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MIPI Camera: Opportunities, Challenges and Solutions for Chromebook Cameras

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Abstract

Smartphone cameras revolutionized for at least two generations in the past decade; i.e. megapixel enthusiasm and multi-camera combination. However, most laptops are still with low resolution fixed focused webcam cameras. The story could have changed recently. The COVID-19 pandemic keeps people working from home; therefore, video conferencing becomes part of the new normal of daily life. The camera quality of laptop computers is in the spotlight when users join video conferences using their laptops webcam. We are working on a MIPI camera solution to drive the Chromebook webcam quality with minimum impact of cost. There are several challenges by porting the current smartphone MIPI camera technology to Chromebook directly: miniature module size and challenge of the hardware product design, limited ISP. There is also no complete evaluation criterion to video conferencing quality. We will discuss each aspect one by one.

Introduction

Smart phones have changed our world of photography in the past decade. We could have never imagined carrying a powerful camera around in our pockets twenty years ago. Smartphone cameras revolutionized for at least two generations recently; i.e. megapixel enthusiasm and multi-camera combination. It expands the user experience from the simplest photography to extreme low light, high-speed photography. Multiple cameras combination enables the pseudo optical zoom lens feature; therefore, the camera can capture zoomed images with good sharpness. In comparison, the majority of laptops webcam, even the high-end laptops for enterprise users, are still with 720P and 1080P cameras.

Why have laptop webcams not changed much in the past 10 years while there have been a couple generations in the smartphone cameras industry? Compared with smartphones, laptops are less mobile. It is larger and heavier, and the camera is less accessible. Users need to unfold the clamshell panel and key in password before they can turn on the camera. People tend to use laptops when they do not have a smartphone handy. However, more and more Chromebooks have one or two cameras as standard configuration due to the dramatic reduction of camera module cost and trend of user's developing behavior. The main user case of Chromebook webcam is video conferencing or chatting. A relatively low resolution (720P or 1080P) 16:9 USB webcam is mainstream on the market and is considered a key component of the device. Users' behavior changes with product form factor. It is found that users are tempted to use a world facing camera of a tablet or convertible laptop (where it is often placed next to the keyboard) more often than a clamshell Chromebook for convenience. This can be particularly useful where the need to capture pictures is occasional, for example a student converting their laptop to tablet mode to photograph a science experiment for their lab notebook. Word facing cameras are usually a standard component for tablet and convertible Chromebook. Users do sometimes hold a clamshell Chromebook to capture photos or video clips but it is less common than using a tablet or convertible.

Opportunities

It is expected that the quality of webcam will be significantly improved for the next few generations of products in the after-pandemic era. A couple of boosters had already reshaped the webcam technology recently, and could impact more in coming years.

Users' behavior has been impacted quickly by the COVID-19 pandemic. The pandemic keeps people working from home in 2020 around the world. Video conferencing becomes popular and is part of the new normal of daily work life. The quality of video conferencing is in the spotlight thereafter. The camera quality of laptop computers is in the spotlight when users join video conferences on their laptops webcam. Users get used to 12MP or 20MP pixel smartphone cameras; and urge a comparable quality webcam for Chromebook.

On the other hand, 5G networking technology could bring in a much broader cellular bandwidth soon. It is another opportunity to enable a less interrupted higher quality video conference experience to users not only at office or home, but also outdoor and even remote areas without WIFI.

The face authentication feature has become a more popular feature of laptops recently. Users do not have to remember the password and login from the keyboard to bring up a camera. Therefore, users have a better chance to spontaneously catch a moment of life using laptop cameras. It is our observation that there are more and more Chromebooks assembled with a better webcam and a decent quality world facing camera.

USB Camera

Chromebooks usually adopt USB cameras for its low cost, easy system integration and supply availability. A USB camera module basically includes a MIPI camera and a DSP chip. The DSP is designed to have multiple functions into a single chip; such as USB data transfer, Micro Processor Unit (MPU), image sensor controller, image signal processing (ISP) engine, MPEG compression, and DC-to-DC regulators. The DSP integrates USB transceiver to transfer video streaming which is compliant with USB Video Class and properly works with the Chromebook driver on USB host. The MPU and ISP engine work together to UVC defined image process and functions such as Lens Shading Correction, defect pixel correction, GrGb filtering, Color Correction Matrix (CCM), histogram statistical analysis, Auto White Balance (AWB), Auto Exposure (AE), Auto Focus (AF), scaling functions etc. Those algorithms are relatively simple and require only a limited memory buffer to achieve the same camera control of the SoC ISP algorithms.

A USB camera module fits well into the modularized component concept, therefore can be easily integrated into a new device with minimum hardware and software engineering effort. A same USB camera can be integrated into many different laptop projects, so it can be built to a much higher volume and life cycle could be multiple years. It helps drive down the unit cost of USB cameras; therefore, it is a convenient solution to laptop products. However, the performance of the USB camera module is obviously limited. The USB interface has limited bandwidth. Imaging data has to be compressed to be transmitted. The DSP of USB cameras is relatively low cost with limited memory buffer; the capability of the ISP algorithm is limited and not comparable to smart phone SoC or GPU.

The USB DSP industry also sees the challenge and is working hard to drive to more capable DPS solutions. The key new features include temporal noise reduction block, face detection based 3A algorithm etc. However, it is still a long way for a USB DSP to catch up to the performance of SoC ISP algorithms. There are several intrinsic limitations of USB camera modules. The mainstream DSP chip with a USB2.0 interface offers a theoretical maximum data rate of 480Mbps; can support FHD 1080P streaming with up to 30fps which is necessary for video conferencing. However, it cannot stream a resolution of 5MP or higher video at the same frame rate; instead of using YUV lossless video format, DSP compress the video content to low frame rate or high compression rate; it significantly reduces the quality of video. USB 3.0 offers a transfer rate of 5Gbps which is 10 times faster than USB2.0. To stream a higher resolution video data, a USB 3.0 interface is required. There are only a few available DSP options on the market to support that. However, it is found that there are a few design limitations and gate it to be a popular design path when we validate the device design in productive projects. First, the DSP becomes more complicated and expansive as sensor pixel count increases. The cost increases quickly as pixel count increases; a 8MP USB camera is much more expensive than the same resolution MIPI camera module. The capability of the DSP is still not as good as a regular SOC ISP. As the calculation complexity increases, the DSP consumes significant power and causes thermal issues of product design. Special engineering design on heat dissipation is required to bring up a 8MP USB camera module. Another challenging factor of USB 3.0 interface is the signal integrity. At the data rate of 5Gbps, PCB trace loss, board-to-board connector reflections, loss of the board-to-board interconnects (FPC, FFC and coax cable) become significantly greater than USB2 interface.

Technical Challenges

Some people may take it for granted to deploy the experience learned from the smartphone camera industry to improve the image quality of laptop computers. However, it is not totally true; there are still several other challenges. 1) The laptop is more cost sensitive than the smartphone; 2) the product mechanical design constraints are even tighter, i.e. the camera module size is not only constrained in Z height but also Y dimension; 3) the interconnect solution to MIPI camera is more challenge; 4) there are limited video conferencing quality evaluation criteria. We will discuss each aspect one by one.

In Chromebook devices, the webcam is usually located at the central region of the top bezel of the display panel for the best video conference posture. Given the trend of narrow bezel display panel design and small device thickness, the camera module size is generally the critical dimension of product design; and it has been pushed to a more and more compact size than before, much smaller than smartphone camera module sizes. As well known, the compact sizes are against physical law of optics and make the camera's low light performance not good.

Another challenge is to transmit the video streaming signal to the SoC processor for video or preview signal processing. It is for user facing cameras of Chromebook with clamshell form factor. The user facing camera is far away from the SoC in clamshell form factor. In addition to signals on PCB, the camera flex cable could be 12 inches or longer. It may add up channel insertion loss beyond the MIPI bus specifications. Extra engineering validation has to be done for MIPI camera design to make sure the signal integrity is not in the way of a smooth video experience. The extra length of flex cable adds cost and desense risk, it is important to have a cheap reliable cable solution to replace the expensive FPCs that common MIPI cameras use.

To fully stretch the final quality to its potential, a comprehensive ISP tuning process is critical. The tuning process includes objective tuning and subjective tuning. The first step of objective tuning is to characterize the camera module and understand the camera module performance limitations. Then it does an initial and coarse tuning by ISP simulator software to make sure the ISP settings are tuned with proper tradeoff among thousands ISP parameters. With the learning of human visual system psychophysical models and quickly developed image quality benchmarking metrics, more and more tuning goals can be achieved in the objective tuning stage. The purpose of the subjective evaluation is to extend objective tuning coverage by simulating user operations to ensure the camera system quality through image quality fine tunes. The subjective image quality tuning process includes repeated cycles of the ISP tuning, user case testing and test data review to cover more and more real-life scene user cases. In the subjective tuning process, as more and more major user cases are tested, reviewed and ISP parameters are repeatedly fine-tuned with more tradeoffs considered, there will be less artifacts in final user experience. The user experience is considered to be balanced and meet the final image quality requirement. As the subjective tuning process can last forever theoretically, the project usually would be launched after major user cases are covered and the tuning process is finished as long as no major quality issue is found thereafter. It depends on project development cycle time; the common ISP tuning process takes from 3 to 6 months and also involves a lot of engineering resources.

To provide a complete user experience, the camera module and ISP tuning is only part of the story. Network bandwidth, video encoder, decoder capability and application software also play critical roles for a smooth, high quality video conferencing experience for webcam. In this paper, we focus on the camera and image quality related topics only.

MIPI Camera Solution

MIPI camera solution has several key advantages over the current USB camera. There is no immediate constraint on interface data transfer rate for current camera pixel count. The MIPI CSI-2 can support up to 18 Gbps using four-lane MIPI D-PHY and up to 41.1 Gbps for C-PHY interface. The technology and mass production industry is ready. As millions of new smartphone devices are delivered to users each year. The technology and production process have been well developed; the major technical challenges have been solved. The supply chain is well established. There are quite several camera module options available on the market to choose from; Therefore the cost of MIPI camera module has been driven down significantly. There are many new technologies or new processes to improve camera low light performance, to reduce module dimension. The DSP component of the USB camera module can be removed by directly streaming the image data to Chromebook's SoC or GPU. It not only gets rid of the BOM cost of DSP components, but also improves the performance by adopting the more powerful SoC ISP algorithm. Given the successful development path of smart phone camera technologies, the industry is following the same track to improve from the following several aspects:

- Increase the sensor pixel number and pairing lens performance
- Improve the performance of auto white balance, auto exposure, auto focus (3A)
- Improve the ISP algorithm of DSP

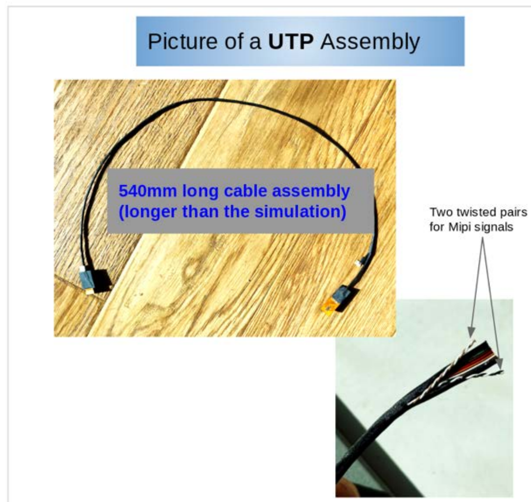
Google launched Pixelbook Go in 2019. It is the first time that a MIPI camera solution is integrated into a mass produced clamshell Chromebook. The MIPI camera facilitated by Intel Kaby lake SoC got tremendous positive feedback from IT reviewers and common users. It demonstrated the possibility of significantly improving the image quality without adding much or even the opportunity of reducing the cost by using MIPI interface cameras.

Interconnect Solutions for MIPI Camera

There are different options of interconnects between motherboard and camera module, i.e., FPC, FFC, micro-coax, etc. To determine which solution to select in a system design is a tradeoff between signal integrity performance, EMI performance, RF desense performance, mechanical constraints, as well as cost. Micro-coax cables are the most flexible to go through the hinge, therefore mechanically it is the easiest solution for clamshell Chromebook designs. From a signal integrity point of view, micro-coax cables have fairly good impedance control and low insertion loss. From EMI and RF desense point of view, since micro-coax cables have good outer conductors wrapping the inner conductors, radiations from the signals are largely shielded. However, the drawback of micro-coax is its cost. FPC is an interconnect solution that has been used on Pixelbook Go. The advantage of FPC is its thin form-factor is perfect for thin profile products. Also, it has good EMI and desense performance and fair insertion loss performance. The cost could be higher than the micro-coax. The disadvantage of FPC is it is physically not suitable for through-hinge design. FFC is a cheap solution of high-speed signal transmission. It has good SI performance, while EMI and RF desense performance are fair if the grounding and shielding are not handled carefully. Like FPC, it is impossible to go through the hinge. Sometimes, people combine micro-coax and FPC as a solution to satisfy through hinge design mechanical constraints as well as thin lid Z-height requirements. Inevitably, the cost of this combo solution increases. The comparison of different cable options is summarized in Table 1. Recently Intel has a solution of FDP link III + shielded twisted pair (STP), while the cost is high.

Table 1. Comparison of different cable options

Solutions	*Pros and Cons*			
	Cost	Mechanical	SI	EMI/RF/ Desense
20" UTP	~$2	Similar to USB	Better	More
20" uCoax	~$4	Easy thru hinge	Best	Less
Micro-Coax + FFC	~$3.5	Easy thru hinge	Good	Some
Micro-Coax + FPC	~$5.5	Easy thru hinge	Better	Less
FDP link III + STP	~$10+	Easy thru hinge	Better	More



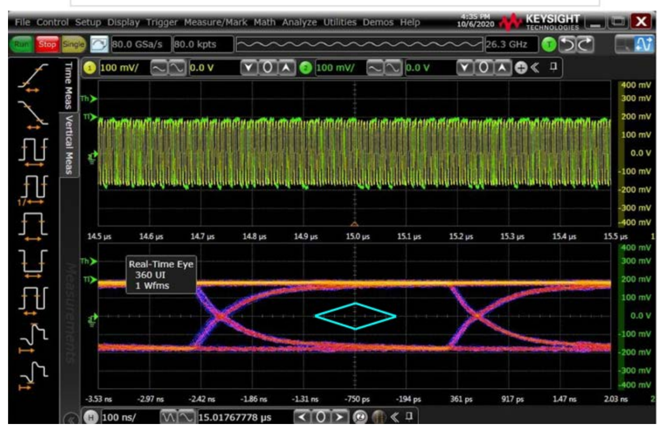


Figure 1. Eye diagram with good timing and voltage margin of UTP.

Google investigated the feasibility to use the unshielded twisted pair (UTP) for interconnection between motherboard and camera module. The purpose is to explore a cheap, easy-to-use, as well as reliable solution. As UTP cables are maturely used for USB cameras and very cost friendly, it would be great choice if they could be used for MIPI cameras. The study was performed on an Intel Jasper Lake reference system. First, eye diagram simulations were done for both 720p and 1080p sensors. 20" long UTP cable samples from two different cable vendors were analyzed. Simulations demonstrated more than 0.35UI timing margin and 180mV eye height margin. Although the UTP cables have no outer conductors, the differential mode of the signals was not jeopardized and were well transmitted and received. At the meanwhile, simulations showed common mode noise met 70mV to 300mV spec. The results are shown in figure 1.

To further validate SI performance of UTP, eye diagrams were measured on a mass produced system. Lab validation tests 3 different types of of cables: UTP cable (see the picture below), Intel Option B cable (STP: overall cable shielded), Intel Option C cable (SSTP: overall cable shielded + each diff pair shielded). Eye diagrams at test points (close to RX pads) showed good timing margin and voltage margin as simulation predicted. Another observation was that the eye margin of UTP was almost the same as STP and SSTP cables.

The study also examined EMI emission performance of the UTP cable assembly. As in the test, the cable was attached outside of the device, the test data could not represent system-level EMI, as the system-level test is sensitive to how the cable is placed in the chassis. But from a component point of view, the UTP cable is 3~10 dB higher in peaks than the shielded cable above 300 MHz. Below 300 MHz, the SSTP may show up to 10 dB higher emissions, possibly due to the grounding of the shield not well connected to the system ground. EMI emission test of UTP cable showed certain level radiation from the component. Properly system level grounding and shielding will be necessary for emission control.

Quantified Image Quality Assessment

Image quality assessment can be broadly classified into two categories: subjective and objective. Subjective image quality assessment offers the most reliable way of evaluating image quality through psychophysical experiments. However, it is known for being time-consuming and expensive. Objective image quality assessment, on the other hand, attempts to create computational models that are capable of quantifying image quality at different scales and attributes to mitigate the differences of personal perception preference of subjective assessment. The Chrome OS team is working on both directions to cover the product portfolio and different users needs. Subjective assessment is well established but limited by engineering resources and long tuning schedule. It is considered costly and hard to scale. It is our goal to investigate the full potential and drive the objective assessment path, leaving only the most challenging user cases to subjective assessment in this paper.

As mentioned above, it is expected that Chromebook cameras have to deliver a more compelling user experience; close or comparable to what smartphone cameras can provide. The main user case of user facing cameras is video conferencing. User seldom takes still pictures using the front camera. The working distance, scenes and content is therefore better defined than common smartphone camera user cases. The ISP tuning should also focus on optimizing the video performance. Unfortunately, most of the earlier work of video quality assessment and metrics modeling focuses on video compression and transmission quality and related artifacts with full reference assessment. Our current video evaluation is still based on still image quality evaluation with more tolerance given to temporal noise metric. We are looking for help on quantitative metrics of video quality.

Among the public available industry standards, we target on subjectively correlated image quality metrics. The key image quality aspects are color rendition, sharpness, noise performance and so on. IEEE std 1858-2016[1] provides fairly comprehensive metrics including spatial frequency response, color uniformity, chroma level, lateral chromatic displacement, local geometric distortion, texture blur and visual noise. The threshold of each metric is defined as the value which increases in image quality are not accompanied by increases in perceived quality. The threshold values are defined not as intended as a general image quality standard for photographs produced by high-end dedicated cameras; but we are investigating if it can serve as good engineering specifications for a pass and fail criterion. Earlier study revealed that objective measurements defined in IEEE1858 CPIQ standard are promisingly correlated with perceived image quality [2].

ML IQ assessment model

Quantified objective image quality modeling can help evaluate image quality at key aspects; but it cannot be used to trade off the subtle user cases for fine and complicated image quality. Despite the subjective nature of quality assessment, machine learning also shows promising results in predicting technical quality of images. In the past decade, there have been a significant number of studies on machine learning image quality assessment (IQA).

The Chrome OS team also teamed up with Google machine learning team to investigate how machine learning IQA can help to drive the subjective assessment work usually done by image quality engineers. NIMA[3] is a deep CNN that learns human perceptual quality and aesthetic factors for images. This allows us to predict which images would look good (technically) or attractive (aesthetically) to the typical user. NIMA aesthetic/quality predictor relies on the success of state-of-the-art deep object recognition, and can be used in a variety of labor intensive and subjective tasks such as intelligent photo editing, optimizing visual quality for increased engagement and revenue growth, or minimizing perceived visual errors in an imaging pipeline.

In the collaborative work, NIMA model is first trained with smartphone photography attribute and quality (SPAQ) database [4] for world-facing camera user cases. We are also working on building the subjective ground truth for Chromebook users facing cameras.

Conclusion

With the opportunities and challenges presented, the Chrome OS team is working closely with Google internal teams, OEM and ODM partners to improve the image quality of the Chromebook ecosystem. The laptop industry has less production volume to amortize costs over compared to smartphones, therefore, the engineering effort aims to minimize the overall cost impact as well. Given the matured MIPI camera technologies, it is our goal to break through the current camera quality limitation by using MIPI camera solution in the next few generations of products. It directly adopts the more advanced SoC's camera 3A and ISP algorithms to lift the Chromebook image quality. We also propose direct deployment of the USB camera's of unshielded twisted pair(UTP) cable to MIPI camera with low data rate for devices with clamshell form factor. The simulation and lab measurement of signal integrity of UTP cable also provide a cost-efficient solution for MIPI camera cabling with good electrical and signal margin. The system level EMI needs to be considered in the coming study. It will help drive down the overall cost of MIPI camera solution if it can replace traditional camera flex. In parallel, we also noticed the USB DSP industry realized the increased user demand. They made significant progress to improve their DSP chip capability by adding more ISP features, such as temporal noise reduction block, face detection based 3A algorithm etc. We expect USB cameras will still paly a critical role in the Chromebook ecosystem.

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Author Biography

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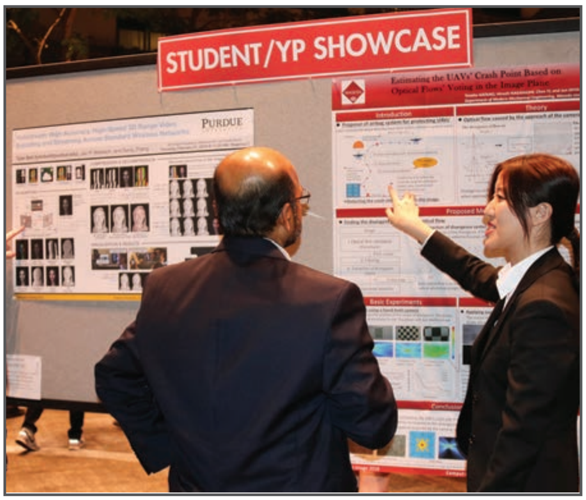
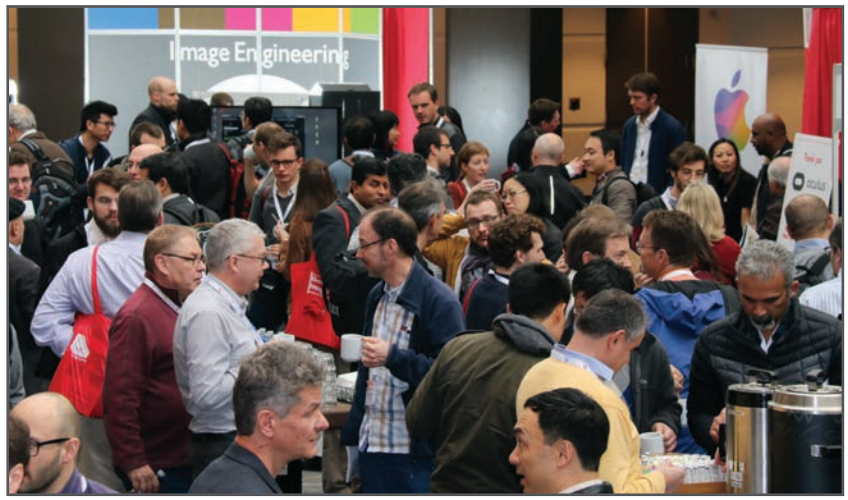


STUDENT/YP SHOWCASE



AR is a fundamental and transformative interface and platform.
20+ years from my initial working demo to today's AR displays
Optimistic that it won't take another 20 to reach ubiquitous consumer AR!
My first working AR prototype
Today's platforms
Ubiquitous consumer AR