# Sensor Fusion based Measurement of Human Head Motion

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**Abstract: Present VR systems often use unconstrained sensors like Polhemus Tracker. These have advantages of unconstrainedness and wider motion range, but have deficiencies of low sampling rate(~ 60Hz) and critical latency (~ 100ms). This paper proposes a method, which raises the sampling rate and compensates the latency of Polhemus on rotational motion through the "sensor fusion" of gyro sensor, and Polhemus measurements and a method of evaluating the performance of unconstrained motion sensors quantatively. The validity of the methods was confirmed by off-line computation of actual data.**

## 1 Introduction

Motion sensors used in present VR systems are classified into two types. One is the constrained link-type sensor like BOOM, and the other is the unconstrained sensor like Polhemus Tracker. Latter has advantages of unconstrainedness and wider motion range but has deficiencies of low sampling rate(~ 60Hz) and critical latency (~ 100ms). Most present VR systems use raw sensor data in spite of decrease in interactiveness by this latency or try ad-hoc methods in order to compensate the latency such as linear extrapolation from both smoothed measurements and crude estimates of its instantaneous differential of user's motion.

Friedmann et al. [1] pointed out that in such approach user's quick motion causes poor prediction which overshoots or undershoots the actual motion and that users are forced to make slow deliberate motions. They solved this problem on translational motion by means of prediction based on optimal linear estimation theory. However they ignored the rotational motion, which is far critical for HMD, and their solution is not directly applicable to rotational motion because of its non-linearity.

This paper deals with rotational motion of human head. We propose a method which raises the sampling rate and compensates the latency through "sensor fusion" of gyro sensor and Polhemus Tracker based on optimal prediction. Althogh gyro sensor has advantages of high sampling rate and negligible latency and dificency of drift, integration of Polhemus and gyro sensor by the proposed method has shown the better performance as the total sensing system compared with Polhemus Tracker or Fastrak only. In order to apply the proposed method to actual motion data of 3DOF(Degree of Freedom), we derived the dynamic model of human head rotaional motion described by Euler angle and confirmed the validity of this method by off-line computation.

We also propose a method which quantitatively evaluates sensor's delay and fidelity by normaized cross correlation between sensor signal and standard signal. By this mehtod we can mathematically define the sensor delay as the shift time to match wave forms of both signals best. We applied this method for quantitatively evaluating the fidelity of Polhemus Tracker and Fastrak under the effect of metalic objects and various electric waves.

## 2 Sensor fusion based measurement

We define "sensor fusion" as realization of a virtual single sensor, which has higher performance compared with each sensor by processing singals from multilple variant sensors. Because of difference of sensors' sampling frequency combination of available sensors differs at each moment. We propose to predict human head motion by optimal estimation based on the data of available sensors at each moment. This approch aims at making full use

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of the latest available sensors, combination of which is time-variant.

### 2.1 Modelling

We adopt ZYX-Euler angle [2] as the expression of human head motion. Let $r = (\gamma\,\beta\,\alpha)^T$ be the Euler angle of a human head at time $t$, $r'$ be the Euler angle at time $t + dt$. Let $\omega = (\omega_z\,\omega_y\,\omega_x)^T$ be angular velocity of the human head in body coordinate.

Define $F'$ as below.

$$F' \equiv \begin{pmatrix} \frac{\cos\alpha}{\cos\beta} & \frac{\sin\alpha}{\cos\beta} & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ \cos\alpha\,\tan\beta & \tan\alpha\,\tan\beta & 1 \end{pmatrix} \quad (1)$$

$$r' = r + F'\omega dt \quad (2)$$

Then we obtain the process dynamics Eq.(2) expressed by angular velocity in body coordinate and Euler angle.

Let $dt$ be unit sampling interval and $T$ be time lag of measurement of Euler angle. State vector $x$ consists of Euler angle and angular velocities like

$$x = (\gamma\,\beta\,\alpha\,\omega_z\,\omega_y\,\omega_x)^T$$

We use the notation of $r = (\gamma\,\beta\,\alpha)^T$ and $\omega = (\omega_z\,\omega_y\,\omega_x)^T$. By this notation state vector $x$ is expressed as $(r^T|\omega^T)^T$. System model is given by Eq.(4), where $w_n$ is a zero mean white noise whose covariance is given by $Q$. Let $H^p$ be measurement matrix corresponding to simultaneous measurement of both Polhemus and gyro sensor. Let $H^g$ be measurement matrix corresponding to measurement of gyro sensor only. When both Polhemus and gyro sensor are available, the measurement model is given by Eq.(8), where $v^p$ is an additive measurement noise and $R^p$ is its covariance. When only gyro sensor is available, the measurement model is given by Eq.(9) and $v^p$ $R^p$ are an additive measurement noise and its covariance.

$$F \equiv \left(\begin{array}{c|c} I & dt\,F' \\ \hline 0 & I \end{array}\right) \quad (3)$$

$$x_{n+1} = F\,x_n + w_n \quad (4)$$

$$\overline{w_m\,w_n^T} = Q\,\delta_{mn} \quad (5)$$

$$H^p \equiv \left(\begin{array}{c|c} I & -T\,F' \\ \hline 0 & I \end{array}\right) \quad (6)$$

$$H^g \equiv \left(\begin{array}{c|c} 0 & I \end{array}\right) \quad (7)$$

$$y_n^p = H^p\,x_n + v_n^p \quad (8)$$

$$y_n^g = H^g\,x_n + v_n^g \quad (9)$$

$$\overline{v_m^p\,v_n^{p\,T}} = R^p\,\delta_{mn} \quad (10)$$

$$\overline{v_m^g\,v_n^{g\,T}} = R^g\,\delta_{mn} \quad (11)$$

### 2.2 Algorithm

The Algorithm [4] consists of two procedures. Procedure 1 is executed when both Polhemus and gyro measurements are available. Procedure 2 is executed when only gyro measurement is available.

**Procedure 1**

$$x_{n+1/n} = F\,x_{n/n} \quad (12)$$

$$P_{n+1/n} = FP_{n/n}F^T + GQG^T \quad (13)$$

$$x_{n/n} = x_{n/n-1} + K_n^p[y_n^p - H^p\,x_{n/n-1}] \quad (14)$$

$$P_{n/n} = P_{n/n-1} - K_n^p H^p P_{n/n-1} \quad (15)$$

$$K_n^p = P_{n/n-1}H^{p\,T}[H^p P_{n/n-1} H^{p\,T} + R^p]^{-1} \quad (16)$$

**Procedure 2**

$$x_{n+1/n} = F\,x_{n/n} \quad (17)$$

$$P_{n+1/n} = FP_{n/n}F^T + GQG^T \quad (18)$$

$$x_{n/n} = x_{n/n-1} + K_n^g[y_n^g - H^g\,x_{n/n-1}] \quad (19)$$

$$P_{n/n} = P_{n/n-1} - K_n^g H P_{n/n-1} \quad (20)$$

$$K_n^g = P_{n/n-1}H^{g\,T}[H^g P_{n/n-1} H^{g\,T} + R^g]^{-1} \quad (21)$$

The algorithm used in procedures 1 and 2 is the same as that of discrete Kalman filter [3].

## 3 Evalution of sensor delay

In tihs section we propose a method which evaluates sensor delay by normaized cross correlation between sensor signal and standard signal. Set $f(t)$ be sensor signal and $g(t)$ be standard signal. Then cross correlation function $\Phi_{fg}(\tau)$ and normaized cross correlation function $\rho_{fg}(\tau)$ are calculated as below.

$$\Phi_{fg}(\tau) = \lim_{T\to\infty}\frac{1}{T}\int_{-T/2}^{T/2} f(t)g(t+\tau)dt \quad (22)$$

$$\rho_{fg}(\tau) = \frac{\Phi_{fg}(\tau)}{\sqrt{\Phi_{ff}(0)}\sqrt{\Phi_{gg}(0)}} \quad (23)$$

$\rho$ ranges from -1 to 1. If sensor delay is $\Delta t$ and $f(t) \simeq g(t+\Delta t)$, $\rho_{fg}(\tau)$ has a peak at $\tau \approx \Delta t$ and the peak value shows the fidelity of $f(t)$ to standard signal $g(t)$.

Suppose the noise on $f(t)$ be an additive random one and be uncorrelatied to standard signal $g(t)$. Set signal power $S$ and noise power $N$. Then $\Phi_{ff}(0) \equiv S+N$ and $\Phi_{gg}(0) \equiv S$. Then peak value is nearly $\sqrt{\dfrac{S}{S+N}}$.

$$\frac{\mathrm{N}}{\mathrm{S}} = \left(\frac{1}{\text{peak value}}\right)^2 - 1 \tag{24}$$

By this N/S rate we quantatively estimate the effects of mettalic object and various electric waves around the Polhemus.

## 4 Experiment

### 4.1 Experimental system

In order to evaluate performance, we compared the result of the proposed method with measurement of link-type sensor [5]. The precision of link-type sensor (accuracy 0.0125 deg. resolution 0.025 deg.) is much better than that of Polhemus Tracker (accuracy 0.1 deg. resolution 0.5 deg.) because rotation angle of each joint was measured by high-precision optical encoder and up-down counter. Lead-time of this up-down counter 2 $\mu s$ and CPU performance determine the delay of this system. This system with 80286 (10MHz) measurerd operator's motion and controled the robot at least 300Hz. So response and communication delay of this link-type sensor is negligilbe compared with Polhemus ($\sim$ 80 ms). We use measurement of this link-type sensor as standard signal.

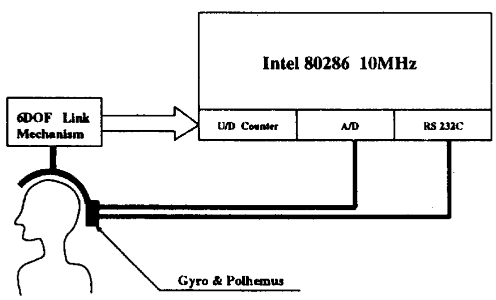


Fig.1 Configuration of experimental system

### 4.2 Noise parameter

Covariant matrices $Q$, $R^p$ and $R^g$ determine process noise and measurement noise. Let $I_3$ be $3 \times 3$ unit matrix. We assume process and measurement noise to be independent. We set unit sampling interval $dt = 10$[ms].

$$Q \equiv \left(\begin{array}{c|c} w_1^2 I_3 & 0 \\ \hline 0 & w_2^2 I_3 \end{array}\right) \tag{25}$$

$$R^p \equiv \left(\begin{array}{c|c} v_1^2 I_3 & 0 \\ \hline 0 & v_2^2 I_3 \end{array}\right) \tag{26}$$

$$R^g \equiv (v_2^2 I_3) \tag{27}$$

$w_1, w_2$ are determined as the standard deviation of remnant error when fitting the data of constrained high-precision link-type sensor [5] to the system model(Eq.4). we used $w_1 = 0.01$[rad], $w_2 = 0.10$[rad/s].

For fine prediction we must roughly estimate $v_1$ and $v_2$. Measurement noise of angular velocity

$$v_2^2 I_3 = \overline{(\omega - \omega^*)(\omega - \omega^*)^T} \tag{28}$$

was determined by specification of gyro sensor. We used $v_2 = 0.13$[rad/s].

We must determine measurement noise $v_1$ taking delay of Polhemus Tracker $T = 80$[ms] into account. Let describe measured value by adding $^*$ and value after T[s] by adding $'$. For example $r'$ is the value $T$[s] after $r$ and $r'^*$ means the measurement of $r'$. Within interval $T$, head moves from $r$ to $r' = r + T\,F'\,\omega + dr$. $r'^* = r^* + T\,F'\,\omega^*$. Suppose the individuality of $r^* - r, \omega^* - \omega, dr$, we calculate standard deviation of $r'^* - r'$, which is nothing other than $v_1 I_3$. Let describe covariance of $v_1$ by $\overline{(r'^* - r')(r'^* - r')^T}$.

$$\begin{array}{ccc} t = t_0 & & t = t_0 + T \\ \begin{pmatrix} r \\ \omega \end{pmatrix} & \longrightarrow & r' = r + T\,F'\,\omega + dr \\ \Downarrow & & \Downarrow \\ \begin{pmatrix} r^* \\ \omega^* \end{pmatrix} & \longrightarrow & r'^* = r^* + T\,F'\,\omega^* \end{array}$$

$$\begin{aligned} \overline{(r'^* - r')(r'^* - r')^T} &= \overline{(r^* - r)(r^* - r)^T} + \overline{dr\,dr^T} \\ &\quad + dt^2\,\overline{(\omega^* - \omega)F'^T F'(\omega^* - \omega)^T} \end{aligned}$$

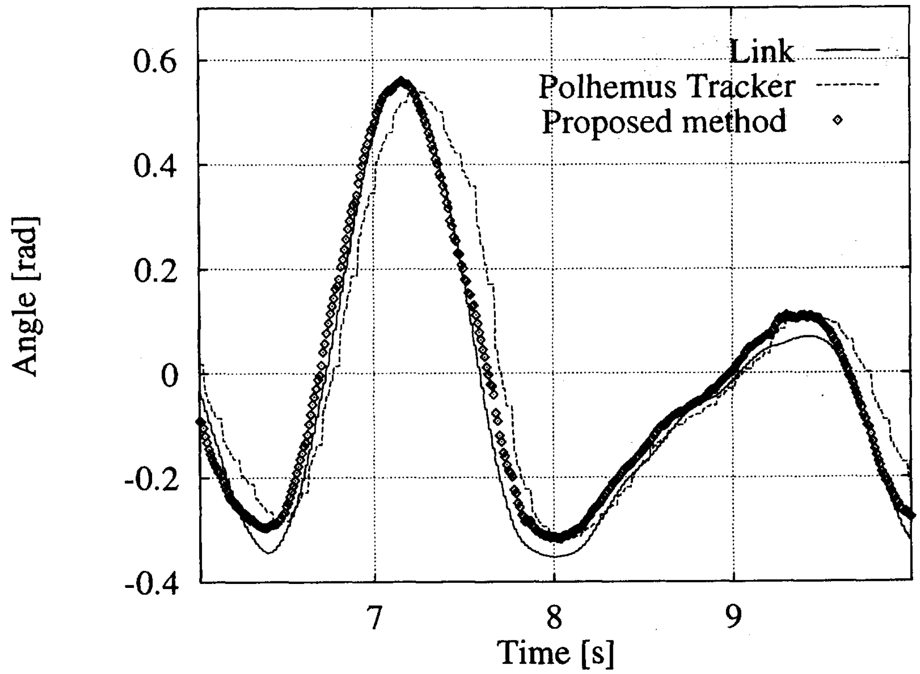


Fig.2 Standard signal(outputs of link-type sensor), raw Polhemus Tracker data and the result of proposed method - pitch angle

We approximate $F'^T F' \sim I$ because $|F'| = 1/\cos(\beta) \sim 1$. We also approximate $\overline{dr\,dr^T}$ by random walk.

$$\begin{aligned} \overline{(r^* - r)(r^* - r)^T} &\equiv 0.013^2 I \\ \overline{dr\,dr^T} &\equiv \frac{T}{dt} w_1^2 I \\ \overline{(\omega^* - \omega)F'^T F'(\omega^* - \omega)^T} &\sim \overline{(\omega^* - \omega)(\omega^* - \omega)^T} \\ &\sim (\frac{T}{dt} w_2^2 + v_2^2) I \end{aligned}$$

Finally we got $v_1 = 0.0252$[rad].

### 4.3 Result

We sampled measurement of gyro at 100Hz, that of link-type sensor at 50Hz and that of Polhemus Tracker at 50Hz for off-line computation. We used the output of link-type sensor as the standard signal. We compared this in the respect of RMS (Root Mean Square) error with the result of the proposed method, raw data of Polhemus Tracker and Kalman filtered Polhemus Tracker raw data.

Table 1 Performance Comparison by RMS Error. "Polhemus" denotes raw data of Polhemus Tracker, "Kalman" denotes result of Kalman filtered raw data of Polhemus Tracker, and "Proposed" denotes result of the proposed mehod.

| | RMS ($\times 10^{-2}$[rad]) | | |
|---|---|---|---|
| | $\gamma$ | $\beta$ | $\alpha$ |
| Polhemus | 7.12 | 9.22 | 9.00 |
| Kalman | 7.42 | 7.09 | 9.16 |
| Proposed | 6.65 | 4.00 | 4.19 |

Fig.2 shows standard signal, raw data of Polhemus and the result of the proposed method. Average delay of Polhemus Tracker was nearly 80ms. It is apparent that the proposed method compensated this delay well. Table 1 shows the RMS(Root Mean Square) error between various outputs and the standard signal. RMS error of Kalman filtered Polhemus Tracker data was larger than

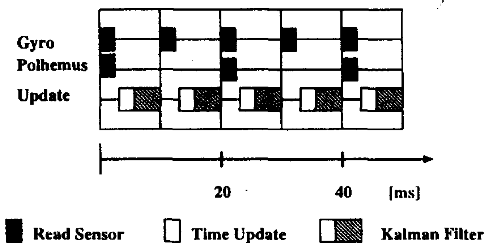


Fig.3 Timing chart of combination of available sensors

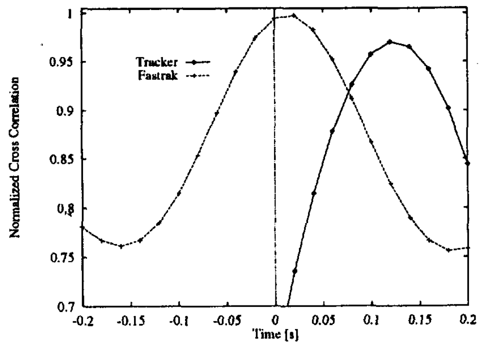


Fig.5 $\rho$ of Polhemus Tracker and $\rho$ of Fastrak under nearly ideal situation (with the 1DOF pendulumn device

that of raw Tracker data because of overshoots and undershoots of its prediction. RMS error of the proposed method reduced nearly half of raw Tracker data except roll angle.

### 4.4 Evaluation by correlation

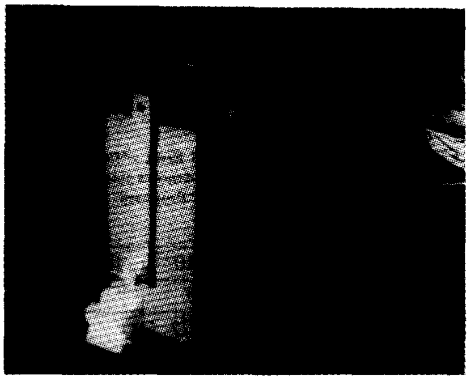

Fig.4 Original 1DOF pendulumn device for performance check of Polhemus

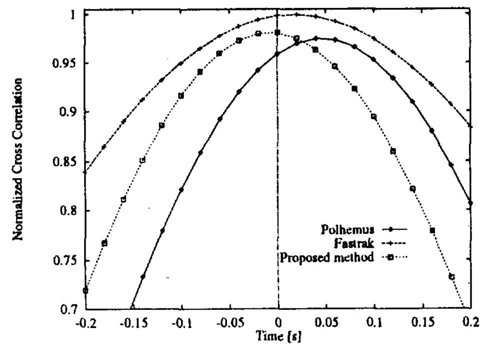


Fig.6 $rho$ of Polhemus Tracker, Fastrak and the proposed method under actual situation(with metalic link-type sensor

We also evaluate the performance of Polhemus Tracker, its improved version Fastrak and the proposed method by the correlation-based method proposed in §2. We received data from Tracker and Fastrak via RS232C.

First we check their performance under nearly ideal situation. We used the device consisted of a pendulumn, potentiometer and mounts for transmitter and receiver of Polhemus. We used the output of potentiometer as the standard signal. This device was constructed with plastic parts and the least metalic parts. We designed the special mounts which enables to measure each element of Euler angle ($\gamma\ \beta\ \alpha$) independently with mechanically fixed axis of the pendulumn. The pendulumn was driven by hand because electric motor generated much noise. But there is no problem because thhe frequency range of hand motion is much wider than that of head motion.

Second we evaluate the performance of Polhemus Tracker, Fastrak and proposed method under acutual situation, where we use metalic link-type sensor[5] as standard signal.

We received data from Tracker and Fastrak via RS232C. The dealy of Polhemus is 120ms and that of Fastrak is

Table 2 Performance evaluation by correlation method under nearly ideal situation

| | Delay [ms] | | | N/S rate [%] | | |
|---|---|---|---|---|---|---|
| | $\gamma$ | $\beta$ | $\alpha$ | $\gamma$ | $\beta$ | $\alpha$ |
| Tracker | 40 | 80 | 120 | 20.8 | 6.5 | 6.3 |
| Fastrak | 0 | -20 | 20 | 1.0 | 2.2 | 0.4 |

Table 3 Performance evaluation by correlation method under ideal situation

| | Delay [ms] | | | N/S rate [%] | | |
|---|---|---|---|---|---|---|
| | $\gamma$ | $\beta$ | $\alpha$ | $\gamma$ | $\beta$ | $\alpha$ |
| Tracker | - | 40 | 80 | 56 | 3.3 | 5.2 |
| Fastrak | - | 40 | 20 | 23 | 17 | 0.2 |
| Proposed | - | -20 | 0 | 56 | 2.0 | 4.1 |

20ms in Fig.5. In ideal situation we see the improved performance of Fastrak. Fig.6 shows the delay and the fidelity of Polhemus Tracker, Fastrak and the proposed method under actual situation. Polhemus delay is about 40ms, that of Fastrak is 20ms and that of proposed method is -10ms. Fastrak is improved in the respect of time delay about 20ms compared with Tracker, but there is still some delay. It is obvious that the proposed method compensates the delay of Polhemus Tracker by the optimal prediction with sensor fusion.

It is guessed from Table 3 that in actual situation roll element of data had a bit different wave form compared with standard signal because of the effect of the shape of the large metallic link-type sensor.

## 5 Conclusion

We proposed a method which improved the performance of Polhemus sensor by optimally integrating the measurement of gyro sensor. We confirmed the validity of this method by off-line computation of actual data. We also proposed a method which made it possible to quantitatively evaluate the delay and the fidelity of unconstrained motion tracking sensor under various conditions.

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