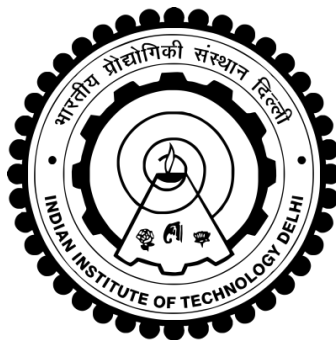


CMOS SENSOR FOR HIGH-SPEED TIME-OF-FLIGHT 3D IMAGING

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CMOS SENSOR FOR HIGH-SPEED TIME-OF-FLIGHT 3D IMAGING

by

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Department Of Electrical Engineering

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



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Dedicated to my loving Mother.

Certificate

This is to certify that the thesis entitled “**CMOS Sensor for High-Speed Time-of-Flight 3D Imaging**”, being submitted by **Chandani Anand** to Indian Institute of Technology Delhi (India), for the award of the **Doctor of Philosophy** in Electrical Engineering is a bonafide research work carried out by her under my guidance and supervision. The research work has reached the requisite standard. I hereby declare that the content of the thesis has not been submitted to any other university for award of any degree or diploma.

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Abstract

This thesis presents a CMOS sensor for high-speed and high-resolution time-of-flight (*ToF*) 3D imaging. *ToF* imaging uses a round-trip travel time of light emitted toward objects and reflected back by them for estimation of distances to different points on the objects. This travel time can be measured by a *ToF* imaging device in a number of ways, one of which is sensing the phase of light intensity modulation at the device and comparing it to the corresponding phase at the light emitter. An array of LED (light-emitting diode) or LASER (light amplification by stimulated emission of radiation) transmits the modulated light, whereas a CMOS image sensor synchronized with the emitter is used at the receiving end. The CMOS image sensor contains *ToF* pixel array, whose pixels sense the light modulation phase and thus distances to objects or scene depth. The pixel's ability to do so is affected by the properties of imaged objects, such as low or specular reflectivity, and by scene contrast, dependent on the intensity of modulated and background light received from the scene. When *ToF* sensor is exposed under high-intensity background light, such as sunlight of more than 100 klx, the depth accuracy reduces due to a lower intensity of the modulated light received at the sensor. The saturation of the photosensing region due to background light does not allow signal integration, which degrades the depth resolution and also limits the sensor's dynamic range. The variance of background light with time and multipath reflections in a scene further degrade the sensor's performance. To improve the depth imaging quality of the sensor under high-intensity background light, pixel level background light subtraction is implemented. The extra processing required by the pixel

for background subtraction and depth estimation provides the lower frame rate. Therefore, reduces the camera speed. At a lower frame rate, the *ToF* sensor may provide incorrect depth information in high dynamic scenes, where objects are moving at high-speed. To increase the depth accuracy and processing speed under high-intensity varying background light, four different solutions are proposed in this thesis:

- High-intensity in-pixel background light subtraction and high-speed three-phase, one-tap *ToF* depth estimation with in-pixel fixed-pattern noise reduction,
- High-speed, column-level, photon-transfer-curve (PTC) inspired compressive *ToF* depth sensing,
- Current mode depth sensing,
- Non-systematic error reduction in *ToF* cameras using a linear polarizer to increase depth accuracy.

A three-phase, one-tap depth estimation using *ToF* principle increases accuracy by subtracting background light using a single-tap/capacitor, while proposed three-phase method provides high-speed depth sensing, as compared to standard four-phase depth estimation technique used in *ToF* cameras. A CMOS image sensor with 24×24 pixel array, $48 \mu\text{m}$ pixel pitch and 17.36% fill factor is fabricated and characterized in AMS $0.35 \mu\text{m}$ OPTO process. The sensor suppresses up to 125 klx background light efficiently with a reduction of around 5 cm (45 %) in distance resolution, from the resolution achieved under zero background light. The in-pixel background light subtraction provides a frame rate of 207 fps

and 100 fps in 2D mode and 3D mode, respectively. To further increase the camera speed, a column-level compressive ToF depth sensing is proposed, where three-phase ToF pixels are integrated with PTC-inspired multiple-slope analog-to-digital-converter (ADC). The multiple-slope ADC increases conversion speed by utilizing its companding quantization characteristics. The ADC voltage-to-bits conversion follows the pixel PTC and conversion cycles are compressed accordingly. On the other hand, the slope of the ramp generator output can also follow the PTC to compress the conversion cycles. Such ramp generator has programmable slopes; for example, from 1x to 16x, which can be enabled by the ADC programmable bits based on the light intensity received by the pixel array. A CMOS imager with 48×48 three-phase pixel array and 10-bit ADC is designed and fabricated in AMS 0.35 μm OPTO process.

To subtract background light of more than 200 klx with reduced pixel size, a current mode ToF pixel is proposed, which works in a log-linear mode and can tolerate a high-intensity background light. A current mode pixel performs background light subtraction at photodiode node. Thus, large size capacitors are not required, which reduces the pixel size and increases the spatial resolution. A CMOS imager with 32×64 pixel array, 35 μm pixel pitch, and 18% fill factor is designed and fabricated in AMS 0.35 μm OPTO process.

While a ToF sensor can be designed to work under bright sunlight, often the depth accuracy and resolution suffer from multipath reflections and background light variance with time, which is difficult to reduce using in-pixel offset correction techniques. To reduce these non-systematic errors, a linear polarizer is used with ToF sensor. An optical polar-

ization filter rejects light reaching the sensor from unwanted propagation paths due to the modulated light that underwent multiple reflections. This gives the modulated component of the incident light that carries valid depth information, relatively more prominence in the entire light input to the sensor's pixels, thus reducing depth estimation error. The idea is validated using three-phase, one-tap ToF sensor proposed in this thesis and SR4000 depth sensor from Mesa imaging. The measurement results provide maximum depth error reduction of 87% when polarization filter is used in front of ToF sensor as compared to when filter is not used.

सार

यह थीसिस उच्च-गति और उच्च-रिज़ॉल्यूशन टाइम-ऑफ़-फ़्लाइट (TOF) के लिए CMOS सेंसर प्रस्तुत करता है

3 डी इमेजिंग। TOF इमेजिंग वस्तुओं की ओर उत्सर्जित प्रकाश के एक गोल-यात्रा यात्रा समय का उपयोग करता है

और वस्तुओं पर विभिन्न बिंदुओं के लिए दूरी के आकलन के लिए उनके द्वारा वापस परिलक्षित।

इस यात्रा समय को एक TOF इमेजिंग डिवाइस द्वारा कई तरीकों से मापा जा सकता है

जो डिवाइस में प्रकाश की तीव्रता के मॉड्यूलेशन के चरण को महसूस कर रहा है और इसकी तुलना कर रहा है

प्रकाश उत्सर्जक पर संबंधित चरण। एलईडी की एक सरणी (प्रकाश उत्सर्जक डायोड) या

LASER (विकिरण के उत्तेजित उत्सर्जन द्वारा प्रकाश प्रवर्धन) संग्राहक को संचारित करता है

प्रकाश, जबकि एमिटर के साथ सिंक्रनाइज़ एक CMOS छवि सेंसर का उपयोग प्राप्तकर्ता में किया जाता है

समाप्त। सीएमओएस इमेज सेंसर में टीओएफ पिक्सेल एरे होता है, जिसकी पिक्सल्स में रोशनी होती है

मॉड्यूलेशन चरण और इस प्रकार वस्तुओं या दृश्य गहराई तक दूरी। पिक्सेल की करने की क्षमता

तो यह कम या स्पेक्युलर परावर्तन और, जैसे imaged ऑब्जेक्ट्स के गुणों से प्रभावित होता है

दृश्य विपरीत द्वारा, प्राप्त और पृष्ठभूमि प्रकाश की तीव्रता पर निर्भर करता है

घटनास्थल से। जब TOF सेंसर उच्च तीव्रता पृष्ठभूमि प्रकाश के तहत उजागर किया जाता है, जैसे

100 से अधिक klx की धूप के रूप में, गहराई की तीव्रता कम तीव्रता के कारण कम हो जाती है

सेंसर में प्राप्त प्रकाश। कारण फोटोशूटिंग क्षेत्र की संतृप्ति

पृष्ठभूमि प्रकाश संकेत एकीकरण की अनुमति नहीं देता है, जो गहराई के संकल्प को नीचा दिखाता है

और सेंसर की गतिशील सीमा को भी सीमित करता है। समय के साथ पृष्ठभूमि प्रकाश का विचरण

और एक दृश्य में बहुपथ प्रतिबिंब सेंसर के प्रदर्शन को और कम कर देता है। सुधार करने के लिए

उच्च तीव्रता पृष्ठभूमि प्रकाश, पिक्सेल स्तर के तहत सेंसर की गहराई इमेजिंग गुणवत्ता

पृष्ठभूमि प्रकाश घटाव कार्यान्वित किया जाता है। पिक्सेल द्वारा आवश्यक अतिरिक्त प्रसंस्करण

पृष्ठभूमि घटाव और गहराई के आकलन के लिए कम फ्रेम दर प्रदान करता है। इसलिए,

कैमरे की गति कम कर देता है। कम फ्रेम दर पर, TOF सेंसर गलत प्रदान कर सकता है उच्च गति वाले दृश्यों में गहराई से जानकारी, जहां वस्तुएं उच्च गति पर चलती हैं। सेवा मेरे उच्च-तीव्रता बदलती पृष्ठभूमि के तहत गहराई सटीकता और प्रसंस्करण गति बढ़ाएं इस थीसिस में प्रकाश, चार अलग-अलग समाधान प्रस्तावित हैं:

- उच्च तीव्रता में पिक्सेल पृष्ठभूमि प्रकाश घटाव और उच्च गति तीन चरण, onetap इन-पिक्सेल निश्चित-पैटर्न शोर में कमी के साथ TOF गहराई का अनुमान,
- हाई-स्पीड, कॉलम-लेवल, फोटोन-ट्रांसफर-कर्व (PTC) से प्रेरित कंप्रेस्ड TOF गहराई संवेदन,
- वर्तमान मोड गहराई संवेदन,
- टीओएफ कैमरों में गैर-व्यवस्थित त्रुटि को कम करने के लिए एक रैखिक ध्रुवीकरण का उपयोग करना गहराई सटीकता।

एक तीन-चरण, TOF सिद्धांत का उपयोग करके एक-टैप गहराई का अनुमान घटाकर सटीकता बढ़ाता है सिंगल-टैप / कैपेसिटर का उपयोग करते हुए पृष्ठभूमि प्रकाश, जबकि प्रस्तावित तीन-चरण विधि मानक चार-चरण गहराई के आकलन की तुलना में उच्च-गति की गहराई संवेदन प्रदान करता है ToF कैमरों में इस्तेमाल की जाने वाली तकनीक। 24 24 पिक्सेल सरणी के साथ एक CMOS छवि संवेदक, 48 मीटर

पिक्सेल पिच और 17.36% भरण फैक्टर को AMS 0.35 m OPTO में गढ़ा गया है प्रक्रिया। सेंसर एक कमी के साथ कुशलतापूर्वक 125 klx पृष्ठभूमि प्रकाश तक दबा देता है शून्य पृष्ठभूमि के तहत प्राप्त संकल्प से, लगभग 5 सेमी (45%) दूरी के संकल्प में रोशनी। इन-पिक्सल बैकग्राउंड लाइट सबट्रैक्शन 207 एफपीएस की फ्रेम दर प्रदान करता है और क्रमशः 2 डी मोड और 3 डी मोड में 100 एफपीएस। कैमरे की गति को और बढ़ाने के लिए, ए कॉलम-स्तरीय कंप्रेसिव TOF डेप्थ सेंसिंग प्रस्तावित है, जहां तीन-चरण ToF पिक्सल हैं पीटीसी-प्रेरित कई-ढलान एनालॉग-टू-डिजिटल-कनवर्टर (एडीसी) के साथ एकीकृत हैं। एकाधिक-ढलान एडीसी अपने बाध्यकारी मात्रा का उपयोग करके रूपांतरण की गति बढ़ाता है विशेषताओं। ADC वोल्टेज-टू-बिट रूपांतरण पिक्सेल PTC और रूपांतरण का अनुसरण करता है

चक्र तदनुसार संकुचित होते हैं। दूसरी ओर, रैंप जनरेटर आउटपुट का ढलान रूपांतरण चक्रों को संपीड़ित करने के लिए PTC का भी अनुसरण कर सकते हैं। ऐसे रैंप जनरेटर है निर्देशयोग्य ढलान; उदाहरण के लिए, 1x से 16x तक, जिसे एडीसी प्रोग्रामेबल द्वारा सक्षम किया जा सकता है पिक्सेल सरणी द्वारा प्राप्त प्रकाश की तीव्रता के आधार पर बिट्स। एक CMOS इमेजर 48 48 तीन चरण पिक्सेल सरणी और 10-बिट एडीसी के साथ एएमएस में डिज़ाइन और निर्मित किया गया है 0.35 मीटर ओपीटीओ प्रक्रिया।

कम पिक्सेल आकार, एक वर्तमान मोड के साथ 200 से अधिक klx की पृष्ठभूमि प्रकाश घटाना ToF पिक्सेल प्रस्तावित है, जो लॉग-लीनियर मोड में काम करता है और उच्च-तीव्रता को सहन कर सकता है पृष्ठभूमि प्रकाश। एक वर्तमान मोड पिक्सेल फोटोडायोड पर पृष्ठभूमि प्रकाश घटाव करता है नोड। इस प्रकार, बड़े आकार के कैपेसिटर की आवश्यकता नहीं होती है, जो पिक्सेल आकार और कम कर देता है

स्थानिक संकल्प को बढ़ाता है। 32 64 पिक्सेल सरणी, 35 मीटर पिक्सेल के साथ एक CMOS इमेजर पिच, और 18% फिल फैक्टर को AMS 0.35 m OPTO प्रक्रिया में डिज़ाइन और गढ़ा गया है।

जबकि एक ToF सेंसर को तेज धूप के तहत काम करने के लिए डिज़ाइन किया जा सकता है, अक्सर गहराई सटीकता

और रिज़ॉल्यूशन मल्टीप्ल प्रतिबिंब और पृष्ठभूमि प्रकाश विचरण से ग्रस्त हैं

समय, जो कि इन-पिक्सेल ऑफसेट सुधार तकनीकों का उपयोग करना कम करना मुश्किल है। कम करना ये गैर-व्यवस्थित त्रुटियां, एक रैखिक ध्रुवीकरण का उपयोग ToF सेंसर के साथ किया जाता है। एक ऑप्टिकल ध्रुवीय

ization फ़िल्टर अवांछित प्रसार रास्तों से सेंसर तक पहुँचने वाले प्रकाश को अस्वीकार करता है

संशोधित प्रकाश जो कई प्रतिबिंबों से गुजरा। यह संग्राहक घटक देता है

घटना की रोशनी जो वैध गहराई की जानकारी देती है, में अपेक्षाकृत अधिक प्रमुखता है

सेंसर के पिक्सल के लिए पूरे प्रकाश इनपुट, इस प्रकार गहराई अनुमान त्रुटि को कम करने। विचार है

इस थीसिस और SR4000 गहराई में प्रस्तावित तीन-चरण, एक-टैप टूएफ सेंसर का उपयोग करके सत्यापित किया गया

मेसा इमेजिंग से सेंसर। माप के परिणाम अधिकतम गहराई त्रुटि में कमी प्रदान करते हैं

87% जब ध्रुवीकरण फ़िल्टर का उपयोग TOF सेंसर के सामने किया जाता है जब की तुलना में
फ़िल्टर का उपयोग नहीं किया जाता है।

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