3P-18

Proceedings of Symposium on Ultrasonic Electronics, Vol. 31 (2010) pp. 491-492
6-8 December, 2010

An Accurate Estimation of 3D Position and Velocity Using Extended Phase Accordance Method and Adaptive Filtering

拡張位相一致法と適応的フィルタリングを統合した高精度な超音波位置速度推定

Shigeki Nakamura[1‡], Tomohiko Sato[1], Masanori Sugimoto[1] and Hiromichi Hashizume[2]
([1]Univ. of Tokyo; [2]NII)
中村 成希 [1‡], 佐藤 智彦 [1], 杉本 雅則 [1], 橋爪 宏達 [2]（[1]東大；[2]国立情報学研究所）

1. Introduction

An ultrasonic localization system is described in the paper. To the best of our knowledge, this is the first system that can simultaneously identify not only the 3D position,[1)] but also the velocity of a moving object. The proposed system uses an original and innovative method called “extended phase accordance method” (EPAM) that can precisely identify the distance between an ultrasonic microphone and a moving transmitter by rapidly estimating the frequency shift of the transmitted signal. Another remarkable feature of the proposed system is that only a single compact receiver unit is required for 3D position and velocity measurements, which reduces deployment labor and cost. In order to further improve the estimate accuracy, we apply the Kalman Filter (KF) to our system. Experiments proved that the 3D position and velocity estimation of the proposed system was improved by the filter.

2. Proposed Method

2-1. Extended Phase Accordance Method

EPAM is an extended version of the phase accordance method (PAM) for localizing a moving object. In PAM, a burst signal called “sync pattern” composed of two ultrasonic waves with different frequencies is sent from a transmitter, as shown in **Fig. 1**. To identify the time of arrival (TOA) of a sync pattern, an epoch at which the phase difference of the waves becomes zero is set at the transmitter and is precisely detected at the microphone.[2)] When a transmitter moves, the frequencies of the transmitted waves change because of the Doppler effect and PAM does not work properly. Despite the Doppler effect, the amplitude of the signal from the transmitter does not change. When the frequency shift is unknown, the amplitude is not correctly estimated by using quadrature detection. However, when the frequency shift is known, the correct amplitude can be found through quadrature detection using a sinusoidal wave of any frequency. This means that by conducting quadrature detection with two waves with different frequencies and assuming that the amplitudes obtained through them become equal, the frequency shift of the received signal is correctly estimated. In our current implementation, we used two different reference frequencies (39.75 and 40.25 kHz) and confirmed that this unique method can rapidly and accurately identify the frequency shift of the transmitted signal.[3)]

2-2. Estimating 3D Position and Velocity

In TOA-based ultrasonic localization, theoretically, the 3D position of an object (e.g., transmitter) is calculated as an intersection point of three spheres whose centers (e.g., microphones) are at different fixed points. In reality, however, the measured distance between a transmitter and a microphone includes errors. 3D positioning errors can be reduced by making the baselines between the microphones longer. On the other hand, we designed a compact receiver unit by mounting microphones with a small baseline, because EPAM performs accurate distance measurements. In our current implementation, four microphones (baseline 76.2 mm) on the unit were used to detect distances to the transmitter and estimate its 3D position. The velocity vector of the transmitter was obtained so that the equations $v \cdot u_i = v_i \quad (i = 1,2,3,4)$ are satisfied, as shown in **Fig. 2**, where v is the velocity vector, u_i is the unit vector directed from the transmitter to the i^{th} microphone, and v_i is the detected velocity at the i^{th} microphone based on frequency shifts of transmitted signals from the transmitter.

2-3. Kalman Filter

The Kalman Filter (KF) is a mathematical method which recursively evaluates an optimal estimates of the state of a linear system. We designed an KF using a state vector $\boldsymbol{\mu}$ with 12

---

‡shigeki@itl.t.u-tokyo.ac.jp

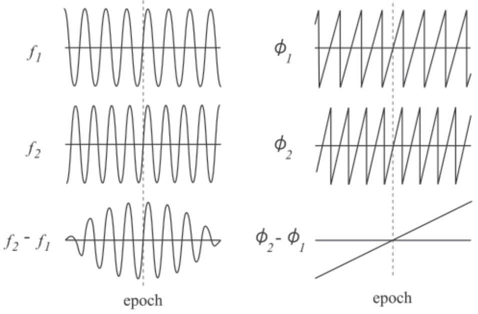

Fig. 1 Sync pattern and epoch

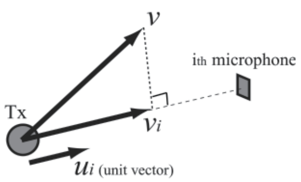

Fig. 2 Geometric relation between Tx and the ith microphone

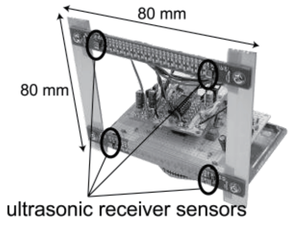

Fig. 3 Ultrasonic receiver unit

components consisting of 4 distance components, 4 projected velocity components and 4 acceleration components. This KF was implemeted based on Equation 1 and 2, which express the state transition and the measurement, respectively.

$$\boldsymbol{\mu}_k = \mathbf{F} \cdot \boldsymbol{\mu}_{k-1} + \boldsymbol{w}_k , \quad (1)$$

$$\boldsymbol{z}_k = \mathbf{H} \cdot \boldsymbol{\mu}_k + \boldsymbol{v}_k , \quad (2)$$

where $\boldsymbol{z}_k$ is the measurement vector whose components are the value that can be obtained using our system at time *k*. $\boldsymbol{w}_k$ and $\boldsymbol{v}_k$ are the vectors of the noise introduced by the state transition and the measurement process, respectively. **F** expresses the state transition matrix and assumes that the tracking object moves at the constant acceleration between the time steps. Δt is the time needed for the transition. **H** relates the state vector to the measument vector, whose size is 8×12.

$$\mathbf{F} = \begin{pmatrix} \boldsymbol{I}_4 & \Delta t \boldsymbol{I}_4 & \Delta t^2 \boldsymbol{I}_4 / 2 \\ \boldsymbol{O}_4 & \boldsymbol{I}_4 & \Delta t \boldsymbol{I}_4 \\ \boldsymbol{O}_4 & \boldsymbol{O}_4 & \boldsymbol{I}_4 \end{pmatrix}, \quad (3)$$

$$\mathbf{H}_{i,j} = \begin{cases} 1 & (i = j) \\ 0 & (i \neq j) \end{cases}. \quad (4)$$

3. Experiments

The experimental setup is shown in **Fig. 4**. The receiver unit whose size is $80 \times 80 \times 60$ mm contains four ultrasonic microphones (SPM0404UD5 by Knowles Acoustics Corporation) as shown in **Fig. 3**. The electrical slider mounts one transmitter (T40-16 by NIPPON CERAMIC Corporation) transmitting a sync pattern composed of 39.75 and 40.25 kHz sinusoidal waves, and moves back and forth perpendicularly to the receiver unit. The distance between the transmitter and the receiver unit varied constantly between 1000~1800 mm. The velocity of the slider was set to 0.1 and 0.5 m/s. The update rate of the 3D position and velocity estimations was set to 5 Hz. Measurements were conducted about 1500 times at each velocity. **Table I** shows that the 3D position estimates of the transmitter were improved by using the KF, at each velocity. The measured velocity results are shown in **Table II**, which also verified the improvement of the velocity estimates by using the proposed KF.

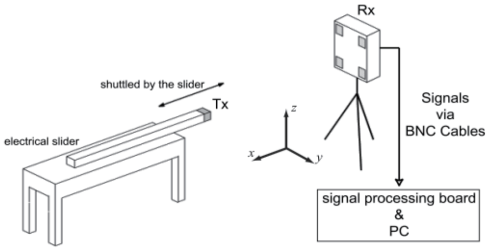

Fig. 4 Experimental setup

4. Conclusion and Future Work

This paper describes an accurate estimation technique of 3D position and velocity using the EPAM and KF. The experimental results prove that the integrated use of them could improve the tracking accuracy of a moving object. One of our future works is to develop innovative applications using this tracking technology, for example, accurate and low-cost gestural interface, and so on.

References

1. M. Sugimoto, K. Tulathimutte, T. Ito, T. Sato and H. Hashizume: *Proc. LOCA, Tokyo, Japan* (2009) 240.
2. H. Hashizume, A. Kaneko and M. Sugimoto: IEICE Trans. **J91-A(4)** (2008) 435[in Japanese].
3. S. Nakamura, T. Sato, M. Sugimoto and H. Hashizume: to be published in *Proc. IPIN, Zurich, Switzerland* (2010).

Table I Results of 3D position estimations
(upper column : without KF, lower column : with KF)

v [m/s]	average error [mm]	S.D. [mm]
0.1	36.0645	18.2219
	26.9611	15.1171
0.5	34.4327	18.7792
	30.9658	18.1993

Table II Results of 3D velocity estimations
(for the same coordinate system shown in **Fig. 3**,
upper column : without KF, lower column : with KF)

v [m/s]	average error [m/s]	S.D. [m/s]
0.1	(-0.0010, 0.0800, 0.1560)	(0.0197, 0.1341, 0.2111)
	(-0.0005, 0.0068, 0.0340)	(0.0103, 0.0532, 0.1152)
0.5	(0.0082, 0.0497, 0.1466)	(0.0238, 0.1554, 0.2613)
	(-0.0086, 0.0351, 0.1111)	(0.0167, 0.1471, 0.2008)