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Interference Model of Two Time-Of-Flight Cameras

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Abstract—The last decade bore witness to increased development of time-of-flight (ToF) camera hardware, algorithms, and applications, particularly 3-D measurement in the fields of human-robot collaboration. Their advantage is in faster digital 3-D image target representation from efficient signal computations. ToF cameras emit modulated light, measuring the round-trip time from its illumination source to its sensor, deriving a distance image. A disadvantage of using multiple ToF cameras is light interference with other cameras' 3-D measurements. Commonly, adopting an access protocol called frequency division multiple access (FDMA) minimizes interference-related errors but does not eliminate them. The quantification of this distance error has remained a challenging research problem. This paper presents an interference model for two time-of-flight cameras, quantitative analysis, and mathematical modeling to determine the interference-related distance error when using FDMA.

Index Terms—Interference model, interference-related distance error, multi-camera interference, time-of-flight cameras.

I. INTRODUCTION

3-D scanning applications, in particular human-robot collaboration, require rapid 3-D mapping of changing environments, where distance measurements are crucial in collision avoidance in shared work environments [1], [2]. A 3-D digital representation for robotics has to be free of occlusions. Therefore, information from multiple camera perspectives is necessary to maintain spatial awareness [3]–[7].

By design, ToF cameras operate with low computational complexity providing accurate distance information with high frame rates, therefore advantageous for monitoring moving objects. The distance image is obtained by illuminating the scene and measuring the time of flight (round-trip time) of emitted and then reflected light (Fig. 1). The simultaneous illumination of a scene by multiple independently running cameras may lead to interference of the light. Researchers have identified the problem of interference-related errors and conducted experiments to quantify it [8], [9]. Furthermore, varying methods for mitigating the errors were proposed, e.g. the application of the commonly used access protocol called frequency division multiple access (FDMA) [10]. FDMA allows for simultaneous image collection, however, in any environment with high accuracy requirements, a detailed understanding of interference-related distance errors is necessary.

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Fig. 1. Cameras 1 and 2 emit light $L1$ and $L2$. The object reflects light to the cameras' sensors. Interference occurs when two cameras emit light simultaneously. (Only two light paths drawn)

When considering a multiple ToF camera environment, a compromise of resolution, maximum measurable distance, and errors is needed. In this paper, an explanation of the relationship between ToF cameras' illumination interference properties and 3-D distance measurement errors is presented. The interference model is derived from a detailed analysis of ToF camera operating principles, in a two-camera configuration. The model allows to quantify the distance error using corresponding equations to calculate these errors for every possible combination of two modulation frequencies.

This paper is organized as follows. Section II covers the related work, the interference model is presented in Section III. The paper closes with results and discussion in Section IV and conclusions in Section V.

II. RELATED WORK

Considerable research exists for ToF error reduction for a single-camera setup. For multi-camera operation, distance errors caused by interference is a current field of research [6], [11]. Several approaches include measuring [8], [9], avoiding [10], [12], and canceling it with statistical calculations [13].

Lange [14] analyzed the relationship between integration time, modulation frequencies, and distance error in frequency domain with interfering sine waves. The possibility to achieve an interference error of less than 1% is demonstrated when choosing optimal integration time and modulation frequencies.

III. MODEL OF INTERFERENCE

A. Principle of ToF

For the study, two state-of-the-art 2-tap amplitude-modulated continuous-wave (AMCW) ToF cameras are used. They emit amplitude modulated light with frequencies between 10 and 100 MHz. The distance information for each pixel is provided by determining the phase of the reflected

Fig. 2. Example pixel structure. The circle represents the photodetector. Multiplexer M_{demod} is controlled by the demodulation clock connecting either tap A or B with capacitors C_A and C_B to the photodetector.

light. The light charges two storages (also called taps) alternately connected to a photodetector. In the following, these storages are denoted as capacitors C_A and C_B with charges Q_A and Q_B . All pixels share a demodulation clock, synchronous to the illumination clock, that multiplexes the capacitors to the photodetector. An illustration of the pixel structure is given in Fig. 2.

The ratio of the charges depends on the distance of the object. The simplest formula to calculate the relative distance d_{rel} in regard to the maximum measurable range is

$$d_{rel} = \frac{Q_B}{Q_A + Q_B} \quad (1)$$

The absolute distance depends on the speed of light c and the modulation frequency f_{mod} . Because of the periodicity of the modulation, the maximum distance d_{max} that can be measured is

$$d_{max} = \frac{c}{2 \cdot f_{mod}} \quad (2)$$

Then, the absolute distance d can be calculated as

$$d = d_{rel} \cdot d_{max} \quad (3)$$

To record an image, the scene is illuminated for a period of T_{int} with modulated light. In the following, we assume rectangular-shaped modulated light. This does not limit the applicability of the model because the model may be adapted to other waveforms.

The charges in C_A and C_B can be expressed as

$$Q_A = \int_0^{T_{int}} \text{rect}_{demod}(t) \cdot I_L(t) dt \quad (4)$$

$$Q_B = \int_0^{T_{int}} \overline{\text{rect}_{demod}}(t) \cdot I_L(t) dt \quad (5)$$

where $\text{rect}_{demod}(t)$ is the rectangular demodulation clock, $\overline{\text{rect}_{demod}}(t)$ is the inverted signal and $I_L(t)$ is the current induced by the received light in the photodetector.

An additional charge to C_A and C_B is caused by ambient light, artificial or natural. It is present independent of the modulated light and assumed to be constant during image capture. To calculate the correct distance it has to be removed. One possibility is to capture two images, one with, and one without illumination. In the difference image the ambient light is removed.

Fig. 3. A timing diagram showing the relationship between the illumination and demodulation clocks, reflected light, and resultant charges in the capacitors. Left: Illustration of the charging process of the capacitors with one camera. Right: Illustration of the charging process of the capacitors with two cameras. The additional charge at C_B is caused by light from camera 2.

B. Interfering light

Interference of the illumination occurs when several lights are present at the same time. The light waves superimpose resulting to a change in amplitude and thus alter the calculated distance. In the following, the interference at camera 1 is studied. The received modulated light in camera 1 from camera 1, $L1$, generates a current I_{L1} and the additional light source $L2$ from camera 2 the current I_{L2} .

The charging process of a few illumination periods is displayed in Fig. 3, with no interference (left) and with interference (right). If we assume $f_{mod} = 20$ MHz and an integration time of 1 ms, the capacitors accumulate charges during 20 000 periods.

Determining the influence of light from camera 2 on camera 1, only light from camera 2 is investigated hereinafter. During integration the current I_{L2} charges C_A and C_B as a function of time and the modulation frequency difference $\Delta f = |f2_{mod} - f1_{mod}|$ of the two cameras. A visualization of the charging process is given in Fig. 4. The waveform S of the charging process repeats every $T_{\Delta f} = 1/\Delta f$ as long as the integration times overlap. One important point is that the light $L2$ from camera 2 charges C_A and C_B in camera 1 equally during every complete period of S of length $T_{\Delta f}$, i.e. $Q_A = Q_B$, or

$$\int_0^{T_{\Delta f}} \text{rect}_{demod}(t) \cdot I_{L2}(t) dt = \int_0^{T_{\Delta f}} \overline{\text{rect}_{demod}}(t) \cdot I_{L2}(t) dt \quad (6)$$

with $\text{rect}_{demod}(t)$ with frequency $f1_{mod}$ and $I_{L2}(t)$ caused by $L2$ with frequency $f2_{mod}$. After every complete period of S , C_A and C_B are charged equally. The effect is the same as caused by ambient light. As mentioned above, ambient light can be removed and is therefore excluded from further considerations. However, the incomplete periods at the start and end of integration time cause the distance errors. The distance error's magnitude is proportional to the ratio of complete and incomplete periods. The frequency difference Δf and the integration time T_{int} determine the number of repetitions of S and therefore the ratio. The number of complete periods in

Fig. 4. Charges Q_A and Q_B due to light from camera 2.

T_{int} is

$$n_{complete} = \text{floor}\left(\frac{T_{int}}{T_{\Delta f}}\right) \quad (7)$$

The maximum number of incomplete periods $n_{incomplete}$ is 1.

Using the ratio $L2_{ratio}$, corresponding to the number of incomplete to complete periods, the amount of this ratio that causes errors can be approximated as

$$L2_{ratio} = \frac{d_{incomplete}}{n_{complete} + 1} = 1 \quad (8)$$

If $T_{\Delta f}$ is similar to or longer than T_{int} this will result in a decrease in complete periods, yielding an undesirable large $L2_{ratio}$.

C. Distance error

$L2$ charges the capacitors with Q_2 . This additional charge depends on the illumination power and scene reflectivity. The amount of Q_2 that causes distance errors is calculated as $Q^+ = Q_2 \cdot L2_{ratio}$. The phase relation ϕ of the illuminations is unknown because of independent camera operation. In the worst case Q^+ is added only to one capacitor, e.g. C_B . Extending (3) yields the distance error

$$d_{erroneous} = \frac{(Q_B + Q^+)}{Q_A + (Q_B + Q^+)} \cdot d_{max} \quad (9)$$

The distance error calculation depends on the charges due to the illumination ($Q_A + Q_B$ and Q^+), the phase relation ϕ , and the distance d to the object. The maximum distance error $d_{rel+} = (d_{erroneous}/d_{max}) - d_{rel}$ in relation to d_{max} can be calculated as

$$d_{rel+} = \frac{Q^+ - \frac{Q^+ \cdot d_{rel}}{Q_A + Q_B}}{(Q_A + Q_B) + Q^+} \quad (10)$$

The absolute distance error is $d_+ = d_{rel+} \cdot d_{max}$.

The equations (1) to (10) together with the pixel model in Fig. 2 form the interference model.

IV. RESULTS AND DISCUSSION

Applying the interference model described, the distance error can be calculated using Δf and T_{int} . Table I shows the relative and absolute distance errors for different values of Δf using (8) and (10) for $T_{int} = 1$ ms and $f_{mod} = 20$ MHz. The errors were calculated under the assumption that both lights $L1$ and $L2$ have the same amplitude and as a worst-case scenario

TABLE I
DISTANCE ERRORS d_{rel+} AND d_+ DUE TO INTERFERENCE FOR DIFFERENT Δf WITH $T_{int} = 1$ ms

Δf	$\frac{T_{int}}{T_{\Delta f}}$	$L2_{ratio}$	d_{rel+}	d_+
10 Hz	0.01	100%	50 %	3.75 m
250 Hz	0.25	100%	50 %	3.75 m
10 kHz	10	10 %	10 %	0.75 m
100 kHz	100	1 %	1 %	0.075 m
1 MHz	1000	0.1 %	0.1 %	0.0075 m

Fig. 5. Distance errors d_{rel+} depending on $Q^+/(Q_A + Q_B)$ for given relative object distances d_{rel} .

$d_{rel} = 0$. From Table I, it can be seen that a larger modulation frequency difference results in a smaller distance error. Using large frequency differences seems to be a good solution, but requires other system configuration considerations, like a change of resolution (i.e. not all cameras produce high-resolution images) or the maximum distance d_{max} a camera can record. In addition, many off-the-shelf cameras offer only a limited number of modulation frequencies, thereby restricting the system configuration.

The results presented correspond to those of Lange [14], although using a different approach.

Referring to (10) there is a dependency between the distance error d_{rel+} and the relative distance d_{rel} of the object in the field of view of the camera. Fig. 5 shows d_{rel+} for different object distances d_{rel} and different relations between the amplitudes of the lights from both cameras. A relative object distance of 50 % of d_{max} gives the minimal error.

The nonlinearity of d_{rel+} corresponds to (10).

V. CONCLUSION

The illumination interference of two ToF cameras has been examined. A detailed analysis was performed on the influence of the modulation frequency difference on distance errors. The developed model provides equations to quantify the maximum resulting distance error for any two given modulation frequencies.

The interference-related distance error reduces with an increase of modulation frequency difference. Cameras operating with similar modulation frequencies may result in large distance errors.

Extending this model to analyze the interference of multiple ToF cameras requires further research. The influence of multiple light sources to the distance error needs to be investigated.

REFERENCES

- [1] S. Foix, G. Alenyà, and C. Torras, "Exploitation of time-of-flight (tof) cameras," Institut de Robòtica i Informàtica Industrial, techreport, 2010.
- [2] T. Ringbeck, "A 3d time of flight camera for object detection," in *Optical 3-D Measurement Techniques 09-12.07.2007 ETH Zürich, Plenary Session 1: Range Imaging*, 2007.
- [3] T. Beyl, L. Schreiter, P. Nicolai, J. Raczowsky, and H. Wörn, "3d perception technologies for surgical operating theatres," *Studies in health technology and informatics*, vol. 220, pp. 45–50, 2016.
- [4] S. Bauer, A. Seitel, H. G. Hofmann, T. Blum, J. Wasza, M. Balda, H.-P. Meinzer, N. Navab, J. Hornegger, and L. Maier-Hein, "Real-time range imaging in health care: A survey," in *Time-of-Flight and Depth Imaging*, 2013.
- [5] I. Coudron and T. Goedeme, "Multi-view tof fusion for object detection in industrial applications," in *Proceedings of the 12th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications - Volume 4: VISAPP, (VISIGRAPP 2017)*, vol. 4, Imai, F. SCITEPRESS; Setúbal, 2017, pp. 203–207.
- [6] Y. M. Kim, D. Chan, C. Theobalt, and S. Thrun, "Design and calibration of a multi-view tof sensor fusion system," in *2008 IEEE Computer Society Conference on Computer Vision and Pattern Recognition Workshops*, June 2008, pp. 1–7.
- [7] Y. M. Kim, C. Theobalt, J. Diebel, J. Kosecka, B. Matusik, and S. Thrun, "Multi-view image and tof sensor fusion for dense 3d reconstruction," in *2009 IEEE 12th International Conference on Computer Vision Workshops, ICCV Workshops*, Sep. 2009, pp. 1542–1549.
- [8] L. A. Seewald, V. F. Rodrigues, M. Ollenschläger, R. S. Antunes, C. A. da Costa, R. da Rosa Righi, L. G. da Silveira, A. Maier, B. Eskofier, and R. Fahrig, "Toward analyzing mutual interference on infrared-enabled depth cameras," *Computer Vision and Image Understanding*, vol. 178, pp. 1 – 15, 2019.
- [9] A. Kunz, L. Brogli, and A. Alavi, "Interference measurement of kinect for xbox one," in *Proceedings of the 22Nd ACM Conference on Virtual Reality Software and Technology*, 11 2016, pp. 345–346.
- [10] B. Büttgen, *Extending time-of-flight optical 3d-imaging to extreme operating conditions*. Sierke, 2007.
- [11] P. Nicolai, H. Mönnich, J. Raczowsky, H. Wörn, and J. Bernshausen, "Überwachung eines Operationssaals für die kooperative robotergestützte Chirurgie mittels neuartiger Tiefenbildkameras," in *CURAC 2010 : Chirurgische Interventionen - Vom Neanderthaler zur Roboterasistenz, Tagungsband der 9. Jahrestagung der Deutschen Gesellschaft für Computer- und Roboterassistierte Chirurgie, Düsseldorf, Germany, 18th - 19th November 2010. Hrsg.: O. Burgert*, ser. CEUR Proceedings, vol. 1475. Der Andere Verlag, Marburg, 2010, pp. 45–49.
- [12] *Multiple range imaging camera operation with minimal performance impact*, vol. 7538, 2010.
- [13] L. Li, S. Xiang, Y. Yang, and L. Yu, "Multi-camera interference cancellation of time-of-flight (tof) cameras," in *2015 IEEE International Conference on Image Processing (ICIP)*, Sep. 2015, pp. 556–560.
- [14] R. Lange, "3d time-of-flight distance measurement with custom solid-state image sensors in cmos/ccd-technology," Ph.D. dissertation, University of Siegen, Germany, 2000.