Frame Synchronization of High-Speed Vision Sensors with Temporally Modulated Illumination

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論文内容の要旨

第1章 Introduction

The emphasis of vision sensor technology becomes more and more evident in various visual measurements, such as automotive, human machine interface, surveillance and security, and industry control. Although the performance of machine systems has not been high enough for these types of applications owing to hardware limitation, systems having near-human capabilities were beginning to appear as a result of the progress of semiconductor technology and the introduction of new sensory information processing methods. For example, if we introduce a vision sensor for high-speed visual information and proposed an appropriate control algorithm for the vision sensor utilizing some unique features, real-time visual measurement and wearable biometrics devices will be achieved.

When multiple vision sensors are used to acquire images of a scene from multiple points of view to achieve, for example, cooperative tracking, wide area monitoring, or 3D motion measurement, the image sequences given by the sensors should be synchronized.

Ideally, synchronization can be achieved without any external triggers or references. A great number of efforts have been done in the computer vision field. Camera synchronization problem was first raised as early as in the beginning of the 20th century, for the sake of silent film. Nowadays, the same issue arises in the fields of stereoscopic and multiview imaging, along with the emergence of computer vision techniques, which requires the acquisition of synchronization to the milliseconds in real time. Multiple groups of images bring much more valuable additional information, such as the depth parameter, to perform accurate measurements in the real world, without the limitation of one-view measurement techniques. Similarly, several image records of the same event help to settle controversies in the sports games.

第2章 Basic Illumination-based Synchronization

For better understanding of the proposed method, we first describe an overview of the PLL theory. The phase-locked loop was introduced in 1932 by de Bellescize. At the present time, it is found in every home: in radio, telecommunications, computers and other electronic applications. It may generate stable frequencies, recover a signal from a noisy communication channel, or distribute clock timing pulses in digital logic designs.

A PLL is a circuit which causes a particular system to track with another one. More precisely, a PLL is a circuit synchronizing an output signal (generated by an internal oscillator) with a reference or input signal in frequency as well as in phase. In the synchronized state the phase error between the oscillator's output signal and the reference signal is zero, or very small. If a phase error builds up, a control mechanism will act on the oscillator in such a way that the phase error is again reduced to a minimum. In such a control system the phase of the output signal is actually *locked* to the phase of the reference signal. This is the reason why it is referred to as a phase-locked loop.

第3章 Signal Normalization for Illumination-based Synchronization in Dynamic Scenes

We have been working on the development of synchronization techniques for multiple vision sensors utilizing optical trigger information from an illumination source. Here, we refer by the term synchronization to produce synchronized vision frames in image acquisition, instead of establishing correct correspondence between the vision frames.

This phase-locked imaging method essentially relies on the time correlation of the reference and the output signals to regulate the relative phase difference between both signals to a certain value by way of negative feedback, as reviewed in Section 2 in more details. Since the time correlation depends on the relative phase difference and also on the amplitudes of the two signals, we need to know the amplitudes of the signals to ensure that the stability of the control of the phase difference.

However, knowing a priori the amplitude of the reference signal is in general difficult. Because the reference signal emitted by the light source is reflected by the scene and then received by the imager, the spatial configuration of scene objects, the light source and the vision sensors must be known. Moreover, since synchronization of vision sensors are needed when one observes dynamic scenes, this configuration, and thus the amplitude of the reference signal, is dynamically changed due to the motion of scene objects, the light source and the vision sensors. Therefore, we need to estimate the reference amplitude in real time and normalize the signal with respect to this estimated amplitude.

It should be noted that simply taking the time average of image brightness does not give correct estimation of the reference amplitude because there may be background light whose intensity is also unknown. In this paper, we apply the quadrature detection technique to our method in order to separate the reference signal component from the background light. The quadrature detection is a common technique for recovering the amplitude and the phase with lock-in measurement. Our contributions are to integrate it into the frame-based operation of a normal vision sensor and to show that it works even in the cases with shorter photo integration time than the full frame time.

第4章 Frame Indexing with Temporally Coded Illumination

After vision sensors are successfully synchronized even in highly dynamic environment, it is necessary to temporally align the images taken by multiple vision sensors by distinguishing the index of each frame sequence and then to successfully reconstruct the images. It is of essential importance to index the successfully frame synchronized multiple video sequences described before. Previously, the illumination-based synchronization with intensity modulated illumination only realized the synchronization of frequency and frame, but not the synchronization of time yet. There are many industrial cameras equipped with wired synchronization trigger inputs/outputs, which send/receive only triggers for shutter timing but without information on frame correspondence, nevertheless they are still useful in many applications. However, adding the facility for frame indexing is not always necessary, but will be sure to expand the application scope.

Although there are many state-of-the-art researches into the temporal indexing technique for wireless communication, we would like to conceive of the most convenient and straightforward temporal indexing method to identify the images taken by the illumination-based synchronized vision sensors. Fortunately, this issue can be addressed due to the virtue of the serial communication mechanism, as well as the virtue of signal normalization technique. If the reference illumination can be modulated to specific format, the images taken with respect to the modulated illumination will carry the sequential information because the reference illumination also plays the role of light source to the vision sensors. In this way, the images can be indexed simultaneously with the synchronization by intelligently encoding the reference illumination. According to the property of the illumination-based synchronization, the reference signal can be encoded by various schemes as long as synchronization is still successful. Temporal indexing in general involves two concepts: one is to add a symbol to the continuous output frames to distinguish a starting time for each images sequence taken by multiple synchronized vision sensors within a work period, with regard to the network protocol, and the other is to refer to the concept of pseudo random binary sequence, such as m-sequence, to distinguish where the image sequences are. The former must modulate a starting time symbol to the regular reference sequence to mark a correspondence time for multiple output image sequences, and can be naturally implemented to the illumination-based synchronization. Therefore, this dissertation deals with the former solution and aims at proposing a straightforward way to distinguish the sequences of vision frames. Based on the time correlation calculation method in the illumination-based synchronization algorithm, even if some bright reference frames are made dark intentionally to generate the index, owing to the virtue of signal normalization method, the synchronization can still tolerate such kind of amplitude fluctuation, while realizing the frame indexing. Many intelligent encoding schemes may be feasible to generate the frame indexing, as long as there are enough bright reference periods to maintain synchronization.

In the most ideal situation, one header for the reference signal is enough to distinguish all the output frame indices, and it is unnecessary to encode the index into a number. However vision sensors do not always work in the ideal situation, because a surveillance system may work all day long, which contains a large number of camera work periods. In the real world situation, it is desirable to index different headers to be different sequential numbers when a large quantity of images is taken during different work periods.

第5章 Conclusions

In this dissertation, the author proposed an innovative frame synchronization of high-speed vision sensors with temporally coded illumination. A phase-locked loop is implemented to synchronize the electronic shutter of high speed vision sensors, by using the time correlation of the reference signal, which is intensity modulated LED illumination with a frame rate of 1,000 fps.

Previously, the conventional synchronization methods of ordinary vision sensors require a cluster of cables to transmit synchronization signals. Dissimilarly, an advanced illumination-base synchronization technique proposed in this dissertation aims to eliminate the bulky communication cables by employing visible light communication, and achieves high quality synchronization results.

Chapter 2 introduces the basic illumination-based synchronization, which is the foundation of the author's research. After a short retrospect of the PLL theory, the synchronization algorithm based on the time correlation feedback control is described. The slight internal robustness to the background light and noise is proven. Both simulation and experiment results reveal the success of this method. The performance evaluation is carried out to mea sure the properties and the jitters theoretically and practically. However, in the real world experiment, the basic synchronization is not robust to rotating targets in dynamic scenes.

To make the system robust to drastic illumination amplitude fluctuation, in Chapter 3, a signal normalization technique based on quadrature detection is employed to remove amplitude fluctuation of the references signal. The signal normalization technique turns out to be effective in both simulation and experiment. A high-speed rotating target in dynamic scene is tested to find out that the illumination-based synchronization employing signal normalization can tolerate as much as 246 Hz high-speed rotation of the targets in dynamic scenes. Therefore, the utility of the synchronization technique can be expanded to a wider field, such as pan-and-tilt cameras, in dynamic scenes with strong fluctuation of both modulated illumination and background illumination. Some inherent disadvantages, such as inherent un-illuminated vision frames, can be solved by applying background light along with the modulated reference illumination. To enhance the system performance, a moving window with per frame feedback of the time correlation is employed, as well as a PI controller to eliminate the frequency mismatch.

To index the sequential information of images taken by multiple vision sensors, a temporally encoded illumination-based synchronization mechanism is introduced in Chapter 4. By encoding the sequential information to the reference illumination, which also serves as the light source to vision sensors, the images taken by vision sensors can be indexed correspondingly. Some bright reference periods can be selectively made into dark ones to generate the index, owing to the synchronization algorithm, which can eliminate all sorts of amplitude fluctuation. Therefore, in the locked state, the output frames can be indexed at any required starting time point. After the simulation ensures the feasibility of this Manchester Encoding modulation, successful real world experiments are carried out by implementing various indices to prove the practicability of the indexing mechanism. It is also found out that with the help of the signal normalization technique the Manchester Encoding synchronization can also tolerate as high as 228 Hz high-speed rotating target in dynamic scenes.

Although our technique has considerable advantages, it also has some trivial disadvantages, such as eye annoyance at low frequency by visible light communication and inability to synchronize ready captured image archives. In these cases, the wireless communication and computer vision synchronization are more useful. However, there are situations in which our technique is essentially important, such as disaster scenes where cables cannot be arranged, high-speed targets in the dynamic industry fields, and mobile cameras without dedicated receiver for radio signal. The author looks forward to the popularization of this technique in near future.

To conclude, a novel frame synchronization technique of high-speed vision sensors with temporally modulated illumination is successfully realized. The system performance is satisfactory compared to the state-of-art techniques, and some vital issues, such as highly dynamic scenes, mobile cameras, and sequential information of image sequences, are also successfully addressed.

論文審査結果の要旨

高速に運動する対象を複数のビジョンセンサで高精度に計測しようとする場合，ビジョンセンサ間の時間同期が重要となる。撮影された画像情報のみから同期を抽出する方法も多数提案されているものの，常に容易に確実に実行できるとは限らず，現実的には外部参照信号に合わせて撮像タイミングを制御することが広く行われている。専用線や汎用通信バスにより同期信号を分配する方法が典型的である。ビジョンセンサ配置の柔軟さや設置の容易さのためには無線通信による信号の分配が望まれるものの，特に高速度撮像を目的とする際には遅延変動が無視できず，十分な同期精度を確保するのが容易ではない。これに対して本研究では，時間変調を施した照明光を参照信号とし，この参照信号への撮像タイミングの同期を実現する手法を提案している。本論文はその成果をまとめたものであり，全編 5 章からなる。

第 1 章は序論であり，本研究の背景，目的および構成を述べている。

第 2 章では，方形波による振幅変調を施した時間変調照明に基づく同期手法を提案している。提案手法は，画像処理結果のフィードバックによる撮像フレーム時間の微小調整を通じて，時間変調光を参照信号，ビジョンセンサの状態を出力信号とする位相同期ループ系を構成するものであり，高精度の同期が実現されている。これは重要な成果である。

第 3 章では，ビジョンセンサ，照明光源，視野内の物体の相対位置関係の変化等により，ビジョンセンサが受け取る変調光の振幅が動的に変化するような状況においては，第 2 章で提案した手法がうまく動作しないことを指摘し，それを解決するために直交検波を用いることを提案している。ここで，露光時間がフレーム時間より短い一般のビジョンセンサを用いた場合，直交検波を素朴に導入すると非露光時間の存在により同期精度が著しく低下することを指摘し，これを回避する方法を提案している。これは極めて重要な成果である。

第 4 章では，2 値の時系列として符号化されたタイムスタンプ情報を埋め込んだ変調照明を用いることにより，撮像フレームの位相を同期させるだけでなく，フレーム間の対応づけも行うための方法について検討している。参照信号系列によっては位相同期が正常に動作しないことが問題となるが，符号化方法が一定の条件を満たす限り，参照信号が単純な方形波の場合との違いは実効的な受信振幅の違いに帰着できることを指摘し，したがって第 3 章で提案した手法が有効にはたらくことを示している。これは有用な成果である。

第 5 章は結論である。

以上要するに本論文は，時間変調を施した照明光を参照信号として，高速度撮像を行うビジョンセンサの撮像タイミング同期およびフレーム間対応づけを実現するための技術を提案したものであり，システム情報科学および計測工学の発展に寄与するところが少なくない。

よって，本論文は博士(情報科学)の学位論文として合格と認める。