FFT-BASED CROSS-COVARIANCE PROCESSING OF OPTICAL SIGNALS FOR SPEED AND LENGTH MEASUREMENT

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ABSTRACT

The National Optics Institute has recently developed an optical velocimeter composed of two parallel laser beams for measuring perpendicularly the speed and the length of vehicles. The system must be capable of measuring speeds varying from 0 to 150 km/h in both directions with an accuracy of 1%. This paper focuses on the algorithms and signal processing aspects of the system. The speed is measured by estimating the time delay using an FFT-based cross-covariance method between the signals generated by the optical velocimeter. The length is estimated using the speed and the time window corresponding to the entire vehicle. The measurement algorithm has been implemented to run in real time on a C31 DSP and a 486 processor.

INTRODUCTION

Optical contactless speed measurements of linearly moving objects, based on the computation of the cross-correlation of two time delayed signals, have gained popularity over the years with the availability of reliable and low cost optical sensors. The application considered here involves the perpendicular measurement of vehicles' speed and length. With the increasing number of vehicles on the roads, surveillance has become a key factor in the field of traffic management. The monitoring of the various traffic parameters, such as speed and flow, requires the use of sensors. Existing technologies include microwave and ultrasonic radars, induction loops and piezoelectric tubes. For certain types of road conditions, the functionality of these sensors may become limited (e.g. induction loops on metallic structures, microwave radars in tunnels). In view of this, the National Optics Institute has developed an optical velocimeter for measuring perpendicularly the speed of vehicles [1]. This paper presents the algorithms that process the optical velocimeter's signals to estimate in real time the speed and the length of vehicles on the road. The specifications state that the system must be capable of measuring speeds varying from 0 to 150 km/h in both directions with an accuracy of 1%. The length of the vehicles must also be measured.

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THE MEASUREMENT SYSTEM

Speed estimation relies upon measuring the time required for a linearly moving object to go over a fixed distance D. The velocimeter is composed of two eyesafe parallel laser beams operating at two different wavelengths (see Figure 1) and separated by a distance D. It is assumed that the axis joining the two detectors is parallel to the displacement of the moving vehicle. When a vehicle passes in front of the velocimeter, the laser light is diffused on its surface. The diffused light is then focused on the two photodetectors, each one optically filtered for each laser wavelength. We thus obtain two signals, $x(t)$ and $y(t)$, which represent the fluctuations in time of the intensity of the light diffused by the vehicle. Since the laser beams are separated by a distance D, one of the signals is simply a delayed version of the other.

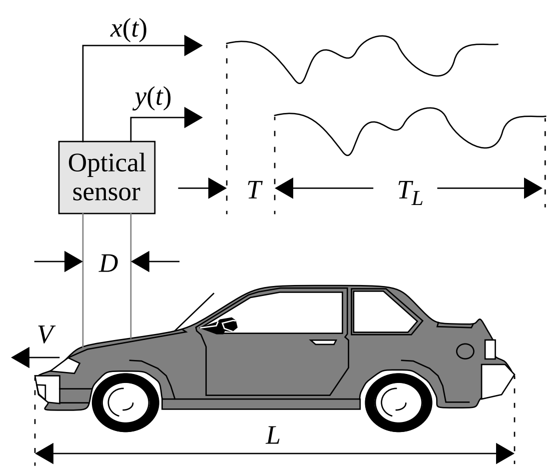

Figure 1. Operation of the optical velocimeter.

Upon estimating the delay T between $x(t)$ and $y(t)$, the speed of the vehicle is readily computed as,

$$V = \frac{D}{T} . \qquad (1)$$

Furthermore, if we can determine the time window T_L corresponding to the entire vehicle, then the length L of the vehicle is:

$$L = V \cdot T_L \quad . \tag{2}$$

SPEED AND LENGTH ESTIMATION

The sampling period is defined as ΔT, i.e., the signals are sampled at $t = n\Delta T$, where n is the sample index. Considering the sampled version x[n] and y[n] of the band-limited signals x(t) and y(t) respectively, we start with the convolution between the N-point segments $x[n]$ and $y[n]$ defined as

$$x[n] \otimes y[n] \quad . \tag{3}$$

Then their cross-correlation can be written as

$$R_{xy}(\tau) = x[-n] \otimes y[n], \tag{4}$$

where $-n$ indicates time reversal and τ the time delay. If $x[n]$ and $y[n]$ have non-zero mean values, defined as μ_x and μ_y, then these will be accumulated in the cross-correlation and the position of the maximum value will become erroneous. To circumvent this, we must subtract the mean from each signal before computing $R_{xy}(\tau)$. The result of this operation yields the cross-covariance:

$$C_{xy}(\tau) = (x[-n] - \mu_x) \otimes (y[n] - \mu_y) \quad . \tag{5}$$

The computational burden associated with $C_{xy}(\tau)$ is largely reduced if we make use of the frequency domain representation. In this case, the convolution operation becomes a multiplication. Thus, defining $X[k]$ and $Y[k]$ as the fast Fourier transform (FFT) of $x[n]$-μ_x and $y[n]$-μ_y respectively, and $F^{-1}\{\ \}$ as the inverse FFT operator, we obtain

$$C_{xy}(\tau) = F^{-1}\{X^*[k] \cdot Y[k] \quad , \tag{6}$$

where * stands for complex conjugation. The product of 2 FFTs is actually a circular convolution. To obtain a linear convolution, $x[n]$ and $y[n]$ must first be zero-padded to $2N$ points. According to (6), a total of 3 FFTs have to be performed in order to compute $C_{xy}(\tau)$. Since the input to the FFT is a complex sequence and $x[-n]$ -μ_x and $y[n]$ -μ_y are real sequences, $X[k]$ and $Y[k]$ can be computed using a single FFT. Let $z[n]$ be the complex sequence

$$z[n] = x[n] + jy[n] \quad . \tag{7}$$

Using the linearity property, the FFT of $z[n]$ is

$$Z[k] = X[k] + jY[k] \, . \tag{8}$$

$X[k]$ and $Y[k]$ can then be recovered from $Z[k]$ using simple manipulations [3]. The cross-correlation measures the degree of similarity between two signals as a function of the time delay τ. In the absence of any *a priori* information about the signals, the time delay τ corresponding to the maximum value of the cross-correlation function is our best estimate of T. Using this estimate and the value of D, we recover V from equation (1). Classical time delay estimators based on correlation and covariance functions are not always optimal in a statistical sense but provide excellent results in the frequency band where the signals are coherent, which is the case here. Indeed, we can assume with this application that the instantaneous speed of the vehicle remains constant when both signals are being measured over the length of that vehicle. In other words, distortion of the correlation peak due to the non-stationarity of the signals, caused by speed variations of the vehicle during measurement, is considered here negligible. The correlation-based estimators are also relatively simple to implement, making them suitable for real-time applications.

Computing the length of vehicles requires the estimation of T_L, which corresponds to the time during which the vehicle is in the velocimeter's field of view. T_L is estimated using a simple threshold-based detection scheme where the car signatures are being discriminated against the background signal. A signal segment must be below the threshold for a minimum period of time in order to be classified as background, thus specifying the beginning and the end of the vehicle.

SYSTEM DESIGN SPECIFICATIONS

According to (1) with D being constant, if V is to have an accuracy of 1% then the estimated value of T must also have the same accuracy. Such an accuracy cannot be reached if the resolution, which is equivalent to the sampling period ΔT, exceeds 1% of T. Thus, we have

$$\Delta T \le \frac{T}{100} \quad , \tag{9}$$

i.e., a minimum of 100 samples must be acquired over the distance D. For a given speed, we can now determine the maximum sampling period required. Substituting (9) into (1), we obtain

$$\Delta T \le \frac{D}{100 \cdot V} \quad . \tag{10}$$

With D equal to 10 cm and V equal to 150 km/h, the maximum sampling period is 24 µsec. We thus require a maximum sampling rate of 41667 Hz.

In order to keep the same relative resolution throughout the entire range of measurable speeds (which covers 2 orders of magnitude) and to avoid oversampling $x(t)$ and $y(t)$ unnecessarily, the sampling rate must be adapted to the average speed of the traffic. The two signals are subsampled by an integer factor, i.e., samples are taken at a fraction of the maximum sampling rate in order for T to lie between 100 and 199 ΔTs. If the four last estimated values of T lie outside of this range, then the sampling rate is changed accordingly. Figure 2 shows the subsampling factor used versus the speed of the vehicle.

The detection of the presence of a vehicle is done by comparing each signal to a threshold which was determined at initialization time. Assuming that vehicles diffuse more energy than the background, the threshold is

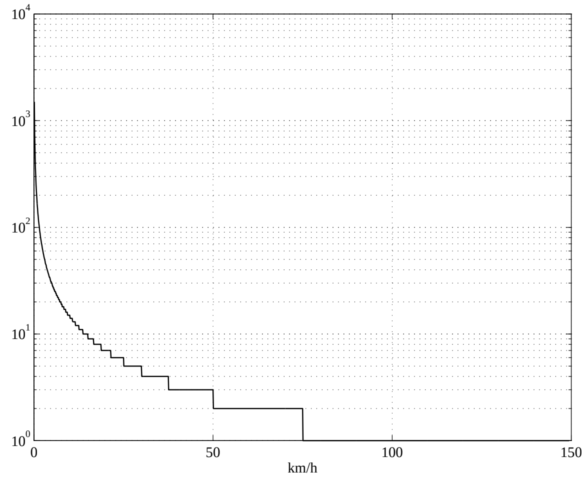

Figure 2. Subsampling factor versus speed.

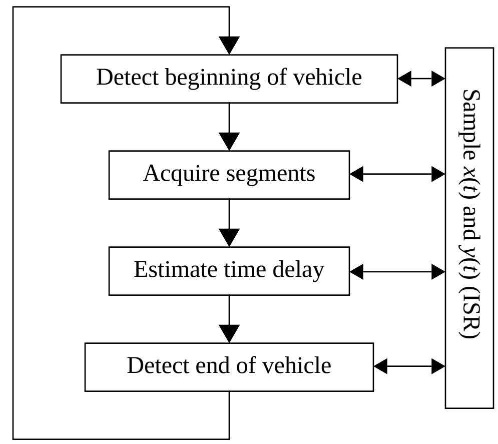

Figure 3. State machine running on the C31.

set to a value above the maximum background level recorded. A detection occurs if either signal remains above its threshold for N_D consecutive samples. With a maximum measurable speed of 150 km/h, the value of N_D, once converted to time, should not exceed 0.5 msec, which represents a vehicle displacement equal to 2 cm.

Once the required sample density is determined, the segment length can be set. Upon detecting a vehicle, two segments of N points are acquired simultaneously. N should be chosen such that the segments cover a length of at least 1 meter on the vehicle. This is to ensure that we have enough information from $x(t)$ and $y(t)$ to properly determine T. Choosing N=2048 yields segment lengths which cover between 1.024 and 2.048 meters on the vehicle. Also, N is a power of 2 and thus is well suited for the FFT algorithm.

Upon estimating T, the end of the vehicle must be detected. This occurs when both signals have returned to a level below the threshold after a minimum period of $5T$, which corresponds to a vehicle displacement of $5D$=50 cm.

REAL TIME IMPLEMENTATION

The algorithms for calculating the speed and the length of vehicles are distributed on two processors: a TMS320C31 DSP with a 60-nsec cycle time and a 80486DX2 PC running at 66 MHz. The C31 is responsible for sampling the signals $x(t)$ and $y(t)$, estimating the time delay between them upon detecting a vehicle, and sending the time delay plus the signature of the entire vehicle to the 486. The 486 then computes the speed and length of the vehicle.

The program running on the C31 is a state machine which comprises four states, as shown in Figure 3. The sampling of the signals $x(t)$ and $y(t)$ is time critical and thus was implemented in an interrupt service routine (ISR). To ensure that the algorithm can actually operate in real time, we must determine the process time associated with each state. The first and last states both work on a sample-to-sample basis with worst case process times (including one ISR) shorter than ΔT. The other two states are more critical. Their combined process time includes the time to acquire the N-point segments and the time to compute T (including one ISR every ΔT).

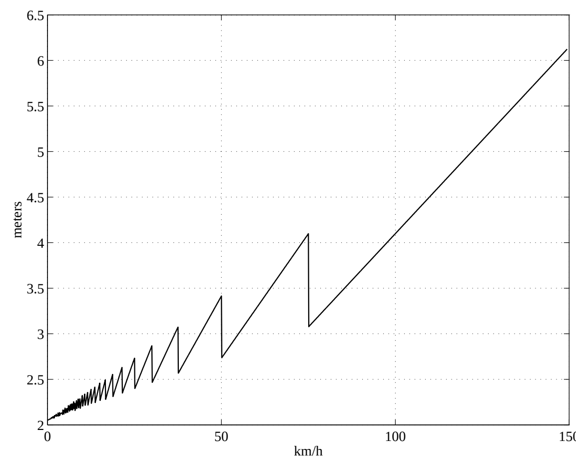

Figure 4. Vehicle displacement during segment acquisition and delay estimation versus speed.

Figure 4 shows the combined process time converted to vehicle displacement versus the speed of the vehicle. The jagged profile is caused by the subsampling factor. This graph shows that it is possible for a vehicle to have moved passed the velocimeter by the time the algorithm starts looking for the end of the vehicle (e.g. a vehicle less than 4.1 m long going at 100 km/h). Thus, the ISR must save a copy of the signal $x(t)$ while T is being estimated and until both signals have returned below the threshold. Then the C31 passes the signature of the entire vehicle and the estimate of T to the 486 and resumes to the first state. The 486 then computes the speed of the vehicle and analyzes the signature in order to identify where the end of the vehicle is actually located.

EXPERIMENTAL RESULTS

Tests were performed using the optical velocimeter in 2 different configurations: above the road and across the road. While the first configuration can only see a single lane, the second configuration allows the velocimeter to survey multiple lanes. However, in such a configuration, the detection success rate is limited due to vehicle overlaps. Figure 5 shows the signatures of the side of a typical automobile, 50 cm above the ground when the velocimeter was looking across the road.

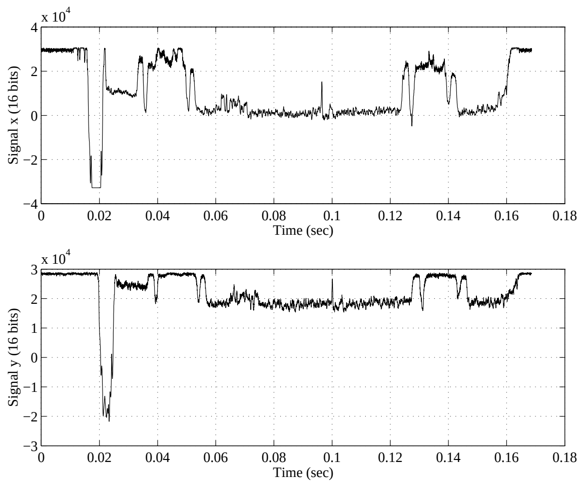

Figure 5. Signatures of the side of a typical car.

When sampling the signals, the polarity is inverted by the A-to-D converters. This explains why the weak background signal, whose level fluctuates around +30000, sits above the car signature. Although this example contains some obvious characteristics about the vehicle (e.g. the two wide upward bumps correspond to the wheels), all signatures from vehicles of the same class do not necessarily bear the same amount of detail. Figure 6 shows the cross-covariance function between the signals of Figure 5. The computation was performed on segments of 57 msec (1.54 m on the car). The maximum value is located at a delay T of 3.7 msec which yields a speed of 97.3 km/h. With T_L=0.146 sec, the length of the car is 3.95 m.

The performance of the algorithm was evaluated in the field. Tests were performed along a 3-lane metropolitan highway. The detection success rate was 90%. Vehicle flows requiring as much as 5 detections/sec were successfully processed. The misses due to vehicle overlaps were visually evaluated to account for 15% of the total count. The count recorded by the algorithm was sometimes higher than the actual number of detectable vehicles since trucks with 1 or 2 trailers would be perceived as several vehicles. Our speed and length estimation schemes gave correct results 95% of the time. Faulty speed estimations occur when there are not enough features common to both car signals or when the signal-to-noise ratio is very low.

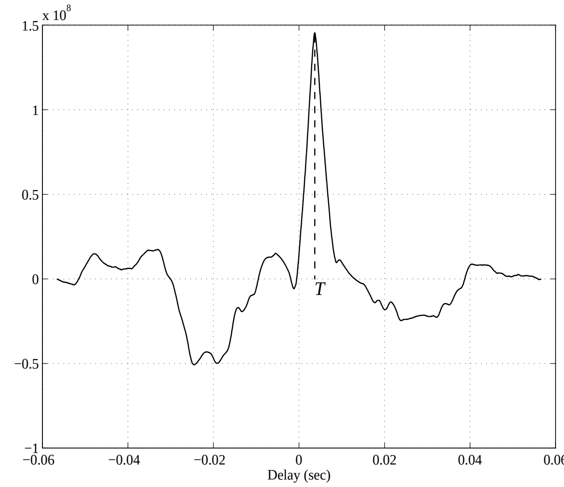

Figure 6. Cross-covariance between the signals of Figure 5.

CONCLUSION

An algorithm that estimates the speed and the length of vehicles in real time was presented. The results obtained show that the system constitutes a promising technology in the field of transportation. Target applications include police radar, remote sensing for vehicle statistics and traffic surveillance. As part of further studies, the 1% accuracy of the speed estimates will be verified in the field using an independent calibrated instrument. The vehicle detection scheme will be improved in order to adaptively follow the background level as the climatic conditions change, and to allow background levels to lie within the dynamic range of the signals. The hardware is being reviewed to consider a single DSP architecture with a shorter cycle time.

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