Single-sensel image capture using an LCD panel

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Abstract

Compressed sensing allows reconstruction of complete image data from sparse sampling. In sequential single-sensel imaging, a spatial light modulator is used to select groups of pixel locations whose transmitted or reflected light is measured by a single detector. This function is commonly implemented using a digital micromirror device (DMD), but DMDs are relatively small and expensive. This work investigates the use of a transmissive liquid crystal display (LCD) panel as a lower-cost, larger-format alternative. The Kentucky LCD One Sensel (KLOS) prototype repurposes a consumer projector LCD and its control electronics, combining them with custom 3D-printed camera components, a projector lens, and a Fresnel lens. Preliminary testing demonstrates that both random and deterministic binary patterns can be used successfully, confirming the feasibility of the concept. However, serious practical limitations were observed, including sample-rate limitations imposed by HDMI control, synchronization lag, limited LCD contrast, and strong sensitivity to panel-to-sensor alignment.

Introduction

A single-pixel imaging system[1] is a camera in which the usual array of light detectors is replaced by a single sensel integrating light from the focal plane regions selected by some type of spatial light modulator (SLM). Although multiple patterns must be sampled to obtain a high-resolution image of the scene, a surprisingly modest number of samples, far below a Nyquist sampling, can suffice using a technique like Compressed Sensing[2]. There is a huge body of work published on capturing sequences of single-sensel samples each summing the contributions of a randomly-selected set of focal plane positions and then using compressed sensing processing to solve for the array of individual pixel values. However, the current work is not about the abstract method of single-pixel compressed sensing. We are attempting to empirically determine if some inexpensive consumer devices have now provided a better way to implement the camera hardware for these techniques.

The SLMs used for single-sensel cameras are most often DMD (digital micromirror devices) chips, which have *mostly* excellent properties for the task. For example, they can very quickly implement an arbitrary pattern and they provide extremely high contrast between areas selected and not selected. However, DMD chips are physically tiny. There are lots of tiny, commodity, image sensors delivering high quality at fast framerates, and single-sensel methods are simply not competitive. Other types of SLMs are available that are somewhat larger, but not that much larger, and larger usually carries a substantial price premium.

For the authors, the primary appeal of single-sensel image capture is that it may be much easier to produce an effectively large-format sensor by using a large SLM rather than by literally constructing a large sensor. Hence, the current work is a very preliminary evaluation of the feasibility of using relatively large commodity transmissive LCD (liquid crystal display) panels as single-sensel camera SLMs.

Figure 1. *Transmissive LCDs are used in projectors and 3D printers*

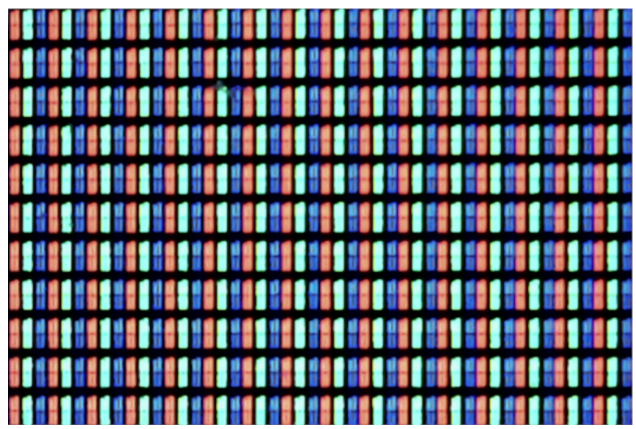

Figure 2. *Macro photo of part of a color LCD panel*

Transmissive LCD panels

Over the last 25 years, physically large, high resolution, LCD (liquid crystal display) panels have replaced cathode ray tubes (CRTs) in both TV sets and computer displays. Unfortunately, those commodity devices almost always bond the LCD panel to a backlight source, which makes the LCD panel difficult to extract for transmissive use. However, over the last decade, two types of low-cost consumer devices have created a significant market for transmissive LCD panels. Figure 1 shows a sub-$100 video projector and a sub-$200 3D resin printer, each of which contains a high-resolution transmissive LCD panel.

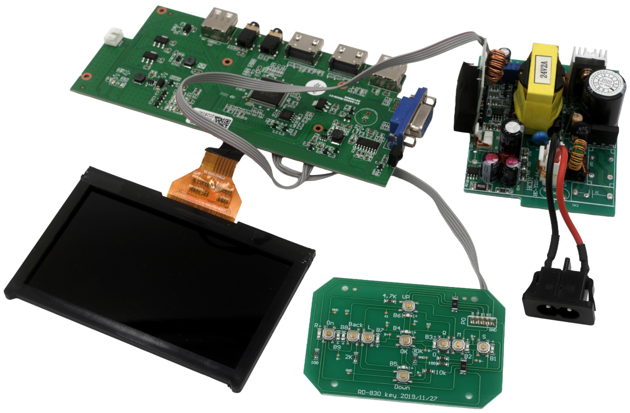

Figure 3. *Electronics extracted from the projector*

Despite projecting color images, low-cost consumer video projectors generally contain only a single transmissive LCD panel. That panel is bonded to a color filter array (CFA) conceptually much like CFAs are imposed on the sensors of digital cameras. However, as shown in Figure 2, the typical CFA pattern used is not the standard Bayer matrix. Whereas a square pixel in a sensor is sampling only one of red, green, or blue light, a pixel transmitted to a color LCD panel is considered to contain a vector of red, green, and blue channel data. Thus, although a ”pixel” is roughly square, each color-channel subpixel is actually a 1:3 aspect ratio rectangle. These subpixels are independently controllable, so a 1080p (Full HD) TV with 1920x1080 pixels in fact has 5760x1080 separately controllable single-color subpixels. Beyond that, the controller board in the projector typically offers not just on/off, but 8-bit resolution proportional control for each subpixel driven by a standard HDMI interface.

Consumer resin 3D printers are not projectors, but essentially a type of lensless contact printer. The liquid plastic resin contains a photoinitiator chemical that causes it to quickly polymerize and harden when exposed to bright UV light. A typical resin printer has a resin-filled tray with a UV-backlit LCD panel on the bottom. A pattern of pixels is displayed on the panel, the UV light is briefly turned on, and the plastic above the selected pattern of pixels hardens. To make a 3D print, a thin layer is first hardened onto the bottom of a moveable support and then the support is raised a layer height. This process of hardening a layer to bond to the layer above it and then raising the support is repeated for each layer of the print. Thus, the X,Y size and resolution of the print is determined by the pixel count of the LCD panel, and very high pixel count panels have been made for 3D resin printing. In fact, 16K LCD panels are used in some consumer resin printers, giving control over 15120x6230, or approximately 94M, individual pixels. The controller boards in resin printers are typically implementing simple on/off control, but are programmable to perform random pattern sequences as a stand-alone device: that is precisely what a resin printer does.

The large area of either type of transmissive LCD panel makes it feasible to build large-format single-pixel cameras, which is not possible with the devices normally used for single-sensel image capture. What other alternatives are there for large-format digital image capture? The authors have previously explored scanning using a smaller sensor[3] and digital camera obscuras (DCOs)[4], and these techniques are useful, but each approach has strengths and weaknesses. Building actual large-format sensors is difficult and expensive. The $26000 LargeSense LS45[5] sensor is one of very few that have been commercially available. It is approximately 140x120mm, which is about twice the area of our projector’s 115x74mm panel, and much smaller than the large-format resin printers (which are often as much as 300x150mm). Note that full-frame 135 film was just 36x24mm, so our LCD panel is nearly 10x that area. The LS45 contains just 6.7M monochrome pixels whereas a 1080p color LCD in a $100 video projector contains 3x1920x1080 single-channel light cells, so using a single sensel with such an LCD panel could produce 6.2MP color images.

Figure 4. *Kentucky LCD One Sensel (KLOS) camera*

For this reason, the current work centers on use of a single-sensel camera built using components extracted from an LCD projector. The LCD panel, controller board, control panel, and power supply extracted from the projector are shown in Figure 3.

The KLOS camera

The fully assembled prototype single-sensel camera is called Kentucky LCD One Sensel (KLOS) version 250625, and is shown in Figure 4. Although any taking lens with sufficient coverage can be used, KLOS is shown here with the lens from the projector mounted.

KLOS is not an easily portable stand-alone camera in the configuration shown. The connector for the AC power cord is visible on the red, 3D-printed, circuitry box. As is seen in Figure 5, the red circuitry box houses the three boards extracted from the projector in Figure 3. The top left board provides buttons that control the projector, turning power on/off, selecting inputs, adjusting display characteristics like contrast and flipping the LCD image for rear/front projection. The second layer in the red box con-

Figure 5. *KLOS rear view, showing housed circuitry*

Figure 6. *KLOS camera main modules*

tains the power supply in a vented area. The power supply's primary job in the projector was powering a super-bright LED light, which KLOS does not use, so power consumption is minimal. In the projector, a blower cooled the power supply, but in KLOS the grid of vent holes above the supply is more than sufficient and a battery-based power supply easily could have been substituted. Finally, the bottom compartment of the red box mounts the controller board with video inputs. We used a separate laptop to drive the HDMI input for setting LCD patterns. That laptop not only generates the LCD pattern sequences, but also reads the single sensel value via the USB cable and reconstructs the image from a sequence of sensel samplings.

The 3D-printed black box portion of KLOS, shown disassembled in Figure 6, provides the focusable optics and mount for the LCD panel.

At the top of Figure 6 is the focusable single-sensel module. In actuality, the ”single sensel” shown here is a $3 USB-interfaced 640x480 pixel endoscope camera. However, the laptop software simply sums the values of all the pixels to get a relatively low-noise, high dynamic range, single sensel reading.

All the light from the image focused on the LCD panel is in turn focused on the single sensel using a Fresnel lens – which the projector originally used to focus light from it's super-bright LED source onto the LCD panel. The panel and Fresnel lens mount in the center module shown in Figure 6.

The front module is essentially a 3D-printed black box that mounts the taking lens on the front and allows the LCD+Fresnel module to freely move forward or backward over a fairly wide focusing range.

No attempt was made to rigidly fix or gear-couple the positions of the modules relative to each other. They are merely light-tight friction fit together. This design choice was made to facilitate rapidly disassembling and reassembling the camera if we needed to make any adjustments, although in retrospect it did cause some problems.

Experimental results

The software running on the laptop was written a C/C++ code using the OpenCV library[6] to create LCD patterns on the HDMI output, read image data from the ”single sensel” endoscope camera, and to display images on the laptop screen. The code was written to execute in an Ubuntu Linux environment, but also works under Windows Subsystem for Linux (WSL) with some differences in how the OpenCV output is split between the laptop display and HDMI video signal to the LCD panel.

Fundamentally, each single-sensel reading gives an equation stating that the weighted sum of the LCD pixel transmissions is equal to the value read from the sensel. Thus, a sequence of readings with different patterns collects a system of linear equations which can be solved for individual pixel contributions. Although we initially tested at very low resolutions using dense sampling and conventional means to solve for individual pixel values, there is a large body of prior work in single-sensel image reconstruction, and we can leverage any of those techniques. More sophisticated methods can still produce good results when the set of equations is grossly underspecified. The KL1p library[7] was used to perform compressed sensing reconstruction utilizing Basis Pursuit or Orthogonal Matching Pursuit (OMP) to recover images from sub-Nyquist sample sequences.

To summarize our findings:

- Although our system captured not a single impressively nice image, repurposing a consumer video projector's LCD and other components is proven viable. The KLOS 250625 device works. Both random and deterministic binary (on/off) pixel patterns have been tested. The depth of field and general behavior of the system is that of a large-sensor camera, which was our primary motivation.
- The use of HDMI limits sample rate. A more direct LCD controller is needed to sample faster than the NTSC video rate of 29.97 frames/s. Lag limits precision of display/sampling synchronization so that even 10 samples/s is difficult to achieve. This issue probably would be even more severe using a monochrome LCD intended for a resin printer, because the printers are designed for framerates slower than 1 frame/s. Obviously, a camera requiring many samples at these low framerates is not usable handheld, nor for scenes with substantial moving content.
- LCDs have a lower on/off contrast ratio than DMDs (typically less than 9 stops), which means the samples have significant leakage from the sum of all off pixels. Without carefully calibrating, this effectively limits the total resolution that can be obtained. Patterns with relatively few pixels on can be dominated by leakage from off pixels.
- Alignment of the sensel with the panel proved surprisingly critical. Perhaps this would not be an issue if we incorporated a diffuser, but the contributions from individual pixels vary significantly with relatively minor misalignments. Recall that our prototype was not designed to maintain precision alignment.

The above results can be simply summarized as proving that the approach is viable, but that a myriad of detail issues must be carefully resolved for an implementation of this to be competitive with the scanning[3] or DCO[4] approaches evaluated in earlier work.

Future work

Had KLOS worked better, there are two assumptions made by typical single-pixel compressed sensing methods that we had intended to break. First, we have been experimenting with use of LEDs as sensels[8], and we were hoping to use this technique not only with a single LED sensel, but with a low-sensel-count LED array to improve resolution. Second, that same work tracks the expected value for each sensel over time as the scene appearance evolves. A LED sensel is read by timing photoconductive transfer of charge, so expected values predict time required per sample. That could enable dynamic creation of pseudorandom pattern sequences that are significantly more efficient to sample.

All of our experiments treated LCD pixels as monochrome on/off. Neither independent control of color channels nor deliberate use of intermediate tones has been tested.

Unfortunately, we do not believe that we could get repeatable results for these experiments using the KLOS 250625 prototype. A much more carefully constructed prototype would be needed.

References

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