Optical Synchronization of Multiple Time-of-Flight Cameras Implementing TDMA

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***Abstract*—Time-of-Flight (ToF) cameras are a promising alternative to current 3-D imaging systems. A setup of multiple ToF cameras is used to overcome their comparatively lower resolution, increase the field of view, and to reduce occlusion. However, the simultaneous operation introduces the possibility of interference resulting in erroneous depth measurements. One option to mitigate interference is the consecutive arrangement of multiple cameras in time slots, such that each camera illuminates the scene exclusively, a procedure known as time division multiple access (TDMA). Instead of requiring a master synchronizing device, an approach is presented requiring no additional hardware or infrastructure to utilize TDMA by adding a synchronization software procedure to the camera's firmware. It effectively enables a camera to sense the acquisition process of other cameras and rapidly synchronize its acquisition times to operate without interference. During the experimental verification with three ToF cameras no interference occurred. The cameras each acquired 29 depth images per second while synchronizing themselves every 10 s. The proposed synchronization procedure implements an interference-free TDMA operation and overcomes traditional hard-wired synchronization setups, offering an easy setup and a methodology to upgrade existing systems without hardware modifications.**

***Index Terms*—Multi-camera interference, multiple camera system, multi-device interference, optical synchronization, time-of-flight cameras.**

I. Introduction

A Time-of-Flight (ToF) camera is a range imaging device, where the pixels' values refer to the distances between the camera and objects in the scene. The camera's illumination unit emits modulated infrared light (illumination) and the time from the camera to the scene and the reflection back to the sensor is measured, providing distance information capturing a complete 3-D scene. ToF cameras provide advantages over stereo vision systems with their low complexity, high frame rate and simplicity of setup making them highly useful in critical commercial operations, like robotics. Disadvantages of ToF cameras are lower resolution, susceptibility to multiple reflections, interference from sunlight, and interference from other ToF cameras operating nearby, often used as multi-camera setups to increase the field of view and to overcome occlusion and the lower resolution limitations [1]–[11]. Light interference in multi-ToF camera setups may result in distance calculation errors [10]–[15].

The authors' previously published work presents a solution for zero illumination interference of two ToF cameras using

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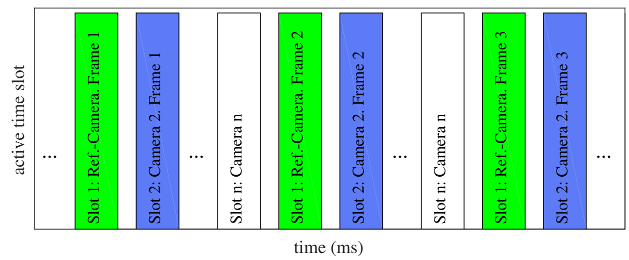

Fig. 1. Graphical representation of time slots in TDMA. Two cameras (depicted green and blue) are assigned to time slots (1 and 2), during which only the assigned camera is allowed to illuminate the scene, therefore avoiding interference.

time division multiple access (TDMA) [16]. TDMA allows several ToF cameras to operate sharing the same frequency channel by dividing the available channel access times into sequential repeating time slots, and assigning the cameras exclusively to one slot, resulting in non-interfering illumination. Using TDMA usually requires a synchronizing unit, wired to the participating devices. Replacing this additional wired complexity, research was undertaken to develop a wireless setup with an optical synchronization software algorithm incorporated into the existing microcontroller's firmware to create a self-contained synchronizing camera for mobility applications.

This paper presents the successive research for a TDMA operation with multiple ToF cameras. The experimental setup, optical synchronization algorithm, and consequential slight frame rate reduction are presented.

This paper is organized as follows. Section II presents related work. The synchronization algorithm is explained in Section III. The experimental setup, measurements, and results are provided in Section IV. The article closes with discussions in Section V and conclusions in Section VI.

II. Related Work

Different channel access methods have been investigated to mitigate light interference from other ToF cameras operating, such as the most commonly implemented frequency division multiple access (FDMA) [17], [18] and code division multiple access (CDMA) [19], [20]. Both techniques allow for a parallel operation of multiple ToF cameras, but in turn lead to increased illuminated light, which can saturate pixels and cause erroneous measurements. TDMA-based solutions include wired setups, as in [1] where the cameras capture images consecutively, and wireless TDMA setups as proposed by Wübbenhorst, where the ToF cameras are additionally equipped with a photodiode to detect other operating ToF cameras [21], [22].

III. Proposed Synchronization algorithm

The proposed operation of multiple ToF cameras uses TDMA to avoid any illumination interference. One ToF camera is selected to be the reference camera. The other cameras synchronize their acquisition timing to the reference camera.

A. Time division multiple access

The standard operation of amplitude modulated continuous wave (AMCW) ToF cameras requires four frames acquisitions to compute distance, one depth image. Each frame acquisition consists of the integration phase (µs to ms), where the scene is illuminated, and the readout phase (in ms), where the illumination is turned off and pixel values are transferred out of the sensor. Implementing TDMA requires a sequential frame acquisition during the integration phases of multiple cameras to avoid interference. To make efficient use of the channel, rather than inefficiently waiting for the preceding camera to complete the acquisition of one full depth image (i.e. four frame acquisition cycles), we propose allowing sequential ToF camera operation within the preceding camera's frame acquisition cycle's readout time (interleaved operation).

Fig. 1 shows the arrangement of n time slots of TDMA. Every time slot allows the assigned camera to run the integration phase (illumination of the scene). The readout process, that follows the integration phase, is executed during the other $n-1$ time slots.

B. Reference camera

Every camera is a priori assigned to a fixed time slot. The camera in the first time slot serves as a reference for subsequent cameras. This definition of time slots and the relation of the cameras to the time slots must be emphasized. There is no central synchronizing device and the cameras operate autonomously without communication between each other. This means that there is no common reference time between the cameras. The reference camera, assigned to the first time slot, defines the timing of the commencement of the first time slot by illuminating the scene. The other (synchronizing) cameras will search for the reference camera's illumination phase and thus infer the timing of the first and successive time slots.

A constant illumination time for the reference camera is set by firmware as the singular important criterion to discriminate that camera from the others, a marker for identification, in contrast to normal camera operation where the illumination times will vary depending on the scene, e.g. ambient light conditions. The discussion section of [16] addresses the justification for this requirement.

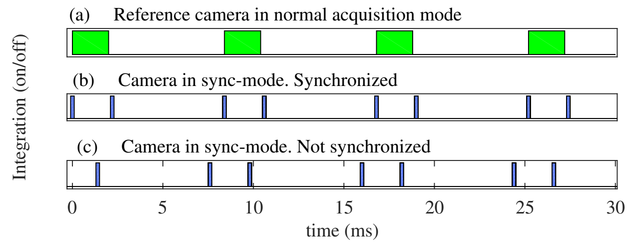

Fig. 2. The frame acquisitions of two ToF cameras are displayed. The bars indicate the integration phases of the frame acquisitions. (a) shows the normal acquisition mode of the reference camera acquiring depth images. (b) and (c) show the integration phases during the sync-mode of a synchronizing camera, (b) shows the synchronized state, where the sync-frames do not receive any illumination, as opposed to (c), where one sync-frame is illuminated.

C. Detection of reference camera

The first step after subsequent camera's power on is the detection of the reference camera. The detection of any other camera operating is performed by performing a frame acquisition without itself illuminating the scene, compared to the normal camera operation where the camera illuminates the scene and receives the reflected light. Therefore, only infrared light from other sources with the same modulation frequency is detected. The reference camera is then identified as such by recognition of its preset constant illumination time interval. This detection phase in startup achieves a high time resolution by shortening the integration time of its acquisition cycle. Multiple acquisition periods are then needed to sample all time slots, where the sampling start points are shifted slightly between successive acquisitions.

D. Regular synchronization to reference camera

An optical synchronization algorithm was developed, allowing for a sequential operation of multiple cameras without any external synchronizing device. Once the reference camera is identified, the exact timing of operation needs to be determined. The algorithm introduces a new mode of operation for the synchronizing cameras, named 'sync mode'. This mode operates with different acquisition parameters, compared to the camera's 'normal mode' for depth image acquisition, and is only used to detect the timing of the reference camera and therefore subsequent timing of time slots. No depth images will be acquired while synchronizing.

In the sync-mode, two frames (sync-frames) are acquired with no active illumination and with specific timing parameters, such that the time interval between the frames equals the constant illumination time of the reference camera. In the synchronized state, the first sync-frame's integration phase ends just before the illumination of the reference camera commences and the second sync-frame starts immediately after the completion of the illumination phase of the reference camera. Thus, the system is considered synchronized if both of these sync-frames receive no illumination from the reference camera. Fig. 2 shows a comparison of the normal depth image acquisition and the frame acquisitions during the sync-mode.

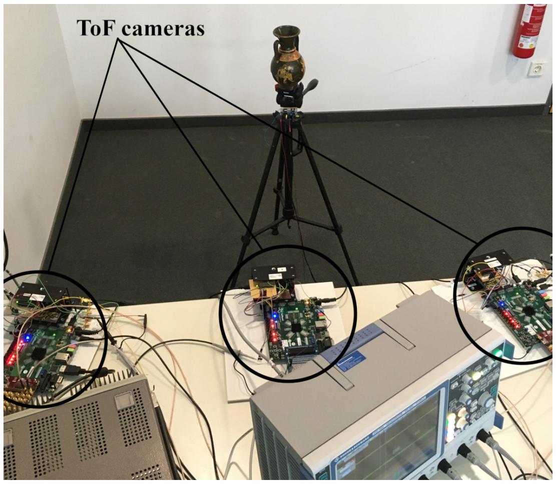

Fig. 3. Experimental setup with three ToF cameras observing the same scene from different perspectives, generating a multi-view 3-D representation.

By knowing the illuminated sync-frame, the synchronization algorithm can determine the required direction of the shift of acquisition starts but not the shift's exact size, therefore the process of time shifting is run iteratively. After every time shift, the sync-mode is executed to check for achieved synchronization. Once synchronized, the operation is changed back to the normal operating mode and the acquisition starts are shifted to the beginning of the assigned time slot.

During the normal camera operation, the acquisition starts will deviate from the designated point within the time slot due to frequency drift of every camera's oscillator. The synchronization is run regularly to compensate for any drift. The synchronization interval depends on the frequency stability of the oscillator and is set at system design time.

IV. Experimental Verification

A. Experimental setup

Fig. 3 shows the experimental setup used to verify the optical synchronization procedure. It consists of three ToF cameras, observing the same object from different perspectives. The ToF cameras from the evaluation kits DME 660 from ESPROS Photonics Corporation were used for the experiments. The cameras consist of an image sensor, an illumination unit, and a microcontroller to start the frame acquisition and to generate the depth images. The microcontroller board was replaced with a ZedBoard from Digilent Inc.

For the experiments, the firmware and the parameters for image acquisition and synchronization were replicated on all ToF cameras. The readout time $t_{readout}$ for a frame is $6.4\,\mathrm{ms}$. This, in combination with a chosen constant illumination time of the reference camera of $2\,\mathrm{ms}$, which also represents the maximum integration time for all cameras, allows for an operation of four ToF cameras with a frame rate of 29 depth images per second for this setup. The integration times for the sync-mode and the detection of the reference camera were set to $0.1\,\mathrm{ms}$.

B. Measurements and results

For experimental verification of the synchronization, two tests were performed. During the first test, 1000 synchronization runs in the sync-mode were performed, synchronizing with one camera to the reference camera. The measured synchronization error has standard deviation of $0.085\,\mathrm{ms}$ and is maximum $\approx 0.26\,\mathrm{ms}$. The second test consisted of three cameras, which were operating continually for one hour with no user intervention to evaluate the viability of the optical synchronization, including an analysis of camera oscillator induced time drift in relation to their time slots. The synchronization interval of $10\,\mathrm{s}$ and an additional time interval between time slots, to allow for drift and synchronization errors, of $0.5\,\mathrm{ms}$ were chosen based on the oscillators' frequency stability of ± 25 ppm, resulting in a worst case drift of $0.5\,\mathrm{ms}$ per $10\,\mathrm{s}$. During the experiment no interference was recorded. The frame rate loss due to the synchronization was about $3\,\%$. The number of depth images, which have to be omitted in order for the synchronization to work is minimum 6 per synchronization run because multiple sync-frames are captured to provide a more robust detection. During the experimental run, the number of omitted depth images were on average 8.6 for camera 1 and 6.1 for camera 2 per synchronization interval ($10\,\mathrm{s}$). These numbers depend on the oscillators' drifts in relation to the reference camera. The measured drift between the two cameras and the reference camera were about $5.5\,\mathrm{\mu s/s}$ for camera 1 and $0.25\,\mathrm{\mu s/s}$ for camera 2.

V. Discussion

The frame rate of a single operating ToF camera is maximum 39 depth images per second with minimal integration times. If, during normal operation, an average integration time of $2\,\mathrm{ms}$ would be used, the frame rate of a single ToF camera would decrease to 29 depth images per second. The proposed TDMA multi-camera operation, with a maximum integration time of $2\,\mathrm{ms}$, also achieved a frame rate of 29 depth images per second for each ToF camera, due to the interleaved frame acquisitions. The reduction of frame rate due to the synchronization procedure, using a synchronization interval of $10\,\mathrm{s}$, was only $3\,\%$ during the experiments, having little impact on the frame rate.

The highest achievable frame rate with TDMA depends on the longest allowed integration time. The maximum number of operating ToF cameras, without decreasing the frame rate, depends on the hardware (readout time, frequency stability, and synchronization error) and the scene (maximum integration time).

VI. Conclusion

A multi-ToF-camera operation is possible, where the cameras synchronize their acquisition times optically to achieve a sequential non-interfering camera operation using only their built-in functionality. The reduction of frame rate due to the additionally required synchronization procedure was only $3\,\%$ during the experiments. In this setup, the three ToF cameras each acquired 29 depth images per second.

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