much dust is accumulated in an open air system cooled by a fan). Removing dust and humidity is possible, but will complicates the system and reduces its efficiency.

Sensitivity to ambient temperature - Cooling fans will not reduce the temperature below the ambient temperature. Additionally the temperature will be affected by changes in the ambient temperature and it will be difficult to maintain a fixed temperature.

3.3.2 Conductive enclosure

Heat conductive material such as aluminium can very efficiently conduct heat while blocking light dust and humidity. A thin aluminium enclosure will be light and can easily[3] conduct the heat generated by the sensor and translation stages. It is the simplest solution that does not require any moving parts or energy to operate. However, Conductive enclosure also has its disadvantages, the first is that while the aluminium enclosure will conduct heat very well, the interface to the air inside and outside the enclosure will not, as air conduction is very low. Heat can be carried by air more efficiently using forced convection, in other words adding fans inside the camera as well as outside the camera - but keeping to two environments separated. Although not very efficient, this is a workable solution that can be considered. The second disadvantage of a conductive enclosure is that temperature will be higher than the ambient environment (even more than with open air cooling fan) and that it too is sensitive to ambient temperature variations.

3.3.3 Active cooling

Active cooling is the most complicated solution - it requires a cooling element as well as fans. Since a large format camera is not air sealed, then in order to prevent water con-

[3] by several orders of magnitude.

densation on the sensor the entire enclosure should be cooled; this will keep the sensor itself at temperature which is above the (cooled) air that surrounds it and therefore prevent condensation. Active cooling has the advantage of reducing the temperature below the ambient temperature and regulating the temperature. Both are important for obtaining high quality low noise images.

Active cooling can be done in basically two major ways - the first is using an external unit (air conditioner) and circulating the cool air through the camera. This is the most powerful solution, but the added unit and pipes will greatly reduce the comfort of operating the camera. The second is using thermoelectric cooling. Thermoelectric cooling uses the Peltier effect in semiconductors as a heat pump. It is a compact and very reliable solution (as long as the heat does not go over the maximum limit). However, its efficiency is quite low.

In our system we have chosen thermoelectric cooling. Detailed explanation appears in the construction section.

4 Constructing the camera

4.1 Mechanical

The core of the camera is the lens and sensor, but without the proper mechanical support the will have little or no value at all. In this section we describe the skeleton of the camera, its enclosure, cooling and mobility.

4.2 The skeleton of the camera

The skeleton of the camera should provide firm support for the components of the camera (mostly lens and sensors), and it should allow motion in designated directions (only).

The skeleton must be rigid and very accurate. Even a slight misalignment will cause the image to be blurred or distorted. To achieve the required rigidity and accuracy we rely on optical table components. These components are specially designed and manufactured for laboratory optical setup and are, by far, the best suitable components that can be obtained off the shelf at a reasonable cost. An overall view of the skeleton is shown in Figure 7. In the following sections we describe the skeleton in more detail.

4.2.1 The baseplate

The baseplate shown in Figure 7(a):4 is the backbone of the camera. Everything depends on this plate being accurate. For this task we selected a solid aluminium optical

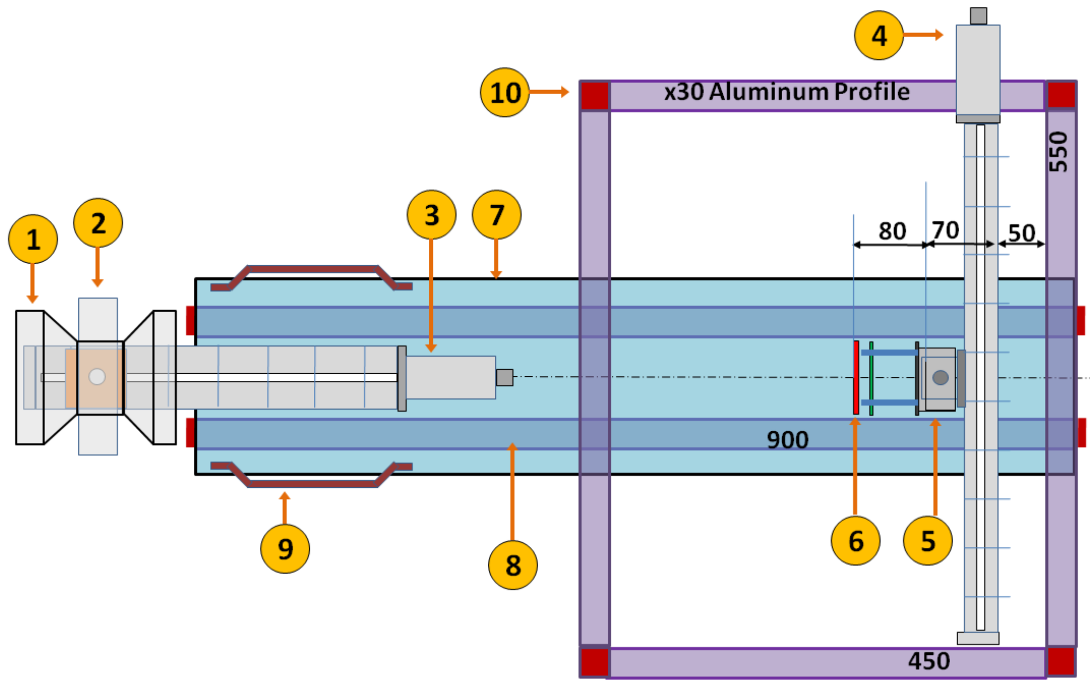

Figure 4: Camera Overview, Top view: The front of the camera (left) consists of the main lens (1) is attached to the lens holder (2) that is attached to the focusing stage (3). The back of the camera holds the main sensor (6), which is attached to the vertical stage (5) that is attached to the horizontal stage (4). All stages are attache to the main breadboard (7), which is supported by two aluminium rails (8). Covers (10) are placed at the open ends of the rails. Two handles are attached to the front of the main board.

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breadboard. We used a 900x200x12.7mm double density breadboard from ThorLabs. The breadboard cannot be just "placed in the air", it requires support. We used two construction rails shown in Figure 7(a):5 to support the breadboard. Attaching the rail to the breadboard is done by sliding a screw through the rail to its location and tightening it by drilling a whole *for the screwdriver* (a Philips type is preferred) as shown in Figure 7(c). A thin felt layer (the same type used to cushion furniture) is placed between the breadboard and the rail to prevent stressing the breadboard in case the rail isn't as accurate.

The baseplate components are listed in Table 1. The serial numbers in the table correspond to the numbers in Figure 7. The constructional rails listed below are XE25 and are better then the ones we used (however, a 30mm would be preferred if the same Styrofoam insulation is used) .

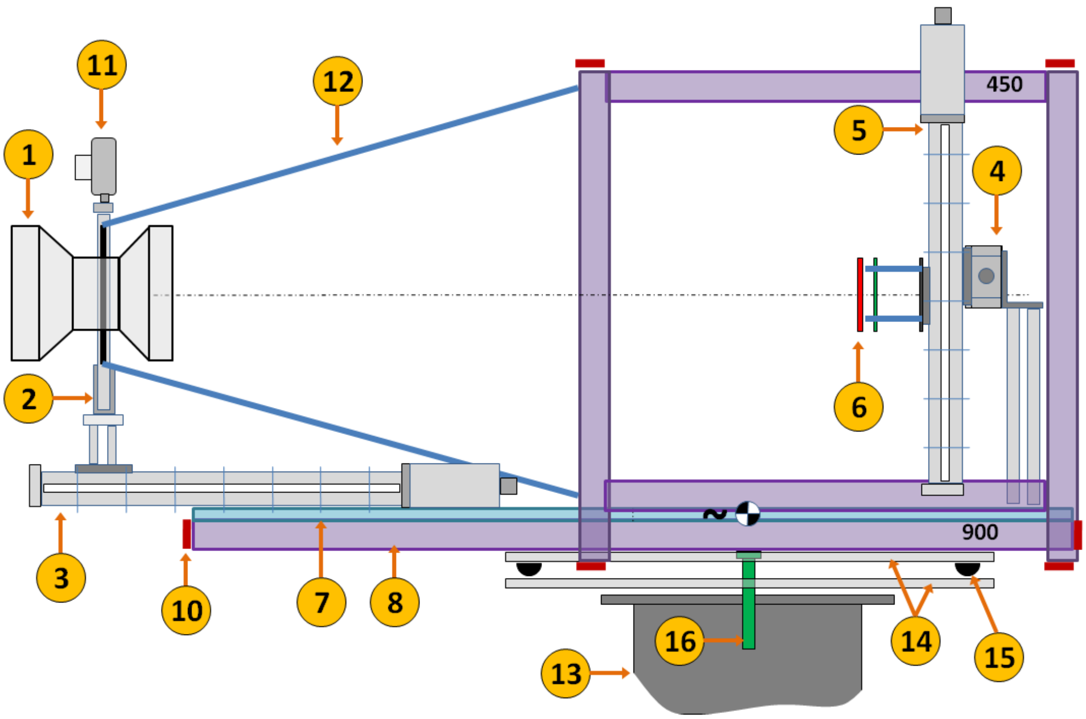

Figure 5: Camera Overview, Side view - Items (1-10) are the same as in the top view, additionally we can see the video camera (11) that is attached to the main lines holder and moves with it, the bellows (12), and the base of the camera. The camera is carried by a telescope pier (13) (only top is shown) (13). Two aluminium plates (14) and four Sorbothane™bumpers provide vibration issolation/damping. A safety screw (16) holds the two plates together while allowing relative motion (see back view for more details).

The handle listed in Table 1 can support up to 250Kg. It is essential to use handles that have guaranteed strength for handle failure can result in damage to equipment as well as severe injury.

4.2.2 The lens holder

The lens holder should *firmly and accurately* attach the lens to the focusing stage, while allowing simple and easy replacement of lenses.

Like the rest of the skeleton, the lens holder accuracy is based on optical table components where steel posts and post holders provide the required accuracy and rigidity. The lens holder is shown in Figure 8. The lens is firmly attached to the lens-board. The

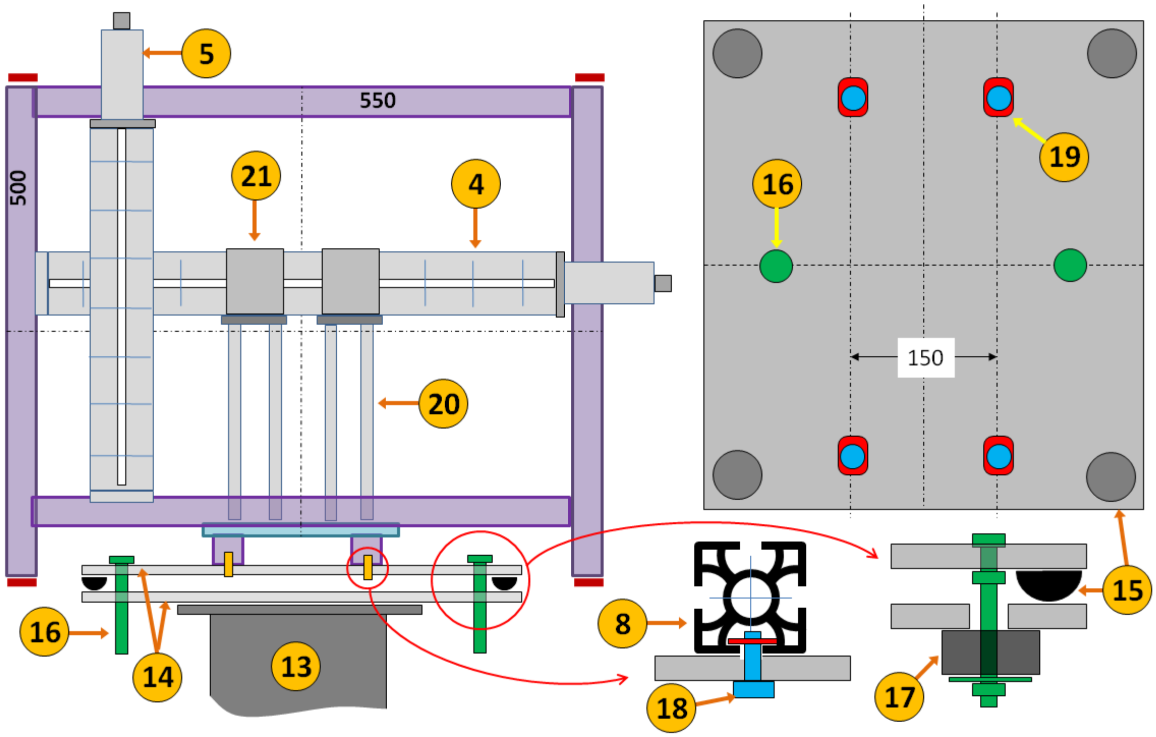

Figure 6: Camera Overview, Back view: This view shows the steel posts (20) and the angle brackets (21) used to attach the horizontal stage (4) to the breadboard. The vibration suspension plates are also shown with magnified inserts on the right. The safety screw (16) is firmly attached to the top plate (14), and goes through a *wider hole* in the bottom plate. It is secured with a rubber spacer (or spring) that is held by a nut. This allows *restricted* relative motion between the boards (horizonal, vertical and angular motion).

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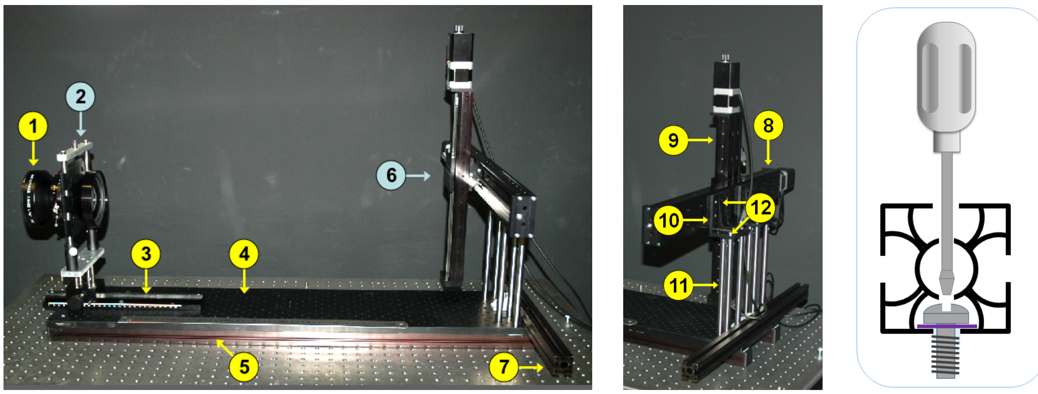
lens-board has grooved edges that align against the two cylindrical posts. Steel paper clips are used to firmly hold the lens board and the posts together[4]. The posts are held by a custom made aluminium bar at the top and by post holders at the bottom. These are securely attached to the base bar, which in turn is secured to the focusing stage by four small steel posts.

To release the lens, the two post lock screws should be loosened, and the lens together with the posts and top bar can be detached from the base bar. Releasing the steel paper clips allows the removal of the lens and the lens board from the posts. Each lens usually will have its own lens board, so no further disassembly is needed in order to change

[4]Though not designed for this purpose, the still paper clips provide an excellent hold and are easy to ally and remove.



(a) (b) (c)

Figure 7: The skeleton of the camera. **(a),(b)** (1:Lens), 2:lens Holder, 3:Focusing Stage (manual) 4:Breadboard, 5:Supporting rail, 6:Image plane stages, 7:First enclosure rail, 8:Horizontal stage 9:Vertical stage, 10:Angle Bracket, 11:Steel post (12mm), 12:M6 screws. **(c)** Tip - to attach a rail to the breadboard, slide the screw through the rail, and drill a hole for the screwdriver (Philips type preferred).

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the lens form the frame. Some lenses will require removing the back part to release the bellows from the lens.

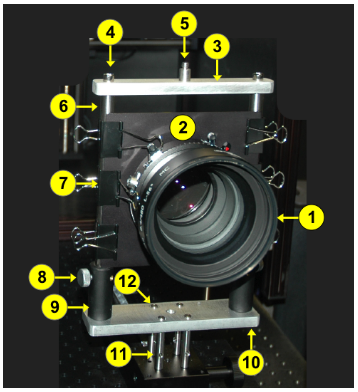
The lens holder components are listed in Table 2, the custom top and base bars are shown in Figure 9. The serial numbers in the table correspond to the numbers in Figure 8. The table includes one source for obtaining each part. It is perhaps the most convenient source, but not necessarily the only option or the cheapest source for each part.

Table 1: Baseplate component list

#	Description	Qty	Made by	Part# (mfr/store)	Buy at
4	900x200mm breadboard	1	TL	MB2090/M	TL[1]
5	900mm construction rail[2]	2	TL	XE25L900/M	TL
-	Cover plate	4	TL	XE25C	TL
-	Handles	4	TL	BBH1/M	TL
-	M6 screws[3]	8	Any	N/A	Any

1. ThorLabs http://www.thorlabs.com/
2. Black anodized.
3. Make sure these fit into the constriction rail

Note: Re recommend using XE25, or if possible 30mm rails. We use local vendor 30mm rails, and therefore the images and schematics show 30mm rails.



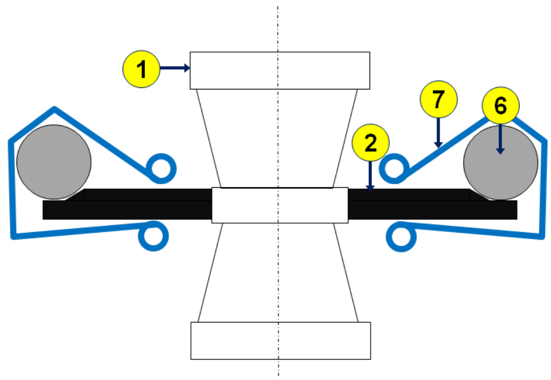
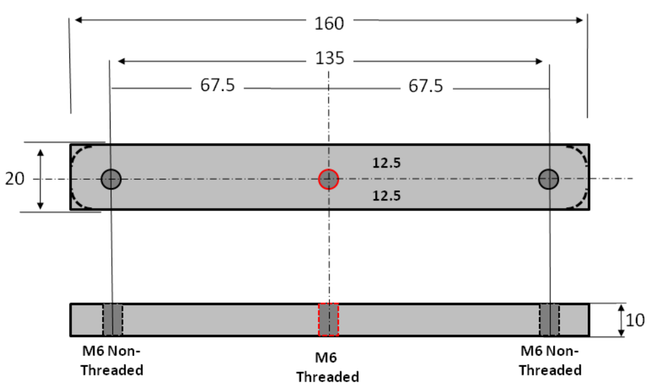


Figure 8: The lens holder. **(a)** 1:Lens, 2:Lens board, 3:Top bar, 4:M6 screw, 5:Auxiliary camera holder, 6:Steel post (12mm), 7:Steel clip, 8:Lock screw, 9:Post holder, 10:Base bar, 11:Steel post (8mm), 12:M4 screws. **(b)** The lens board is held by pressing the steel posts against grooves in the lens-board by steel clips. (The post holders support the lens board at the bottom). (image not to scale)



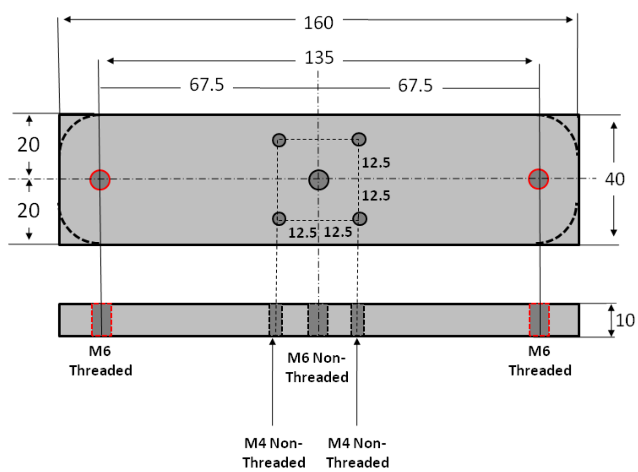


Figure 9: Lens holder custom made aluminium bars. All measures in mm.

4.2.3 The focusing stage

The focusing stage should move the lens holder (and the lens) closer or further from the image plane. It must provide firm support to the lens holder and have accurate motion to serve its purpose.

As with other parts of the skeleton, we used optical table parts for the focusing stage as these allow very accurate focusing.

The focusing stage can either be a manual one or a motorized one. A manual focusing stage will be less costly and quite comfortable and intuitive in its use, however, it will not allow computer controlled auto focus. A motorized stage will allow auto focus, be more accurate, but will cost more and may actually be slower than the manual stage if a fine lead-screw is used. Table 3 lists the parts of the focusing stage, the number(s) refer to Figure 7.

Table 2: Lens Holder component list

#	Description	Qty	Made by	Part# (mfr/store)	Buy at
2	Lens board 141x141 Copal #3	1	Arca-Swiss	0910304 / ARLB3141	BH[1]
3	Top bar (custom made)	1	N/A	N/A	N/A
4	M6 socket head cup screw	2	Any	NT56-384	EO[2]
5	F:M6 to M:1/4”x20	1	Any	NT53-928	EO
5	+ M6 socket head screw	1	Any	NT58-641	EO
6	12mm x20cm post f:M6	2	MG[3]	07 RMS 006	MG
7	Steel paper clip	6	Any	N/A	Any
8,9	Post holder + lock	2	EO	NT58-972	EO
10	Bottom bar (custom made)	1	N/A	N/A	N/A
11	8mm x4cm post f:M4	4	MG	07 RMU 005	MG
12	M4 socket head cup screw	2	Any	NT56-384	EO

1. B&H Photo video. http://wwww.bhphotovideo.com
2. Edmund Optics. http://www.edmundoptics.com
3. Melles Griot. http://www.mellesgriot.com

Table 3: Focusing stage component list

#	Description	Qty	Made by	Part# (mfr/store)	Buy at
3	Manual 250mm stage	1	EO	NT56-796	EO
-	Motorized stage (optional)	1	ZR[1]	KT-LSR300A[2]	ZR
-	M:M6 to M:M4 thread adapter[3]	1	TL	AP6M4M	TL

1. Zaber Technologies http://www.zaber.com/
2. KT-LSR300B with faster (less fine) lead-screw can also be considered.
3. Only required for the motorized stage.

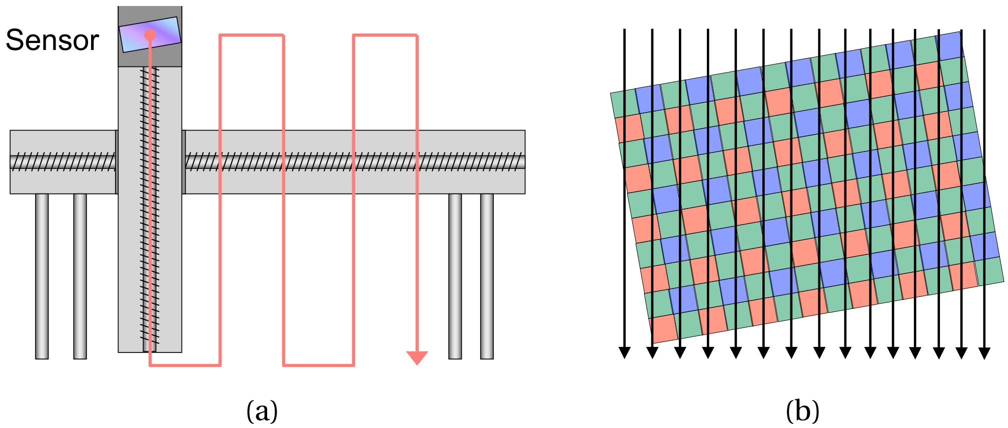


Figure 10: Image plane stage scanning. (a) the ZigZag motion minimizes the moving mass. (b) Rotating the sensor slightly about the optical axis (optional) allows scanning though all color channels.

4.2.4 The image plane stages

The image plane stages are responsible for moving the sensor. They need to be very accurately aligned so the image place will be perpendicular to the optical axis, and they must allow fast and accurate motion of the sensor and be able to hold the sensor stable when at rest. As with the rest of the frame we used optical table components to build the image plane setup. The components are listed in Table 4, and the back stage is shown in Figure 7. The arrangement of the stages and scanning order are shown in Figure 10(a). Note that this arrangement minimizes the torque on the stages and the moving mass as the vertical stage needs to move only the square root of the number of sensor positions (to prevent motion blur and allow multiple image capture at the same location, the sensor scans the image plane step by step and not continually). Rotating the sensor slightly about the optical axis allows scanning though all color channels thus eliminating the need for demosaicing. This step is optional and is not usually needed if the sensor slightly over-samples the optical image and a good demosaicing algorithm is used.

4.3 The main lens

The consideration when selecting a lens has been discussed at the beginning of this document. This section discusses a few specific lenses that can be considered either as a sole lens or as part of a set. This section should be considered as a guideline. In particular if constructing a smaller, more modest camera using this guidelines, many more lenses become available. In this section we only describe lenses from Schneider Optics, however, other manufacturers such as Rodenstock, should also be considered when selecting a lens.

At the time of writing digital lenses have a relatively small image circle, the largest being 120mm. This, however may change if manufacturers will more attention to scanning back cameras. Digital lenses are naturally better suited for digital sensors than film lenses are, they have better resolution (60-80 lp/mm at 40% MTF) and focus all color channels at the same plane. Should a truly large format (300mm or larger) digital lens appear in the market it should definitely be considered among the first choices. Note, however, that a very high spatial resolution on a smaller area means more compact (and convenient camera) but a nosier one.

4.4 Schneider Optics Apo Symmar L 480/8.4

This is the lens we choose to use in our camera. It is a large (105mm filter size) and heavy lens (1.850Kg). It has 6 optical elements arranged in 4 groups and has an image circle at infinity - 500 mm @ f22, FOV of 56^o. The large image circle ensures coverage at all locations of our translation stages, and usually the camera will not use the far edge of the image circle, which is an advantage.

This lens is not the sharpest (in terms of angular resolution) lens in this set, however it is well balanced and being optimized to work at f22, it provides a relatively large depth of field. Figure 11 shows the MTF of this lens at difference focal places (corresponding to magnification factor (reciprocal - 1/B') of ∞, -10, -5 respectively).

Relative illumination, transmittance and distortion are also shown. We can see that light fall off is fairly monotonic and that the distortion is low.

4.5 Schneider Optics Super-Symmar XL 210/5.6

This lens belongs to a new line of aspheric photographic lenses. It also consists of 6 elements in 4 groups and also has an image circle of 500mm @ f22. However its field of view is double of the Apo Symmar 480/8.4 and is capable of wider aperture when

Table 4: Back stages component list

#	Description	Qty	Made by	Part# (mfr/store)	Buy at
9	Motorized stage 300mm	1	ZR	KT-LSR300D	ZR
8	Motorized stage 450mm	1	ZR	KT-LSR450D	ZR
10	90 bracket, metric	2	ZR	AB90-M	ZR
11	20cm x 12mm M6 post	6	MG	07 RMS 006	MG
12	M6 socket head cup screw	6	Any	NT56-384	EO

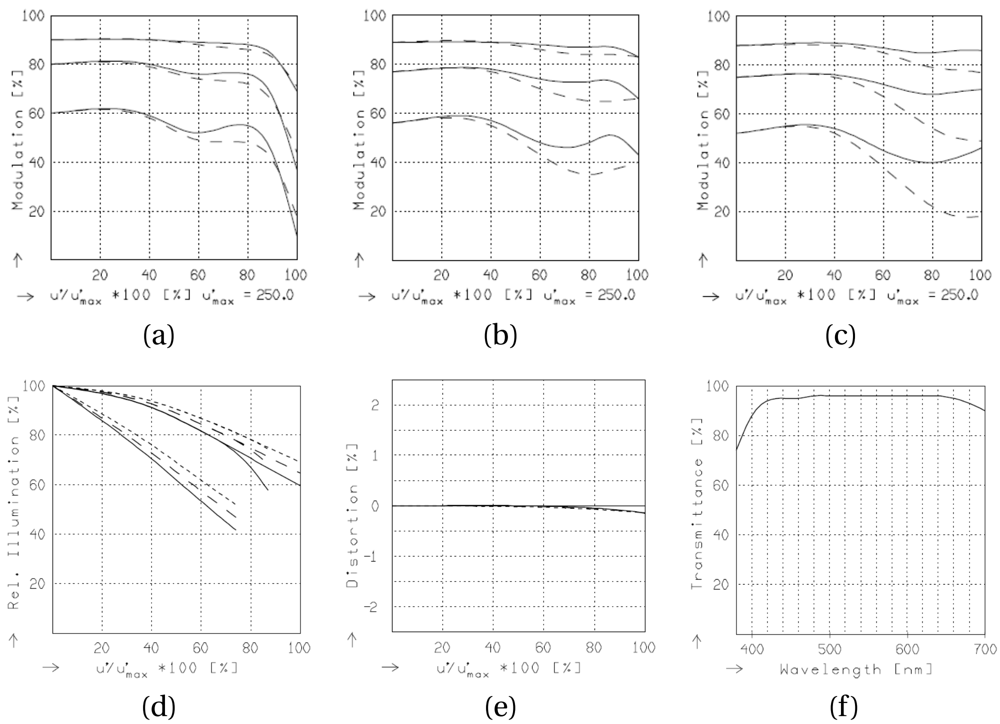


Figure 11: MTF of the Schneider 480/8.4 @ f22 and focal distance (OO') at ∞ (a), 5.6m (b) and 3.3m (c). Spatial frequency is 5,10,20 lp/mm, solid lines are for radial orientation and dashed lines for tangential. (d),(e),(f) show the relative illumination, distortion and transmission of the lens. Note that our camera operates at 0.6 (vertical) 0.9 (horizontal) of the image circle size. Source: manufacturer web-site. Unaltered, faithful to original.

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needed. The MTF of the lens is shown in Figure 12 for f22 and the same magnification factor. Note the difference between the tangential and radial lines and the distortion. *This does not mean that there will be noticeable visual degradation for the human observer*, however, in absolute terms the performance degrades at tangential orientation.

4.6 Schneider Optics Apo-Tele-xenar 12/800

This is a 35^o telephoto lens. It also consists of 5 elements in 2 groups and also has an image circle of 500mm @ f22. The MTF of the lens is shown in Figure 13 for f22 and (reciprocal - 1/B') of ∞, -20, -10 respectively. Note the difference between the tangential and radial lines and the distortion.

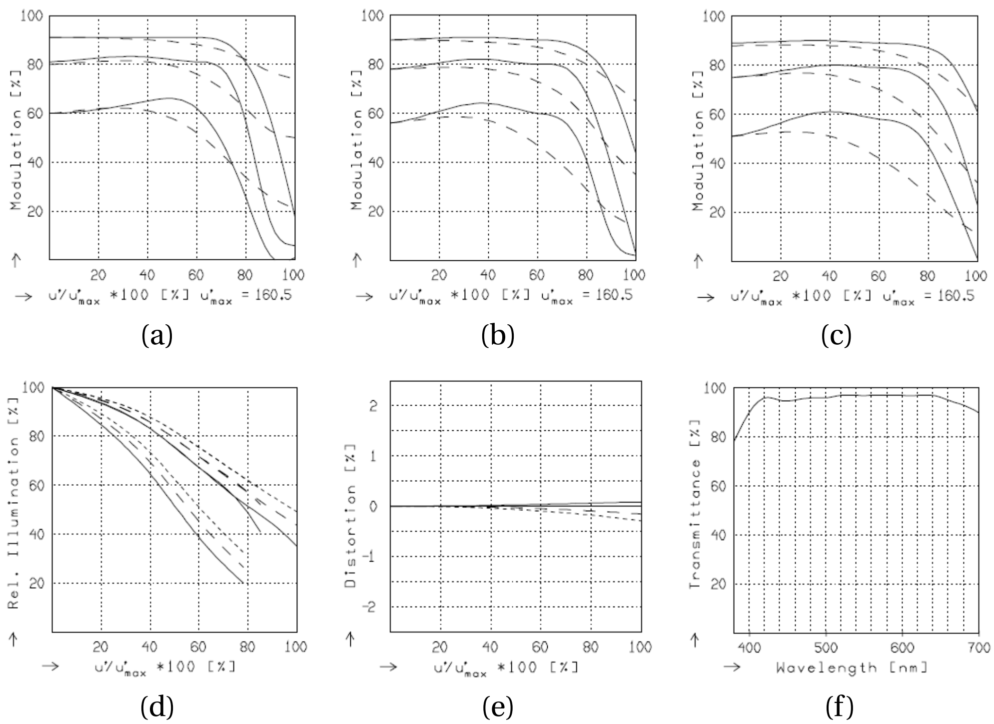


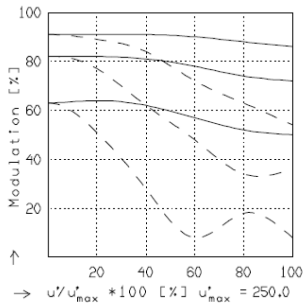
Figure 12: MTF of the Schneider 210/5.6 @ f22 and focal distance (OO') at ∞ (a), 2.5m (b) and 1.5m (c). Spatial frequency is 5,10,20 lp/mm, solid lines are for radial orientation and dashed lines for tangential. (d),(e),(f) show the relative illumination, distortion and transmission of the lens. Note that our camera operates at 0.6 (vertical) 0.9 (horizontal) of the image circle size. Source: manufacturer web-site. Unaltered, faithful to original.

4.7 Schneider Optics Macro-Symmar HM 180/5.6

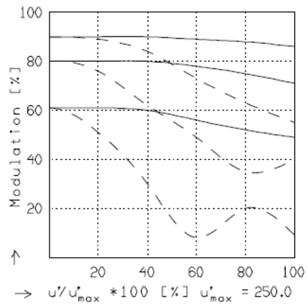
Note: this lens requires a different lens board than the previous ones. Also note that a macro (only) lens does not have an ∞ focus setting.

When working with macrolenses, having a long focal length is preferred. These lenses provide magnification a ratio between 1:2 to 2:1 or even 1:4 to 4:1, which is a very significant range of magnification factor that can produce extremely fine details. This lens consists of 8 elements in 2 groups, and its image circle is less than the previous lenses "only" 375mm are covered. Moreover, only 80% of the image circle @f16 are recommended for use. This lens will therefore cover the full height of our camera image (300mm) but only $\frac{2}{3}$ of the maximal width.

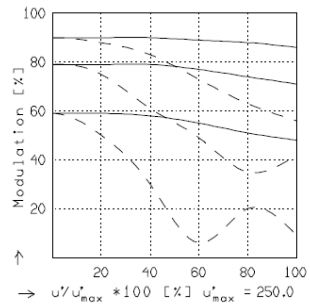
4.8 The main sensor



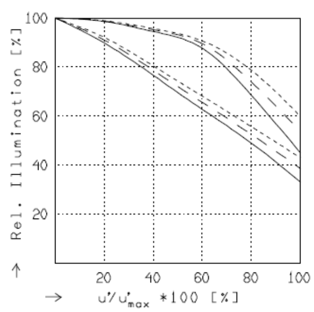
(a)



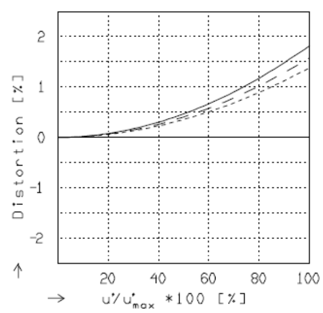
(b)



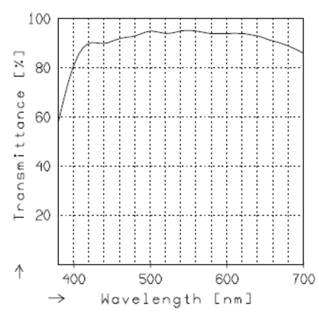
(c)



(d)



(e)



(f)

Figure 13: MTF of the Schneider 800/12 @ f22 and focal distance (OO') at ∞ (a), 17.3m (b) and 9.5m (c). Spatial frequency is 5,10,20 lp/mm, solid lines are for radial orientation and dashed lines for tangential. (d),(e),(f) show the relative illumination, distortion and transmission of the lens. Note that our camera operates at 0.6 (vertical) 0.9 (horizontal) of the image circle size. Source: manufacturer web-site. Unaltered, faithful to original.

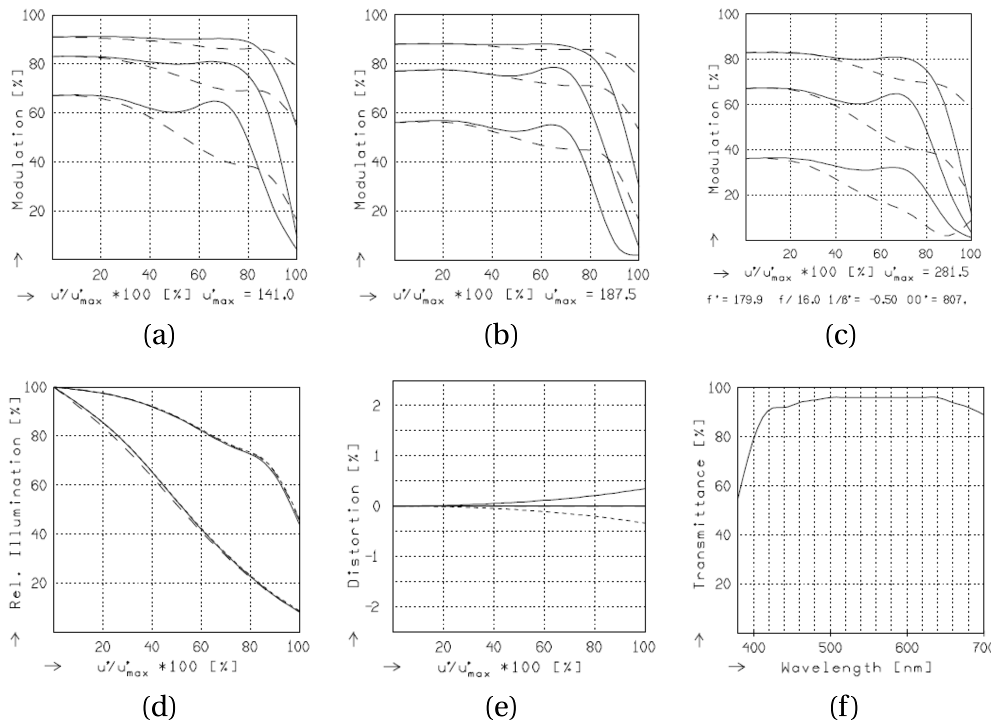


Figure 14: MTF of the Schneider macro 180/5.6 @ f15 and magnification factor (1/B') -2 (a), -1 (b), -0.5 (c). Spatial frequency is 5,10,20 lp/mm, solid lines are for radial orientation and dashed line for tangential. (d),(e),(f) show the relative illumination, distortion and transmission of the lens. Source: manufacturer web-site. Unaltered, faithful to original.

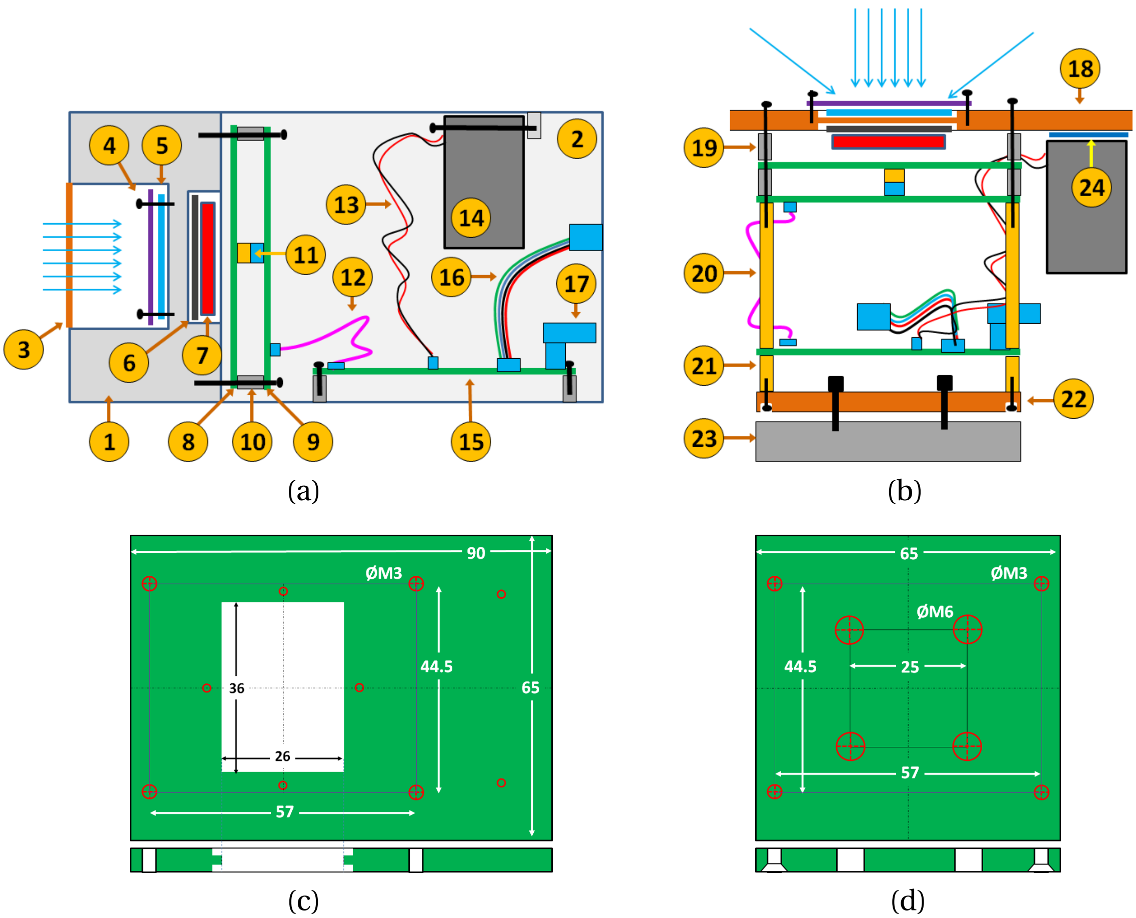


Figure 15: **(a)** The Lumenera enclosure is made of two main blocks, the sensor part (1) and the electronic part (2). The sensor part is a solid aluminium component that has the lens adapter (3) attached on one side and the sensor (7) and sensor electronics (8,9) attached to the other side. The CCD (7) is sealed by a rubber ring (6) in one side and an optical window (5) at the front. The optical window is attached using a thin frame (4). The two electronic cards (8,9) are connected by a thin bar (11) connecter in the middle, and aluminium spacers (10) are placed at the corners where 4 screws secure the whole setup to the aluminium block. The electronic part (2) is a thin aluminium box containing the USB connector (17), power connector (not shown) and Digital I/O connector (16), all connected to a single board (15). This board is connected to the sensor electronic board by a flat cable (12). A fan (14) is also attached to this part and gets its power from the electric board by a short wire (13). A felt layer (24) is added to damp any vibrations from the fan. **(b)** The sensor setup. A Top plastic plate (18) replaces the bulky aluminium part. The plate is thinned at the window getting the CCD closer to the optical window, allowing a much wider field of view. Spacers (19) connect the top plate to the sensor electronic boards. Thin Steel posts (20,21) firmly connect the electronic boards to each other and to the bottom plate (22). The bottom plate is attached to the vertical translation stage (23) using 4 M6 screws. **(b),(c)** Top and bottom plates respectively.

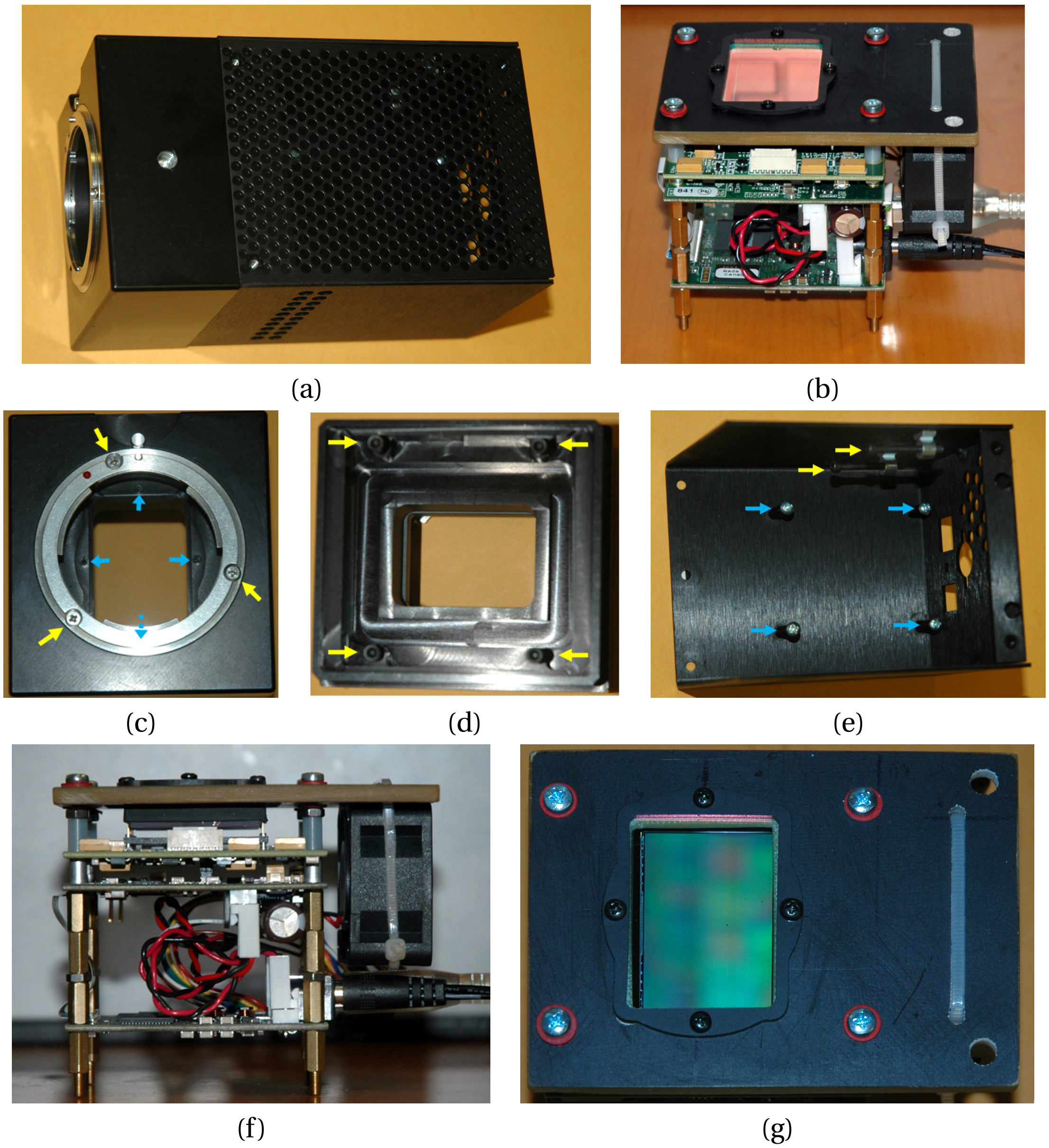


Figure 16: **(a)** Original camera enclosure. **(b)** Modified setup overview. **(c,d,e)** Open enclosure, arrows show screws locations. **(f,g)** Modified setup side and top view. Note images show temporary posts (20,21 in previous figure).

As mentioned above, we selected an interline CCD without microlenses. We have chosen a camera from Lumenera Corp. that provides a flexible SDK and a comfortable

USB-2 interface. The Lumenera camera arrives in its original enclosure shown in Figure 16(a). This enclosure is too large, too heavy, and and does not allow light to reach the CCD at an angle. It therefore cannot be used as is, and needs to be modified to the form shown in Figure 16(b). This section describes how. This procedure will void the warrantee and may damage the camera - proceed with extra care. Double check for changes and/or omissions.

It is recommended to use gloves and a static discharge wrist cable and work on a clean soft pad to protect the optical surface and electronics when handling the camera.

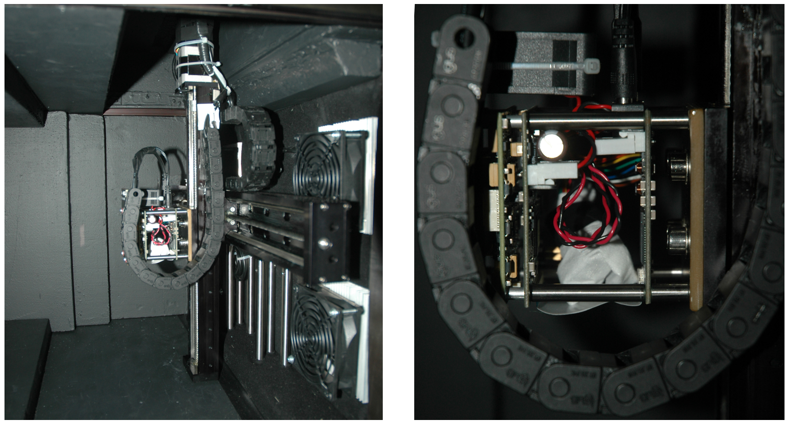
A schematic view of the enclosed camera is shown in Figure 15(a). First open the cover of the camera an loosen the I/O connector (16). The two part enclosure will slide open but will still be connected by the flat cable (12) and power connector (not shown in the diagram). Loosen the power connector to the Fan, and the screws that hold the electronic board (15) and part (2) should be separated with the Fan still attached to it. Release the screws that hold the sensor boards (8,9) to part (1) of the enclosure and carefully separate the sensor boards, the sensor and the sensor rubber ring from part (1). Although the sensor is protected by a cover glass, take extra care to not touch, scratch or harm the sensor surface in any way.

At this point you should have the all electronic parts of the camera, including the CCD, completely separated from the enclosure. Release the fan from part (2) of the enclosure. To release the optical window (5) and holding ring (4) the lens adopter (3) must be released first.

Now the camera parts need to be reassembled as shown in Figure 15(b). First attach the shot posts (21) to the bottom plate (22); attach the bottom plate to the translation stage (23). Separately attach the optical window to the top plate. Then attach the sensor and the electronic boards using the long posts (20). Keep the top screws loose so you can attach the long post to the short one (that is already attached to the translation stage). Finally tighten the top screws. *when attaching the sensor, carefully clean all surfaces to prevent dust from being trapped between the sensor and the optical window.*

4.9 Translation stage and camera wiring

The translation stages are all daisy-chained. The horizontal and the focusing stages receive external power, whereas the (moving) vertical stage receives power through the daisy chain. Therefore only three wires need to be routed inside the enclosure - the camera power cable, the camera USB cable and the vertical stage daisy-chain cable. To prevent the wires from being entangled with the moving stages - which damage the camera, the cables are routed using two flexible wire guides. One connects the two stages, and one connect the vertical stage to the sensor as shown in Figure 17.



(a) (b)

Figure 17: **(a)** Power and USB wires to the camera are guided via wire guides. **(a)** Closeup at the sensor. The wire guide is attached to the edge of the top plate. Note: Final steel posts (20,21) and connection to the translation stage (23) are shown in this image.

4.10 Camera enclosure

The primary function of the enclosure is to provide a light tight environment - the “Camera obscura”. The enclosure also protects the sensor and sensor side of the lens, and depending on the cooling methods provides either insulation of heat dispersion. In this section we describe the enclosure used in our camera.

Table 5: Main sensor components

#	Description	Qty	Made by	Part# (mfr/store)	Buy at
-	10.7MP CCD USB camera[1]	1	LU[2]	Lw1105xC	PT
-	13 x 6mm posts	4	TL	MS05R/M	TL
-	38 x 6mm posts	4	TL	MS1.5R/M	TL
-	Plastic top plate	1	-	custom made	
-	Plastic bottom plate	1	-	custom made	
-	Flexible Wire guide	1	-	07.20.018	see comment 3

1. Order Color sensor, **without microlenses, with cover glass**.

2. http://www.lumenera.com/

3. The flexible wire guide shown in the pictures is IGUS 07.20.018 (approx. 15mm x 25mm chain) bought from Thorlabs. This part is no longer available from Thorslabs at time of writing, however this or similar chain can be obtained form http://cableorganizer.com/ or directly from Igus http://www.igus.com/.

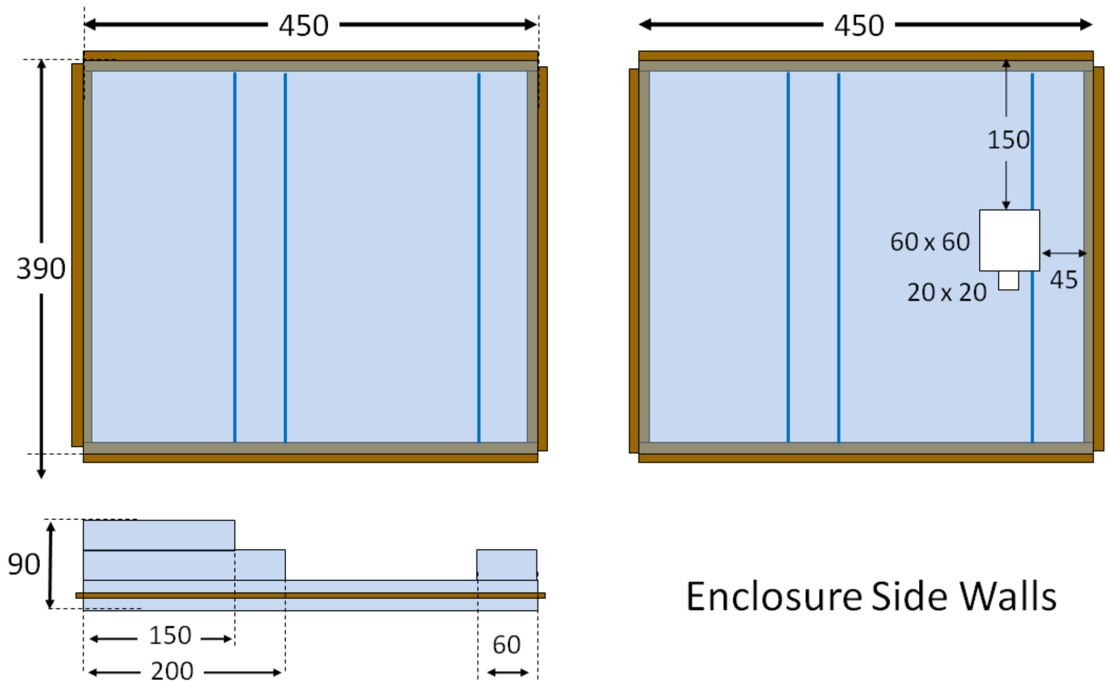


Figure 18: The enclosure walls are made of 3cm thick Styrofoam plates (blue). The brown bars are wooden bars that are inserted into the Styrofoam and later slide into the rails of the aluminium frames. The hole on the right is for the head of the horizontal stage that is kept outside the enclosure.

4.10.1 Enclosure walls

Since we use active cooling, the enclosure walls should provide good thermal insulation. Using standard enclosure material as the hardboard supplied by Thorlabs will *not* provide sufficient thermal insolation. By far the best thermal insulation will be provided by walls with vacuum cambers, but these can only be made by special order and in large quantities. If you are considering such a solution, a good place to start is to check ThermoCor (http://acutemp.com/highPerformanceInsulation/thermoCor.asp).

The second best option is using aerogel, also known as "blue smoke" (http://en.wikipedia.org/wiki/Aerogel). Aerogel is a manufactured solid material having the lowest density known. However, blocks or plates of aerogel are *extremely* expensive. A much more affordable option is to use granulated aerogel or aerogel wrap. which is granulated aerogel embedded in fabric. The granulated aerogel can be placed between double hardboard walls to create a light-tight thermal insulating wall.

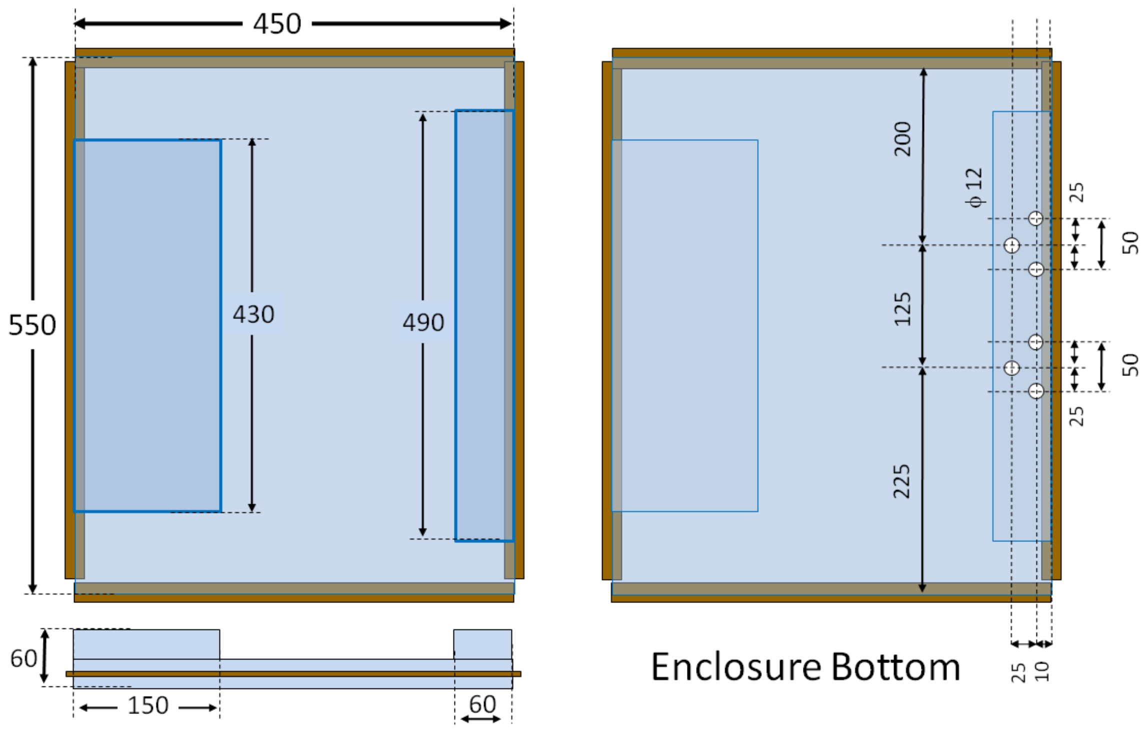


Figure 19: The enclosure bottom, or floor, is made similarly to the sides. The 6 holes in the right figure are for the steel posts that hold the horizontal translation stage.

In our camera we have used granulated aerogel from Cabot, known as Nanogel^{TM} (http://www.cabot-corp.com/aerogel) in the critical insulation of the thermoelectric cooling (see below). For the walls of the camera we have used Styrofoam or extruded-polystyrene which are the blue (usually) foam blocks used in construction and by hobbyists. The material is light weight, relatively strong, and has low thermal conductivity ($0.033 \frac{W}{m \cdot K}$). Note that extruded-polystyrene is not opaque and needs to be coated and painted. Simple *water based* putty and matt black paint will do fine (also use water based glue).

4.10.2 Camera bellows

A standard camera bellows will not fit the required size. We therefore need a custom made bellows. Our camera bellows was ordered from Gortite (http://www.gortite.com/). We used a Neoprene/Nylon folded bellows. Figure 23 provides information needed when ordering such a bellows.

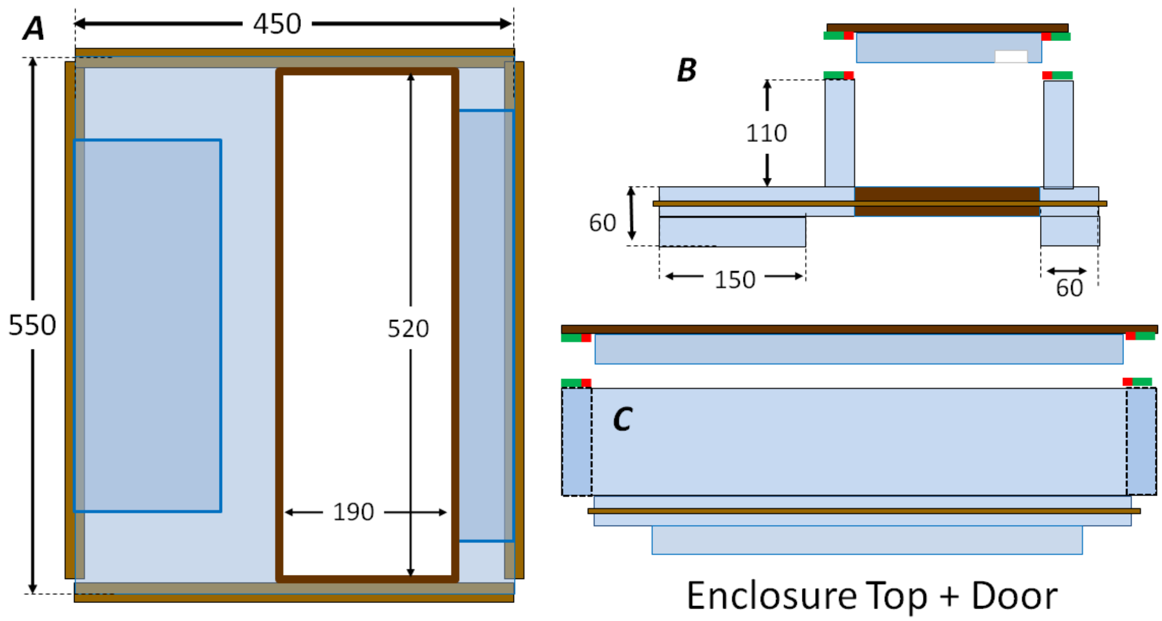


Figure 20: The top wall of the enclosure includes a box that provides a moving space for the vertical stage as well as access to the stages and sensor from the top through the door shown on the right. The green and red bars are a felt and magnet/metal pair respectively used to seal the door.

Bellows assembly

The wide side of the bellows is attached to the frame by simply sliding it into the rail (like all walls). The narrow side is attached to the lens board using steel clips as shown in Figure 23. Depending on the lens used and the narrow side width, it may be cecessary to unscrew the two parts of the lens to inset the lens into the narrow side of the bellows. A better option is to attach the bellows to the lens holder (instead of the lens board).

4.10.3 Insulation

The main insulation is provided by the Styrofoam walls. However, the bellow cannot be insulated by Styrofoam since it needs to be flexible. A good solution would be to place an optical window inside the enclosure as shown in figure 24. Ideally the optical window would be anti reflection coated optical grade plastic (s.a. CR39) that has good thermal properties. Unfortunately, we could not find such a window. Instead we recommend to insulate the bellow by using several layers of fleece and mylar that provide thermal insolation as well as the flexibility required by the bellow.

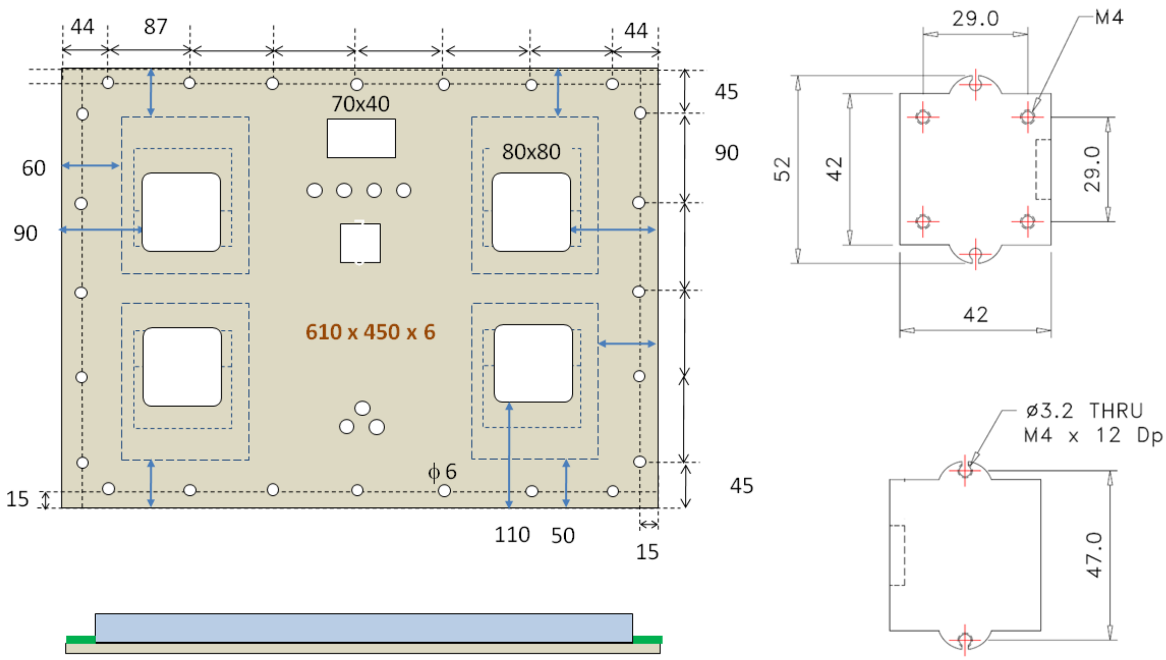


Figure 21: The back wall of the enclosure is made out of wood to support the cooling assembly. Unlike the other walls, it does not slide onto the rails but is attached to the frames using M6 screws and spring nuts that are inserted into the rails. The back includes four 8x8 cm openings for the spacer blocks of the cooling assembly (shown on the right), as well as openings for the (middle, top to bottom) temperature controller display, cooling assembly on/off switches, ventilation opening for the controller, and power input for 15V, 12V and COM. A 3cm Styrofoam (blue) and rubber seal (green) are used to seal and insolate the back.

4.11 Cooling

As mentioned earlier, we selected thermoelectric active cooling for the camera. Keeping a regulated temperature not only reduces the thermal noise but mainly allows better photometric calibration (using dark current images). Since we would like to operate our camera at relatively low light conditions (as in museums if strong light is not allowed) that require long exposures - this is important. It becomes even more important if cross polarization is used which further reduces the amount of available light.

4.11.1 How much cooling power is needed?

Although thermoelectric devices (TECs) can achieve impressive temperature differences ($\Delta T = 65^o - 70^o$ for a single stage device), their efficiency of heat is quite low and

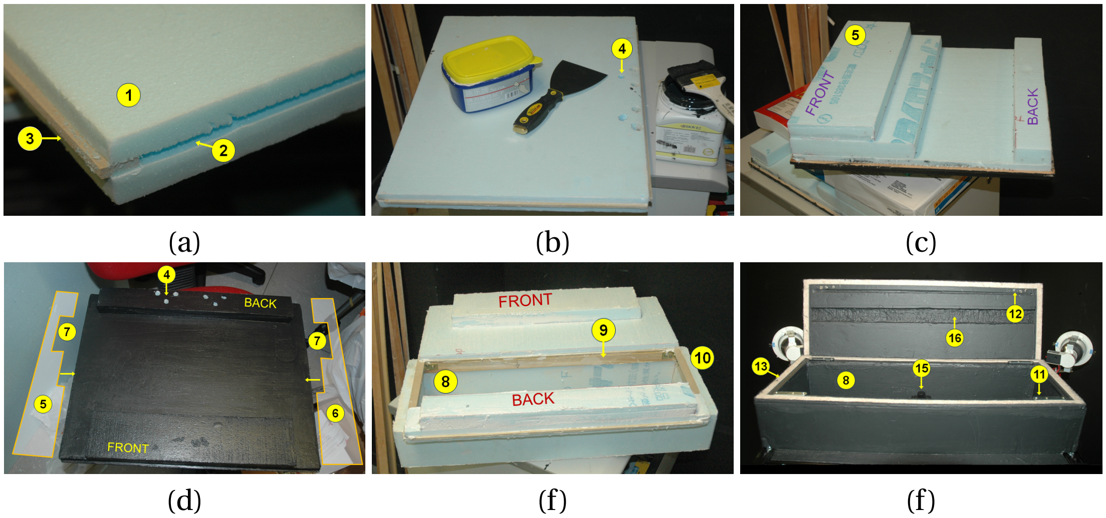


Figure 22: Enclosure walls. **(a)** The enclosure walls are made of styrofoam plate (1). A narrow groove (2) is cut using a router at the side of the plate and a wooden bar (3) is placed inside the groove. This bar will later slide into the slit of the aluminium frame to securely hold the wall. **(b)** The wall needs to be coated with base (putty) and matt black *water based* color. The image shows the bottom wall, The steel posts that hold the translation stages go though the holes (4). **(c)** Additional layers (5) of styrofoam are added, where possible. The image shows the side wall. **(d)** The complete bottom wall. The side walls (5,6) are placed at the sides of the bottom wall. The narrow part (7) is the location of the translation stages and the image plane. **(e)** The top wall (viewed from below). The hole (8) is for the vertical stage controller, and provides access to the sensor from the top. A wooden frame (9) support the structure, and the side walls (10) are placed *on* the side aluminium frame. **(f)** Top wall, view from above and the door. The door is held by small magnets (12) and metal plate (11). The door is a wood plate with styrofoam attached to it for insulation. A felt layer (13) is used to seal the door. A groove (16) in the styrofoam allows horizontal movement of the vertical translation stage (15).

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their efficiency is usually not more than 10%, which is much less than the conventional compression cycle used in refrigerators.

At equilibrium state the thermal load should equal the heat transfer capability of all TECs used. A rough estimate can be obtained by the following equation:

$$n\, P_T\, e_T = Q_a + \frac{k\, A\, \Delta\, T}{L}. \tag{1}$$

The left hand side is the heat transfer capability consisting of: n, the number of TEC units used; P_T, the power of the TEC unit in Watt; e_T, the efficiency of the TEC unit, typically $(0.05 \ldots 0.1)$. The righthand side is a simple thermal load estimate consisting of: Q_a, active heat in Watts dissipating from the electronic/electromecanic compo-

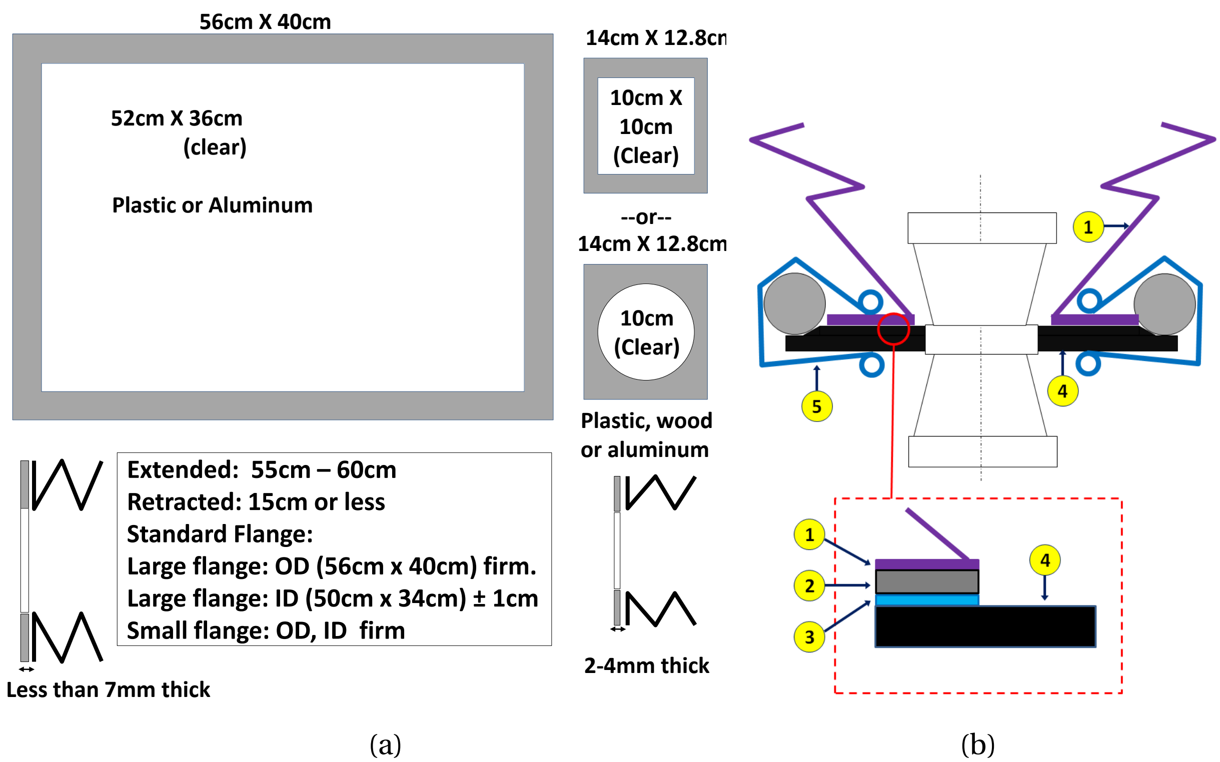

Figure 23: Bellows. **(a)** Bellows and flange information. **(b)** The bellows (1) is attached to the flange (2) which is attache to the lens-board (4) by steel clips (5). A layer of felt (3) is placed between the flange and the lens-board.

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nent inside the enclosure. In our case the main sensor, the vertical translation stage and the cool-side fans. To Q_a we need to add the ambient heat that enters the enclosure through the insulation layer. The constant k is the thermal conductivity of the insulation (0.033 for Styrofoam) ΔT is the temperature difference and L is the thickness of the insulation layer. Convection and radiation were excluded from this simple description. A more complete design (as well as TEC components) can be found at: http://www.marlow.com/.

4.11.2 The thermoelectric cooling assembly

Our thermoelectric assembly is show in figure 25. The figure shows the assembly schematics as well as images of our camera back that contains four such assemblies.

The components needed for this assembly are listed in table 6, the numbers refer to the tags in the figure. The cooling assembly is powered by two 300W 15V power supply

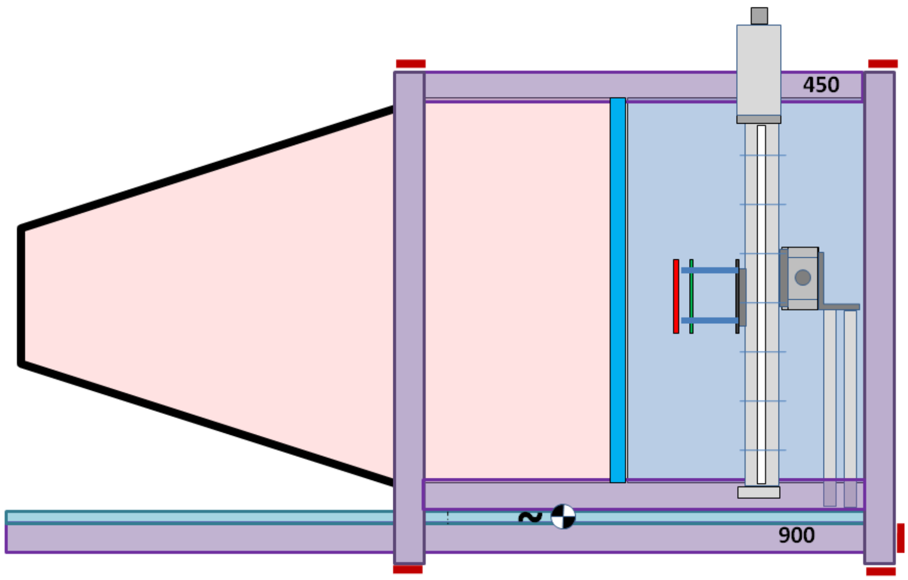

Figure 24: Optical window (blue) reduces the volume to be cooled and can significantly increase the cooling efficiency. **Not yet implemented**

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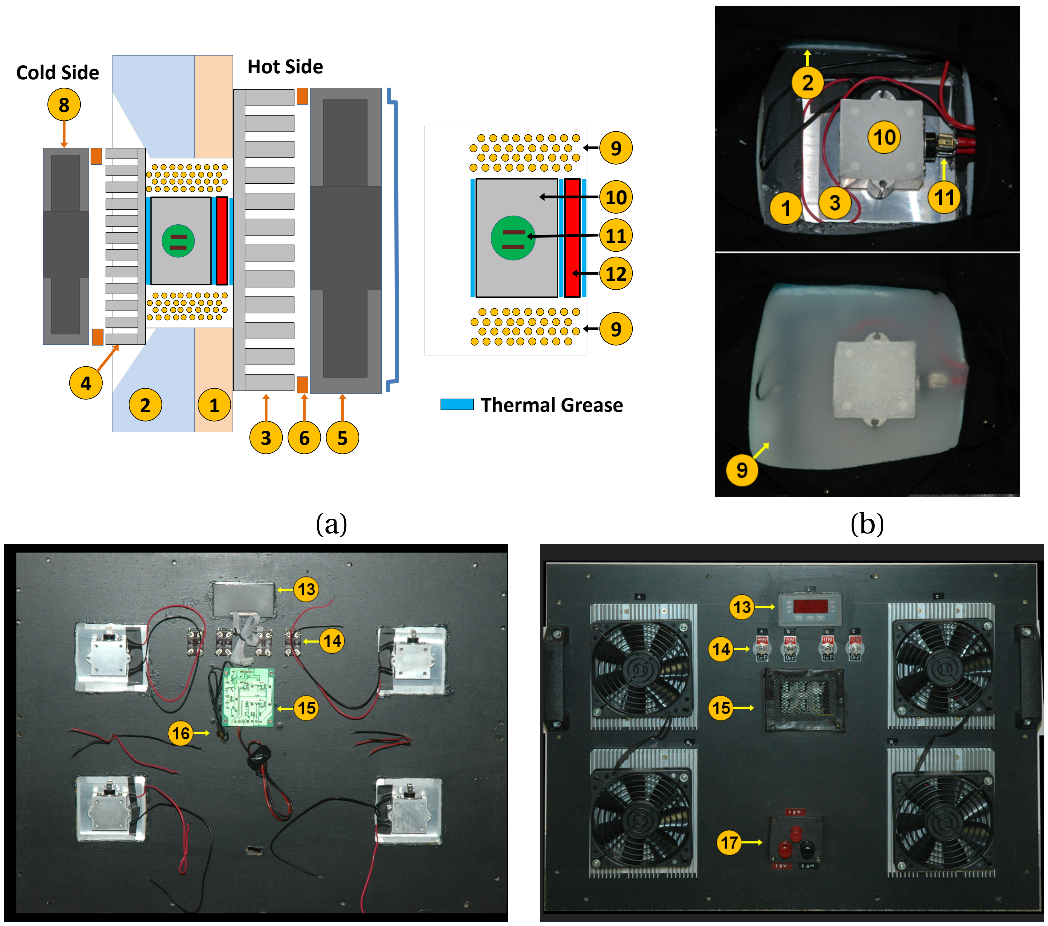
units and two 150W 12V power supply units. The 15V supply powers three of the four TEC devices directly whereas the 12V powers the forth TEC that is attached to the controller and can be used to regulate the temperature. The 12V supply also powers the fans. We used two units instead of a more powerful single unit to provide some redundancy in case one power supply fails. *Thermoelectric cooling works with low voltage but high current, make sure to use wires that are thick enough for the current used. Consult an AWG (American wire gauge) guide to find the proper size.*.

Water condensation

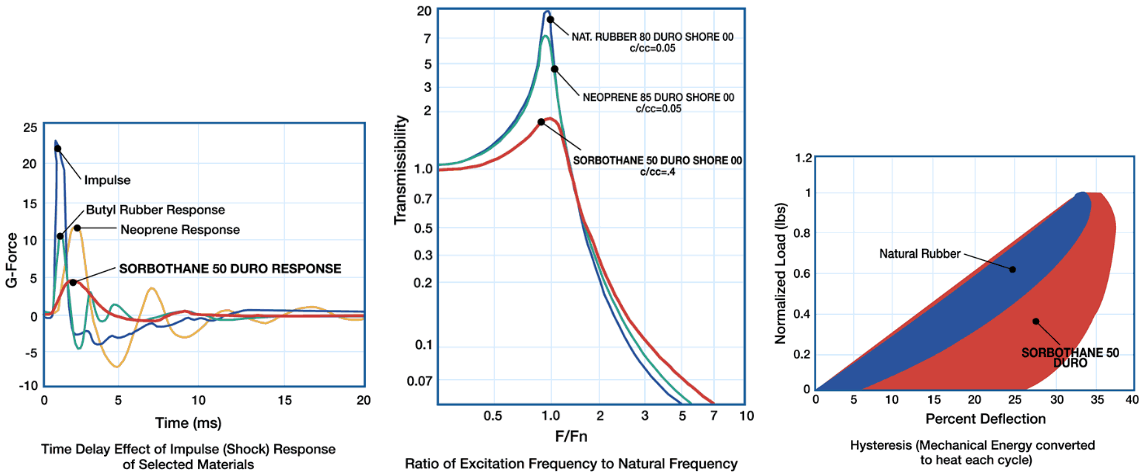
When cooling a camera, water condensation is a significant concern. Water condensation on the sensor or lens can significantly distort the capture image. Additionally water condensation or dripping on the sensor can damage it. This is the main reason for placing the cooling assembly at the back. The lens is located as far as possible from the cooling assembly and thus kept relatively warm. The sensor is kept above the ambient temperature by its own generated heat, and finally any water condensation on the cold heat sink can drip to the bottom of the camera where it is absorbed by a cloth placed there for this purpose. In extreme cases, the cooling unit can be placed outside the enclosure (which will reduce its efficiency), alternatively a water duct, or super-absorbent polymers (as these used in baby diapers) can handle a significant amount water condensation. We have not faced such conditions.



(a) (b)

(c) (d)

Figure 25: Thermoelectric assembly: **(a)** The thermoelectric assembly transfers heat from the cold side (camera) to the hot side (room). Air is forced into the cold heat sink (4) by the cold side fan (8). The heat is conducted by the aluminium spacer (10) to the cold side of the TEC device (12). The TEC device actively transfers the heat to the hot heat sink (3), where it is dissipated by by air from the hot side fan (5). Both fans are mounted on the heat sinks using rubber washers to reduce vibrations. The assembly is mounted to the back wall of the camera that consists of a wooden plate (1) for rigidity and thermal isolating Styrofoam (2). Granulated aerogel (9) are used to insulate the critical area TEC and spacer. A safety switch (11) will cut the power off at 85^o to protect the TEC device. **(b)** View from the cold side showing the spacer, wood and Styrofoam (covered with black cloth), the hot sink and the safety switch. The translucent granulated aerogel is shown in the bottom image. **(c)** The cool side during assembly, (15) is the TEC controller, (13) is its display and (16) is a thermometer. The switches (14) control each TEC assembly. **(d)** The hot side, showing also the power connectors (17).



(a) (b) (c)

Figure 26: Sorbothane properties. **(a)** Response to shock **(b)** Vibration isolation **(c)** Energy dispersion.

4.12 Camera Pier and vibration suspension

The camera will not fit on a conventional camera tripod. Instead we use a telescope pier to mount the camera on. The telescope pier is rigid and it allows for moving the camera on wheels, securing the camera to a fixed location, and adjusting its height.

Table 6: Thermoelectric cooling component list

#	Description	Qty	Made by	Part# (mfr/store)	Buy at
12	TEC Module, 40 mm single-stage	4	-	TEC1-12708	PS[1]
-	Thermal interface film	8	-	TI-1010	PS
8	Fan, brushless, 80 mm 12 VDC	4	-	DCF80	PS
5	Fan, brushless, 120 mm 12 VDC,	4	-	DCF120	PS
15	Controller	1	-	SDC-45	PS
4	aluminium heat sink, small	4	-	HS-S	PS
3	aluminium heat sink, large	4	-	HS-L	PS
10	aluminium spacer block	4	-	SB42-24	PS
11	85 degree C cutoff switch	4	-	CO-85	PS
9	Granulated Aerogel (Nanogel)	1L	Cabot		CB[2]

1. Pacific Supercool http://http://www.pacificsupercool.com//
2. Cabot Corp. http://www.cabot-corp.com/

There is no tilt axis and usually none is required[5]. Figure 27 shows the camera on its pier.

However, holding the camera firm is not sufficient as it will be subject to vibrations either from the floor (for example a person walking or a car passing nearby will cause noticeable vibrations) as well as vibration caused by the camera's mechanical parts. It is therefore important to isolate the camera from vibrations and to dampen existing vibrations.

We used Sorbothane bumpers for vibration isolation and damping. Sorbothane is a visco-elastic polymer used, among other things, to protect the space shuttle camera during takeoff. Figure 6 shows the vibration isolation setup. The Sorbothane bumpers (14) are placed between two aluminium plates (14), one is firmly attached to the camera base (8) and the other is firmly attached to the pier (13). Safety screws with rubber spacer (16,17) allow relative motion of the aluminium plates while keeping them safely attached to each other. Figure 26 shows the physical characteristics of Sorbuthane. We can see that it is nearly non oscillating after the initial shock and that its vibration isolation and energy dispersion is much better than these of rubber. These characteristics are important for capturing speed as the camera stabilizes very fast (within a second) after the movement of the translation stages.

Note that the aluminium plates are relatively wide, this is minimizing camera tilt resulting from the shifting of the center of gravity due to motion of the translation stages.

Also note that wind is a problem - Wind and turbulence apply a continuous varying force directly to the camera body, bypassing the vibration isolation mechanism. The Sorbuthane can damp the vibrations caused by wind but it cannot cancel them.

Table 7 shows the components of the pier and vibration isolation setup. Numbers refer to the numbers in Figure 6.

5 Auxiliary Video Camera

The auxiliary video camera shown in Figure 5 (11) provides a continuous view of the scene. It is the view finder of the camera and is also used for other functions (not included in this document). In order not to load the USB bus (important when a laptop/small form factor computer is used), we use a IEEE-1394 (firewire) bus for the auxiliary camera. Our camera used a Dragonfly camera from PointGrey research as the auxiliary camera.

[5] if needed, a first surface mirror can be used to capture images at any direction

Figure 27: Camera pier and caddy: The camera is mounted on a telescope pier that allows for adjusting the height of the camera. A caddy allows the camera to move on wheels and firmly located using legs (that lift the wheels slightly off the ground).

The lens of the auxiliary camera should have a field of view that (slightly) exceeds this of the main camera. For a $1/3$" CCD format a $4mm$ lens will fit the Schneider lens used in our camera. However, if we intended to exchange lenses of the main camera (use Wide angle, Tele photo or macro lenses) it is recommended to use a varifocal lens. Suggested lenses appear in Table 8.

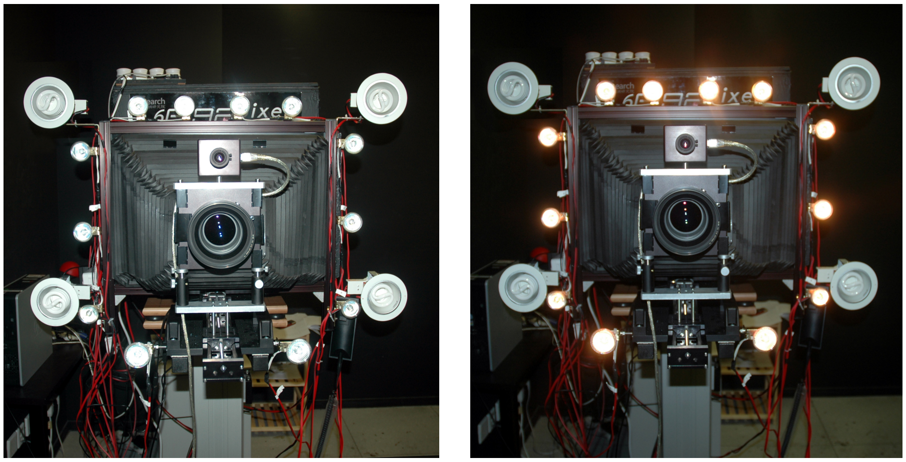
6 Illumination

The illumination in this section is in addition to any studio illumination. Flash illumination is intentionally not used since it may not be allowed in museums. We use two types of illumination, a static ring illumination and computer controlled directional il-

Table 7: Pier and vibration suspension

#	Description	Qty	Made by	Part# (mfr/store)	Buy at
13	Telescope pier-II	1	PT[1]	PT2-220/110[2]	PT
-	Pier caddy	1	PT	PC	PT
15	Sorbothane bumpers	4	-	NT35-264	EO
14	Aluminium plates	2	Any	-	Any
16	M10 screws (safety screws)	2	Any	-	Any
17	rubber spacer washer nut	2	Any	-	Any

1. http://www.pier-tech.com/
2. Select by Voltage



(a) (b)

Figure 28: Illumination. **(a)** The camera has a ring of dim-able halogen lights that provides spatial and spectral full balanced and four computer controlled lights (shown here with CFL used only for testing) used primarily for photometric stereo. **(b)** With ring light on (dimmed).

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lumination. The first is used to obtain accurate color information, whereas the second is used for computer vision tasks such as photometric stereo and multispectral imaging using wide band illumination.

Table 9 shows the illumination components used in our camera.

6.1 Ring illumination

The ring illumination shown in Figure 28 consists of 12 halogen lights arranged around the lens to reduce shadows. We use halogens with an integral UV filter and color temperate correcting filter (OSRAM Cool Blue, or regular halogen with Roscolux illumination correction filter). Thanks to the favorable spectral distribution these lights, a

Table 8: Auxilary video camera

#	Description	Qty	Made by	Part# (mfr/store)	Buy at
	Dragonfly camera	1	PG[1]		PG
	CS 4mm LENS	1	CR[2]	T0412FICS	CR
	CS varifocal[3] 3.5-10.5mm LENS	1	CR	T3Z3510CS	CR

1. Point grey research http://www.ptgrey.com/
2. Computar http://computarganz.com
3. Specific range should be set by the actual set main lenses used.

faithful and rich full color range can be obtained (after color calibration).

At full brightness these lights are bright enough to let the camera work at full frame rate fully compensating for the low fill fator of the sensor. Moreover, if needed these lights can be dimmed to any desired level. The cooled sensor and dark current calibration images allow for capturing images without exposure without significant noise.

6.2 Polarized Illumination

For some applications, in particular photometric stereo mentioned below, it is desirable to reduce specular reflection (highlights) as much as possible. To do this we use polarize the illumination as well as the incoming light. For the light polarization we use a linear polarizing filter, specially designed for illumination purposes (better temperature tolerance, lower cost, higher transmission (though less strict) than photographic filters). On the camera side we use a photographic circular polarizer (light polarization affects the response of a CCD at different incident angles, therefore it is essential to use a circular polarizer in the camera).

Notes:

Table 9: Illumination related components

#	Description	Qty	Made by	Part# (mfr/store)	Buy at
-	12V/50W Cool Blue halogen	12	OSRAM[1]	DECOSTAR 51 ALU	any
-	24W warm white CFL[8]	4	Philips	any	
-	Light polarizing filter[3]	4	RO[2]	073001720	Amazon, RO
-	Full Blue correction filter[4]	12	RO	#3202,3,4	Amazon, RO
-	Light diffusing filter[5]	16	RO	#111, #112	Amazon, RO
-	105mm Circular Polarizer[6]	1	B+W	65016142 / BWKCP105	BH[7]

1. http://www.osram.com/osram_com/Professionals/
2. http://www.rosco.com
3. This filter has better temperature resistance and and better light transmission that polarizers used for imaging and is better suited for polarizing illumination (however it is not as strict as an imaging filter and is not optically flat). Rosco filters come in sheets (different sizes) and should be cut to have the number of filters at the 'Qty' column.
4. Optional $3200K \rightarrow 5500K$ filter - if regular halogens are used. The OSRAM already has 5000K correction filter.
5. Optional filters with different densities are available (#111 being densest).
6. Circular is required for the sensor, Kaeseman is optional (better though).
7. http://www.bhphotovideo.com/
8. Compact Fluorescent Lamp

(a)

(b)

Figure 29: Cross polarization. **(a)** Aligned filter **(b)** Crossed filter. Highlights are highly polarized whereas the diffused reflection (of non metallic objects) is largely depolarized, this enables good suppression of highlights.

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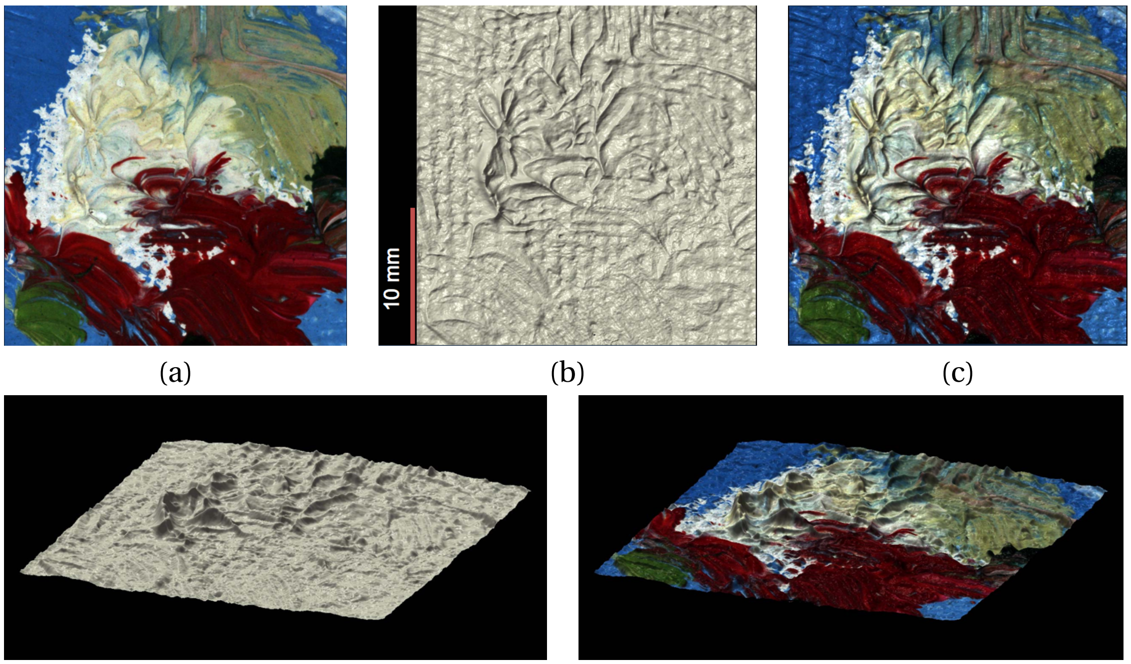
1. Avoid using a photographic polarizer for illumination as it will most definitely be ruined by heat generated by the lamp.
2. The performance of the systems is determined by its weakest part. Use high quality polarizer for the camera (we use B+W Kaeseman circular polarizer in our system).

6.3 Controlled illumination

Some functions such as photometric stereo require illumination that can be controlled by the capturing computer during image capture. Our camera has four directional lights shown in Figure 28. These lights are attached to the camera frame and are controlled by a USB relay. By using these lights we can apply photometric stereo to obtain fine 3D details as shown in Figure 30.

The lamps currently shown in the figure are compact fluorescent lamps (CFL). We use these because the can be turned on/off rather quickly (no cooling time is needed) and because they do not produce a lot of heat. **However, CFLs are not designed to work this way**, in fact, CFLs require a warmup time of up to few minutes to reach *full* brightness, and their working life time can be significantly shortened by rapid on/off cycles . Additionally, CFLs can produce UV light that is harmful to painting and other sensitive colors. We therefore replace the (convenient) CFL with (preferably daylight) incandescent bulbs when used for actual photography. Note that spectral distribution is not very important for some functions, such photometric stereo, that use grey scale images.



(a) (b) (c)

(d) (e)

Figure 30: Controlled illumination for photometric stereo. **(a)** A flat color image of small patch of oil painting **(b)** 3D Texture recovered by photometric stereo. **(c)** Texture mapping. **(d,e)** A different view of (b,c).

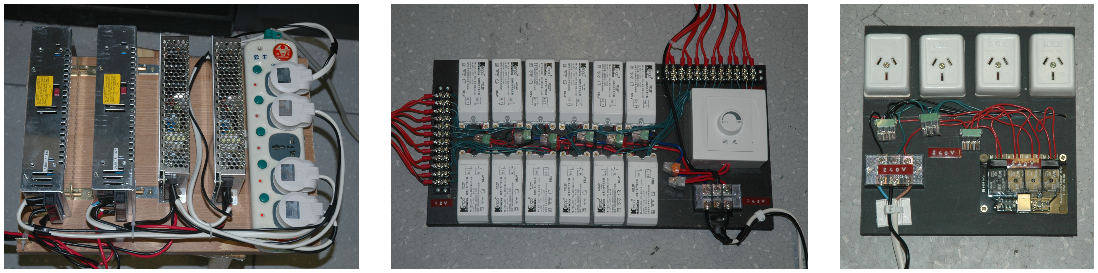
7 Miscellaneous

7.1 Light Controller

The light controller used in the this system is simply a USB controlled relay. We used a relay from (http://www.phidgets.com) Part (1014 - PhidgetInterfaceKit 0/0/4) however, many other USB relays are available over the web for example, (http://www.controlanything.com/Relay/Relay/USB_Devices) carry a large variety of USB relays. Figure 31 shows the (bare) light controller, the USB relay is located on the lower right corner.

7.2 Power Supply

The camera uses 12V DC supply for the camera, cooling fans, cooling controller and one of the four TEC that is directly controlled by the cooling controller. 15V DC supply is used by the translation stages, and three of the TEC units that are connected directly to the power.



(a) (b) (c)

Figure 31: Power Supply. **(a)** TEC cooling supply **(b)** Halogen Illumination supply. **(c)** Controlled Illumination relay.

The light controller as well as the auxiliary camera are fed via their computer connection (USB, Fire-Wire respectively).

The ring halogen illumination is fed with 12V AC power, and finally the camera pier, the four controlled illumination (currently fluorescent lights) and the controlling computer are fed with 240V AC grid power.

For increasing reliability the camera and translation stages are fed using separate power supplies. All grid power (including power to the AC and DC transformers) connected to the grid via surge protector.

Table 10 summarizes the various power source used.

Make sure all grid power parts as well is the camera is properly grounded for user protection and discharging possible static electricity.

Table 10: Power Supply

Nominal	**Powers**	**Qty**	**Comment**
12V-DC / 1A	Lumenera camera	1	Obtained from Camera manufacturer
12V-DC / 8A	Cooling Fans and TEC	2	Generic
15V-DC / 1A	Translation stages	2	Obtained from stages manufacturer
15V-DC / 15A	Cooling TEC	2	Generic
12V-AC / 1A	Halogen illumination	12	Compact, **dim-able** halogen transformers
240V-AC	Camera pier, illumination		
	Computer, etc.	N/A	Via surge protector

8 Summary

Congratulations!, you have just completed reading a detailed, technical document describing how to construct a digital large format camera. By now, it should be clear that there is much more than a lens and a sheet of film to such a camera (in fact there is much more than a lens and a sheet of film to an analog camera as well, yet a digital camera is considerably more complex). Design is in the details. This makes the difference between a camera that works in principle, and a camera that realy works.

Acknowledgments

The author thanks Hyeongwoo Kim[6] for generating the photometric results shown in Figure 30.

[6]While he worked in MSRA as a full time Intern.