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Improved Modulation Techniques for Time-Of-Flight Ranging Cameras using Pseudo Random Binary Sequences

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A Current Assisted Photonic Demodulator (CAPD) correlates received modulated light with the original modulating signal and can be used as pixel in real-time 3D cameras. We show how the use of well-chosen Pseudo-Random Binary Sequences (PRBS) as modulating signals allows multiple 3D cameras to operate in the same area by reducing crosstalk and increases the maximal unambiguously measurable distance. Simulated results are compared to measurements performed on a CAPD-based circuit developed in our lab. The influence of parameters such as the length and base frequency of the PRBS on the measurements is also discussed.

Introduction

Ever since the first working model of the radar was demonstrated in 1936, scientists have continued research on distance measuring devices. Most efforts have been focused on improving performance of devices that measure the distance to a single point. Several applications, however, require complete 3D information analogous to human vision about their surroundings. Many attempts to provide such 3D information, including stereovision, depth-from-focus and structured light, fall short in providing both high framerates, high accuracy, high dynamic range and a low cost implementation. Recent breakthroughs in research on CAPD structures [1] predict a promising future for Time-Of-Flight based 3D cameras, which could outperform other approaches in all areas mentioned above.

Principle of operation

Three-dimensional information about the environment is gathered by means of the Time-Of-Flight principle, which is illustrated by Figure 1. A continuously modulated near-infrared (NIR) light wave is sent out by the camera, which travels towards the scene and is reflected. These reflections are focused on the newly developed camera chip, where they are correlated with the original waves. From these correlation values, the total traveling time of the light wave can be extracted. Because the NIR light is transmitted towards the whole scene, every pixel of the camera continually receives reflections. This allows all pixels to perform their correlations concurrently, making the 3D camera useful for real-time applications.

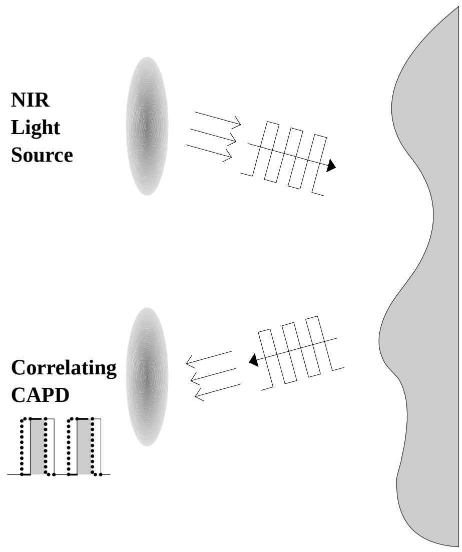

Figure 1: 3D camera based on the Time-Of-Flight principle

Correlation models of modulating signals

Correlation between the original modulating signal and the reflected modulated signal is performed by the CAPD. As the distance to the object increases, the phase shift between the original modulating and the received signal increases, and the correlation between them decreases. The trajectory of this correlation value for varying phase shifts follows the autocorrelation function of the modulating signal.

A straightforward approach would be to use a square wave as modulating signal. Figure 2 displays the theoretic autocorrelation function of a square wave, compared to measurements performed on one of our CAPD enabled devices. The result was obtained by artificially shifting the phase of the reflected signal, and displays the normalized correlation between the original modulation signal and the reflected modulated signal, with B indicating the amount of phase shift corresponding to 1 bit. In order to obtain the measurement below, a 500 kHz square wave was used as modulating signal.

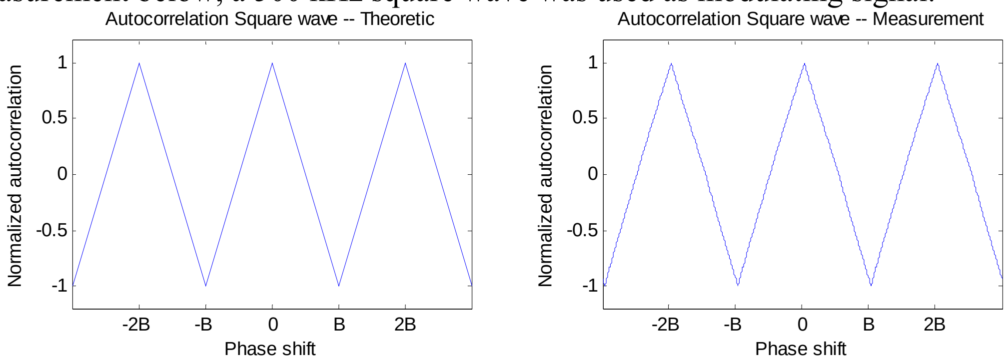

Figure 2: Theoretic and measured autocorrelation function of a square wave

From any normalized value δ found within the [0, B] region, one can easily find the corresponding distance D the light has traveled using Equation 1, where c is equal to the speed of light and f indicates the frequency of the modulating signal.

$$D = \frac{(1-\delta)}{2} \cdot \frac{c}{f}.$$

Equation 1: converting correlation to distance

Using a square wave as modulating signal, one can define 2 problems:

1. Every correlation value $x = \delta + k \cdot B$ corresponds to the same distance as δ corresponds to. This means the measured distance is not unambiguously defined.
2. In the event of 2 cameras operating in the same neighborhood, crosstalk will occur if both cameras are using the same modulating square wave.

In order for the Time-Of-Flight based 3D camera to be of general interest, both problems need to be solved. These problems of autocorrelation have been identified in the field of communications [2] , and certain results of research on that area can be reused here. Figure 3 displays the theoretic autocorrelation function on the left of the image for a maximal-length PRBS sequence (m-sequence) of 15 bits. On the right, a measurement is shown where the same m-sequence was used as modulating signal. The normalized correlation was plotted against the applied phase shift.

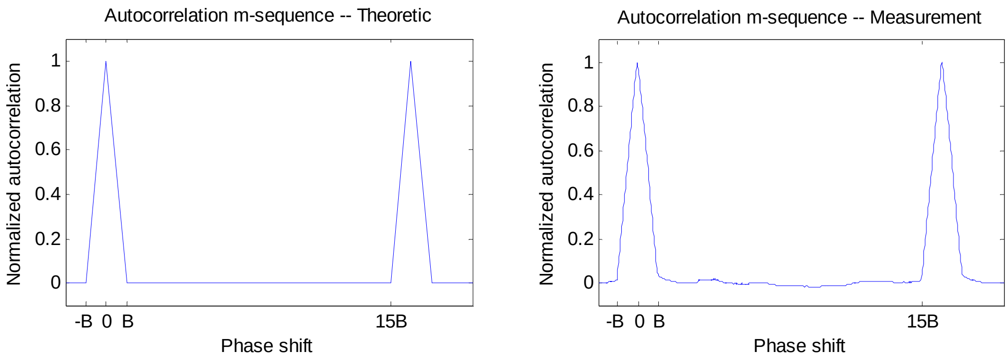

Figure 3: Theoretic and measured autocorrelation function of a maximal-length sequence of 15 bits

However, to obtain the normalized correlation, multiple measurements need to be conducted. Using the approach described in [3], 4 signals are required. These signals consist of the correlation between the original modulating signal and the reflection light modulated by:

- the original modulating signal, yielding S0 (see also Figure 3)
- the inverse of the modulating signal, yielding ~S0
- the original modulating signal, shifted by one bit, yielding SB
- the inverse of the original modulating signal, shifted by one bit, yielding ~SB

The simulation of these correlation values is shown in the left part of Figure 4. Measurements of those 4 signals on a CAPD enabled device are shown on the right part.

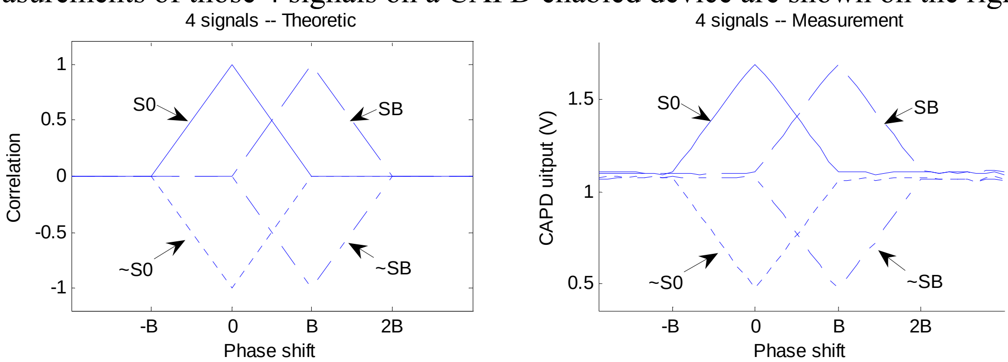

Figure 4: Theoretic and measured correlation functions of the 4 m-sequences

One can notice the slight offset between the positive and inverse signal in the measurements. This offset is due to the fact that a complete m-sequence of $2^n - 1$ bits contains 2^{n-1} '1' bits and only $2^{n-1} - 1$ '0' bits. Hence, averaged over a complete m-sequence, the correlation with a positive signal will be higher than the correlation with an inverse signal. Because of this, the offset decreases as the length of the m-sequence increases, which is shown in Figure 6.

By subtracting the inverse signals from the corresponding positive signals, one obtains the nil-referenced discriminator signals C1 and C2. The difference between C1 and C2, D, must be divided by the normalization factor N, which is the sum of C1 and C2, to obtain the normalized function F, which is linear in the [0, B] region. Each value in this interval corresponds to exactly 1 distance, which can be calculated using Equation 1.

The simulated functions for D and N are shown on the left side of Figure 5. On the right side, you find the measured values, as well as the normalized discriminator characteristic for the [0, B] region, which has a standard deviation of only 0.54%.

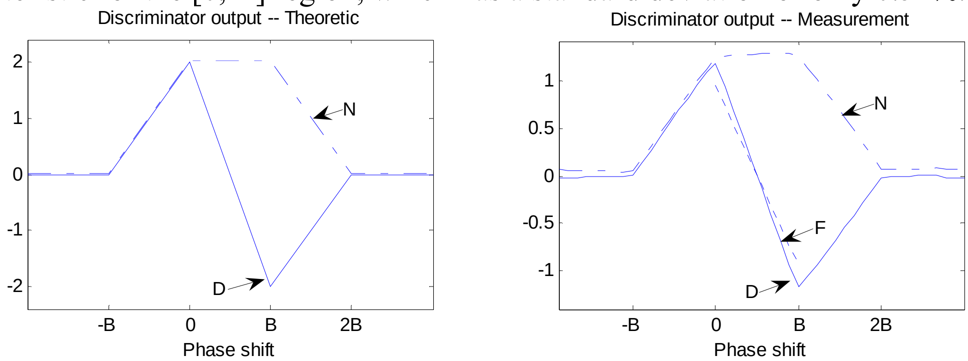

Figure 5: Theoretic and measured discriminator functions of the 4 m-sequences

Discussion & Future work

M-sequences can be used as modulating signal for Time-Of-Flight based 3D cameras. When the base frequency of those m-sequences is raised, the linearity of the discriminator function suffers, as displayed in Figure 7. Future research is necessary to model the causes of these non-linearities, and to find a way of correcting them.

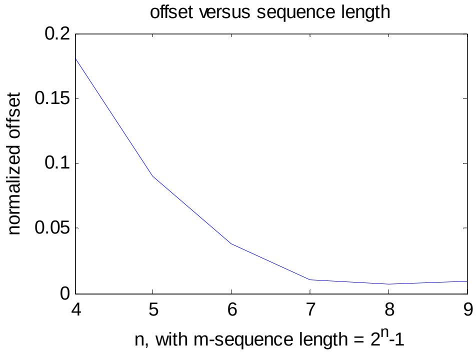

Figure 6: Correlation offset between positive and inverse signals versus m-sequence length

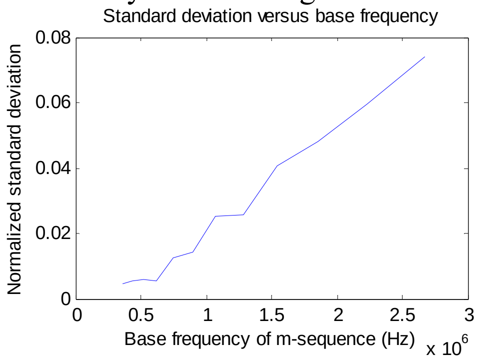

Figure 7: Normalized standard deviation between the [0,B] region versus base frequency

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