Fuzzy rule-based Hand Motion Estimation for A 6 Dimensional Spatial Tracker

Sanghoon Lee*, Hyun Seok Kim*, Il Hong Suh*, and Myung Kwan Park**

* School of Electrical Engineering & Computer Science, Hanyang University, Seoul, Korea
(Tel : +82-31-400-5172; E-mail: {shlee, hskim}@incorl.hanyang.ac.kr, ihsuh@hanyang.ac.kr)
** Department of Computer Control Engineering, Dongyang University, Seoul, Korea
(Tel : +82-54-630-1109; E-mail: mkpark@phenix.dyu.ac.kr)

Abstract: A fuzzy rule-based hand-motion estimation algorithm is proposed for a 6 dimensional spatial tracker in which low cost accelerometers and gyros are employed. To be specific, beginning and stopping of hand motions needs to be accurately detected to initiate and terminate integration process to get position and pose of the hand from accelerometer and gyro signals, since errors due to noise and/or hand-shaking motions accumulated by integration processes. Fuzzy rules of yes or no of hand-motion-detection are here proposed for rules of accelerometer signals, and sum of derivatives of accelerometer and gyro signals. Several experimental results and shown to validate our proposed algorithms.

Keywords: 6-dimensional Spatial Tracker, Accelerometer, Gyro

1. INTRODUCTION

Spatial tracker systems should be capable of measuring and reporting information about position, orientation, acceleration, or joint angles. For example, six degree-of-freedom (6DOF) sensors provide both 3D position and 3D orientation information. Two 6DOF tracker technologies are currently in popular use; electromagnetic and ultrasonic. However, these technologies cannot create self-contained systems not requiring external transmitter and receiver. Furthermore, electromagnetic trackers are sensitive to metallic objects and magnetic fields. On the other hand, ultrasonic trackers are sensitive to noise and reflections, and require a direct line of sight between transmitter and receiver. Several other technologies for tracking position or orientation are gyroscopes, magnetic compasses, inclinometers, and accelerometers, which can be used to create self-contained, wearable systems that do not require an external transmitter or receiver. Here, it is remarked that in the design of self-contained spatial tracker system, trade-off must be made relatively high accuracy, short range and tethered system versus relatively low accuracy, long range and wireless systems[1].

In this work, a design experience of a low cost 6 DOF hand motion tracker system will be described, where relative low accuracy, and relatively long range wireless communication will be achieved by means of low cost accelerometers and gyros with a contemporary microprocessor. To be specific, it is remarked that INS(Inertial Navigation System) using accelerometers and gyros is a self-contained device which requires no external electromagnetic signals. However, there are two key problems; one is the bias drift problem. These errors would be accumulated and the accuracy is deteriorated as time increases due to integration[2]. The other problem is that single or double integration of an acceleration signal suffers from not only noise but also nonlinear effects caused by gravity[3][4]. Actually, such a signal integration may often lead to divergence far from a true value. To cope with a bias drift problem, noise and the nonlinear gravity problem, several algorithms were proposed[7]. And, in [7], beginning of hand motions was detected by comparing fixed threshold values with magnitudes of accelerometer and gyro signals where such fixed threshold values were experimentally obtained. However, such a fixed threshold comparison technique would not guarantee accuracy enough to differentiate true hand motions with noise and/or unwanted hand-shaking motions. Thus, fuzzy rules of yes or no of hand-motion-detection are here proposed for rules of accelerometer signals, and sum of derivatives of accelerometer and gyro signals.

On the other hand, for the effective real time signal processing, software agents are designed in such a way that an agent takes change of signal processing and state recognition of a sensor where 3 agents for 3 accelerometers and 3 agents for 3 gyros are designed. And our proposed algorithms are experimentally shown to be effective.

2. SIGNAL PROCESSING FOR 6-DIMENSIONAL SPATIAL TRACKER PAPER SIZE AND FORMAT

Fig. 1 shows the block diagram of our designed spatial tracker system. Output signals of the accelerometers $(\alpha_x, \alpha_y, \alpha_z)$ and gyros $(\omega_x, \omega_y, \omega_z)$ are analog signals whose voltages are proportional to acceleration, angular velocity in each axis, respectively. The accelerometers and gyros outputs can be measured directly with A/D converter inside the microprocessor. UART of the microprocessor packetizes the sensor data and transmits them via radio frequency module at a rate of at least 62Hz. The receiving station then relays the sensor records via serial connection to the personal computer.

In this work, our software structure for spatial tracking system is organized as in Fig. 2. For real timeness of our spatial tracking system, sensor agents are designed in such a way that an agent takes change of signal processing and state recognition of a sensor. Here 3 agents for 3 accelerometers and 3 agents for 3 gyros are designed. These agents are working in parallel to process the data from DAS (Data Acquisition System) whose occurrence would be signaled as an event. Thus, agents could perform necessary signal compensations, whenever they get an event without checking time and condition for the compensation. An event is usually signaled when starting or stopping motions of the spatial tracking is detected by rotate- or position-detector-object. These two detector-objects employ velocity information from corresponding sensor agents to effectively determine the occurrence of an event. And in the spatial-tracker-object, reference coordinate is reconfigured to reduce any possible accumulated errors, whenever stopping motion is detected.

Fig. 3 shows internal state diagrams of gyro agent and accelerometer agent, where signal processing could be specialized and thus simplified to meet state characteristics. Specifically, in Fig. 3, two states are considered : Stop and Move. Output velocity of Stop-state is given as zero, and expected actual velocity of each sensor is computed only in a Move-state.

Stop-state of the gyro agent can be detected by checking if angular velocity of the gyro is null. But, in case of accelerometer agent, null velocity does not necessarily imply stop motion, since there exists a constant velocity moving state. Thus, Move-state of the accelerometer agent is made to differentiate acceleration state and deceleration state.

Fig. 4 shows our proposed signal processing algorithm which would be performed whenever sensor data from dispatcher flow into the sensor agent. Followings are summary of our primary signal processing algorithms;

2.1 Zero bias drift compensation

The accelerometers and gyros have zero bias drift due to slight misalignment and the effect of temperature. When the measured acceleration $\alpha_m(t)$ and angular velocity $\omega_m(t)$ involve constant errors α_e and ω_e , α_e and ω_e can be obtained by $\alpha_e = \frac{1}{M}\sum_{N=1}^{M}\alpha_m$, and $\omega_e = \frac{1}{M}\sum_{N=1}^{M}\omega_m$, where M is the number of samplings of stationary accelerometer and gyro data which is taken to know zero bias drift error. Then $\alpha_r(t)$ and $\omega_r(t)$ are actual acceleration and actual angular velocity can be given by

$$\begin{aligned}\alpha_r(t) &= \alpha_m(t) + \alpha_e \\ \omega_r(t) &= \omega_m(t) + \omega_e\end{aligned} \tag{1}$$

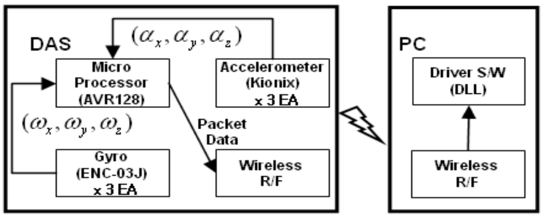


Fig. 1 Spatial tracker system block diagram.

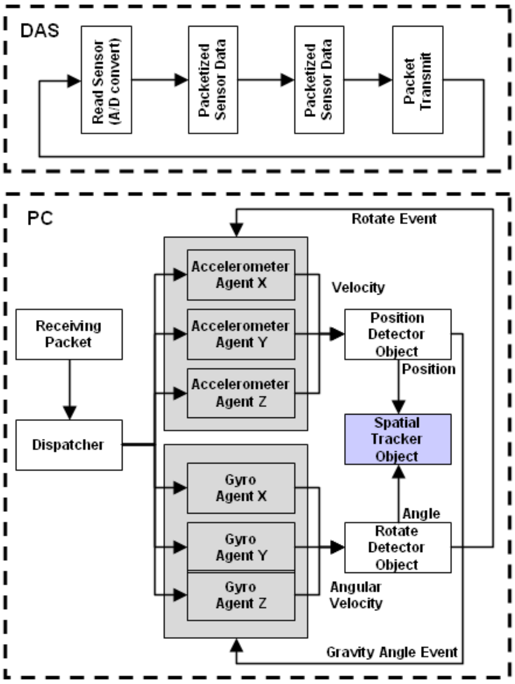


Fig. 2 Spatial tracking system software structure.

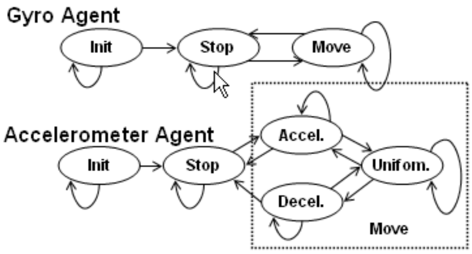


Fig. 3 Spatial State Diagram of Sensor Agent's.

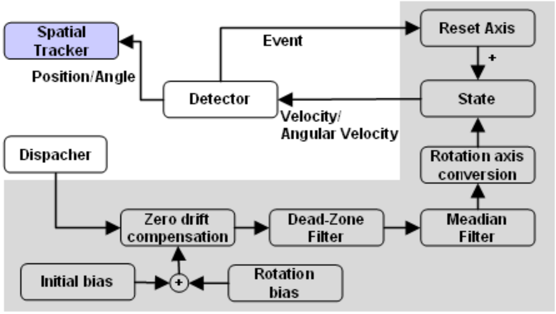


Fig. 4 Spatial Signal processing flow in the Sensor Agent.

2.2 Noise reduction by Dead-Zone filtering and Median filtering

The accelerometers and gyros may have small error signals, since they may be sensitive to hand vibration. For reduction of this type of small error signal, the dead zone k is established as

$$y(t)=\begin{cases} f(t), & |f(t)|\geq k, \\ 0 \quad , & |f(t)|<k. \end{cases} \tag{2}$$

Here, the value of k has been obtained after some experiments to provide better filtering results.

On the other hand noise reduction by median filtering is employed to reduce random peak noise, since it looks like a low pass filtering. Specifically, the filter replaces the center value in the window with the median value of all the points within the window given by

$$y[n]=\frac{1}{N+M+1}\sum_{k=-N}^{M} y[n-k] \tag{3}$$

2.3 Gravity compensation by rotation axis conversion

The coordinates of the spatial tracker system are fixed with respect to body of sensor system. Thus, when body of the spatial tracker system (hand) is rotated those coordinates hardly agree with absolute coordinates that fixed on the floor. Here, it is noted that before integrating the signal from the accelerometer, we have to compensate nonlinear gravity effect. For this, it is essential for us to know how much body of the spatial tracker system is rotated with respect to the absolute reference coordinate.

To be specific, following rotation axis conversion technique is employed;

Let ${}^{A}a=\begin{bmatrix} a_{x_1} \\ a_{y_1} \\ a_{z_1} \end{bmatrix}$ be the measured accelerometer signals and let ${}^{B}a=\begin{bmatrix} a_{x_2} \\ a_{y_2} \\ a_{z_2} \end{bmatrix}$ be the desired modified signals. Then ${}^{B}a$ can be obtained by

$${}^{B}a=R_z(\theta)R_y(\theta)R_x(\theta)\,{}^{A}a, \tag{4}$$

where

$$R_x(\theta)=\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}, \quad R_y(\theta)=\begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix},$$

$$R_z(\theta)=\begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Here, θ will be estimated or measured by gyro signals.

2.4 Fuzzy rule-based hand-motion detection

Spatial tracker states can be classified as Move-state and Stop state. In a Move-state gravity effect on accelerometer (dc-component) is made to be compensated by utilizing angular velocity from gyro sensors, and compensated velocity information is integrated to get the moving distance. But, in a Stop-state, any possible accumulated error of gyro sensor is made to be compensated by employing magnitude of gravity effect obtained from accelerometer sensor. And then, reference coordinate is reconfigured for position error not to be accumulated.

To reduce errors due to noise and/or hand-shaking motions, hand motion needs to be accurately detected to initiate and terminate integration process to get position and pose of the hand from accelerometer and gyro signals. For this, fuzzy rules of yes or no of hand-motion-detection are here designed for rules of accelerometer signals, and sum of derivatives of accelerometer and gyro signals. To be specific, let $K=\{a_x,a_y,a_z\}^T$ and $U=\{g_x,g_y,g_z\}^T$. And let K_d and U_d be dK/dt, and dU/dt, respectively. Also let

$K_v=\|K_d\|=\sqrt{\sum k_{di}^2}$,

$U_v=\|U_d\|=\sqrt{\sum u_{di}^2}$,

and $K_a=\|K\|=\sqrt{\sum a_i^2}$.

In Fig. 5,6, P, Z, and N imply Positive, Zero, and Negative, respectively. And B is given as in Fig. 5. And, to get crisp value of fuzzy output left most maximum technique is employed as in[7]. Then, fuzzy rules for motion detection are designed as

IF K_v AND U_v AND, THEN K_a possibility of motion detection is B.

Fig. 5, 6 and Table ** shows membership function of K_v, U_v, and K_a, and fuzzy rule of yes or no of hand-motion-detection.

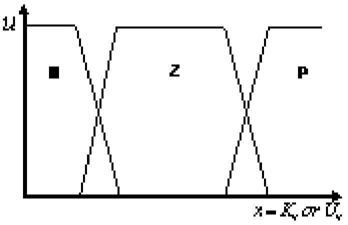


Fig.5 Membership function of K_v, U_v, and K_a

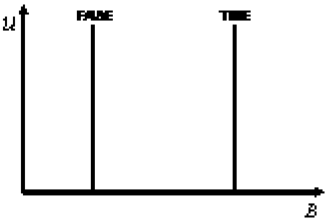


Fig.6 Membership function of B

Table 1. Fuzzy rule of yes or no of hand-motion-detection K_v and U_v at $K_a=Z$

		K_v		
		N	Z	P
U_v	N	YES	NO	YES
	Z	NO	NO	NO
	P	YES	NO	YES

Table 2. Fuzzy rule of yes or no of hand-motion-detection K_v and U_v at $K_a = N$

		K_v		
		N	Z	P
U_v	N	YES	YES	YES
	Z	YES	YES	YES
	P	YES	YES	YES

Table 3. Fuzzy rule of yes or no of hand-motion-detection K_v and U_v at $K_a = P$

		K_v		
		N	Z	P
U_v	N	YES	YES	YES
	Z	YES	YES	YES
	P	YES	YES	YES

3. EXPERIMENTS

3.1 Experimental Set-ups

For our experiments, the KX120-L20 (Kionix) accelerometers are used since they are low cost, low powered and complete 2-axis accelerometer with a measurement range of +/-2g. The KX120-20L can measure both dynamic acceleration (e.g., vibration) and static acceleration (e.g., gravity)[5]. And the Murata ENC03J gyros are used to measure angular velocities, where the gyro is capable of measuring angular velocity up to +/-300 deg/sec and has dynamic response up to frequency 50Hz with a linearity 5% full scale [6].

The microprocessor used in a data acquisition board is ATMEL ATmega323. It has 32Kbyte flash, 1Kbyte EEPROM, 2Kbyte of SRAM, 8 channels 10-bit ADC and serial communication interface. The commercially available radio transmitter/receiver pair of 433MHz frequencies is employed. Our own developed spatial tracker system is shown in Fig. 5. The robot arm is used to move the spatial tracker system a Samsung FARAMAN-AS1. Fig. 7 shows a photograph of spatial tracker evaluation hardware setup.

3.2 Evaluation methods and Experimental results.

Two experiments which estimate the moving distance of operator are conducted by using fuzzy rule-based method and threshold value according to the moving speed. The accuracies which estimate the actual moving distance by two methods are comparatively shown in table 4. To find the optimum threshold values according to the moving speed of operator, distance estimation experiments are performed for four level of moving speed. For each speed level, the threshold values of accelerometer and gyro signal are subdivided by 20 levels. And, the accuracy which recognizes the beginning and stopping of motion is shown in 3 dimensional plots. In figure 8, it can be seen that the optimum threshold values of accelerometer and gyro are different according to the moving speed

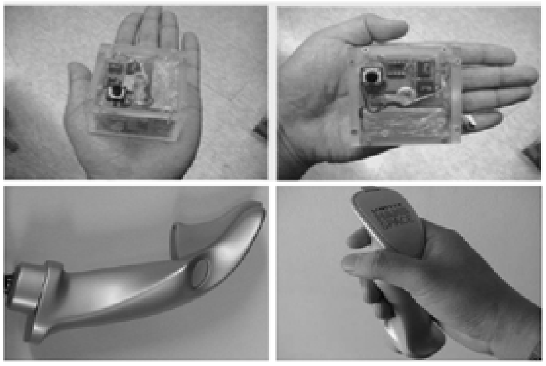


Fig. 6 Developed Spatial Tracker System.

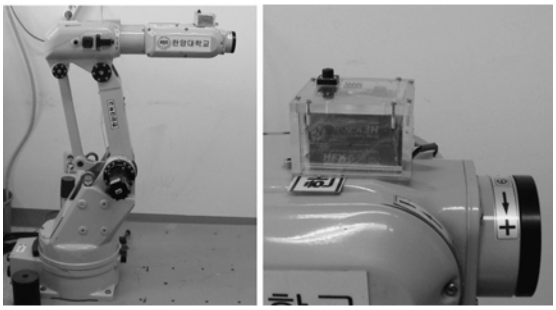
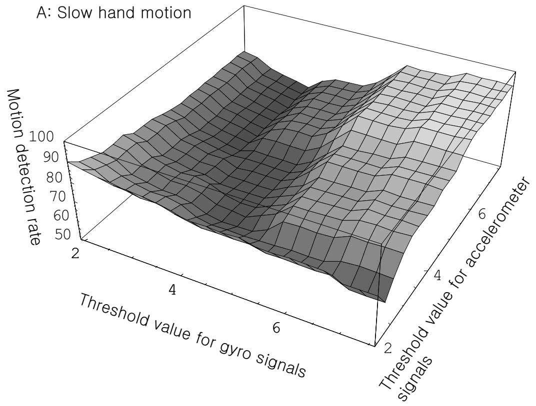
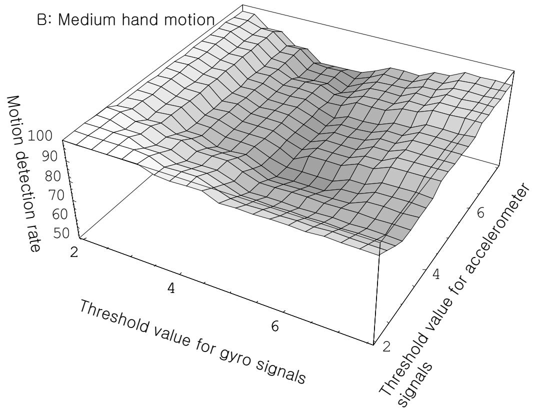


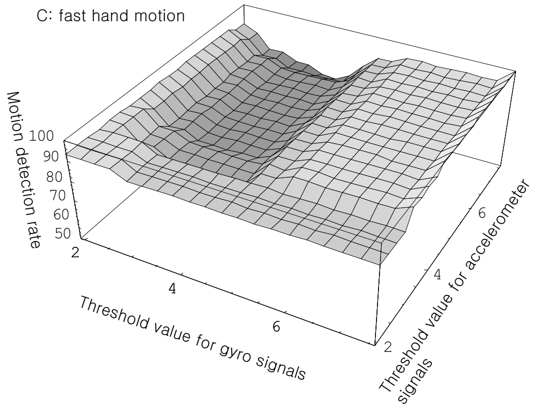
Fig. 7 Experiment Setup to Evaluate the Spatial Tracker System.

Table 4. Estimation results of the actual moving distance by two methods

number of trials	Actual moving distance(a)	Moving distance estimated by experimentally obtained threshold vlalues(b)	accuracy $(\frac{b}{a} \times 100)$	Moving distance estimated by fuzzy rules in Table 1,2,and 3 (c)	accuracy $(\frac{c}{a} \times 100)$
1	219.01	200.27	91.44	217.81	99.44
2	214.26	196.12	91.53	203.16	94.82
3	238.34	212.58	89.19	247.24	96.26
4	182.00	170.43	93.64	190.97	95.07
5	217.73	181.67	83.43	213.05	97.84
6	192.32	172.02	89.44	192.92	99.69
7	209.22	193.40	92.44	205.57	98.26
8	210.21	183.42	87.26	215.78	97.35
9	233.01	202.04	86.71	243.19	95.63
10	187.43	183.30	97.80	192.34	97.38
11	210.73	180.04	85.43	212.39	99.21
12	262.91	207.07	78.76	248.64	94.57
13	235.94	208.20	88.24	226.05	95.81
14	256.06	213.52	83.39	238.32	93.07
15	218.49	190.78	87.32	191.86	87.81
16	208.21	176.54	84.79	204.34	98.14
17	242.89	210.68	86.74	218.02	89.76
18	249.76	215.41	86.25	218.32	87.41
19	217.48	185.32	85.21	209.01	96.11
20	222.00	193.41	87.12	213.97	96.38
Average			87.80		95.50







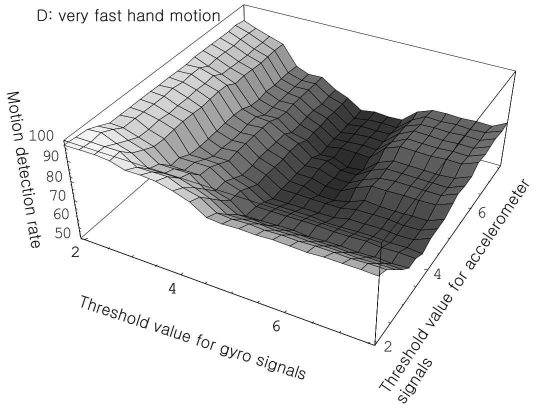


Fig. 8 motion detection rate of various speeds of hand motions according to threshold values for gyro and accelerometer signals

Table 5. The accuracy which recognizes the beginning and stopping of motion

	Threshold value for accelerometer signals ($10^{-3} \cdot m/s^3$)	Threshold value for gyro signals ($10^{-3} \cdot \deg/s^2$)	ABS (%)		Fuzzy (%)	
			Start Pattern Detection rate	Stop Pattern Detection rate	Start Pattern Detection Rate	Stop Pattern Detection Rate
A	3.4	3.7	70.97	66.67	85.42	83.23
B	3.4	6.7	82.86	86.67	94.29	87.67
C	2.8	7.6	90	90	90.67	89.31
D	2.8	7.6	71.79	63.33	92.62	85.67

4. CONCLUDING REMARKS

In this work, a design experience of a low cost spatial tracker system was reported. Our developed spatial tracker system was composed of three accelerometers and three gyros with a contemporary microprocessor. From experiment results, it can be concluded that the performance of our proposed spatial tracker is shown to be acceptable as a device for low cost 6 DOF hand motion measurement system.

The effectiveness the proposed fuzzy rule-based estimation algorithm, which adjusts the threshold value automatically by the moving speed of operator, is shown by some experiments. The proposed method is expected to be used for hand motion tracking as well as interaction with 3D virtual environment.

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