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# Portable Orientation Estimation Device Based on Accelerometers, Magnetometers and Gyroscope Sensors for Sensor Network

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**Abstract**

*In this paper, we developed a portable orientation estimating device equipped with the bluetooth network module. Accelerometers and magnetometers are used to measure the absolute orientation against the earth. Gyroscope sensors are used to measure the local angular velocity. By integrating the measured absolute orientation with the local angular velocity using Unscented Kalman Filter (UKF), the stability and the robustness of estimating the absolute orientation are improved over either sensor alone. Since this device has the bluetooth module, we can easily construct sensor networks.*

## 1 introduction

With a paradigm shift where computers become invisible in our lives, it is increasingly important to develop orientation sensors that are connected through wireless networks. For example, orientation sensors that are connected wirelessly can be applied to a daily motion capture system. A system which connects orientation sensors with vital sign sensors such as blood pressure sensors through wireless network helps care persons to monitor activity of elderly people in the daily life.

Many devices have been developed for measuring orientation. InertiaCube (InterSense) is commercialized and widely used for Virtual Reality applications [1], HMDs to track a head motion [2] or gesture recognition by attaching them to hands. Bachmann developed MARG sensor, which contains a three-axis magnetometer, a three-axis angular rate sensor and a three-axis accelerometer[3] [4]. Since they don't have wireless networking functions, they are used alone or connected by wire.

There are many motion tracking systems such as magnetic tracking systems [5], optical tracking systems [6], ultrasonic tracking systems [7] and position tracking system using spread-spectrum ranging technique [8]. Since cameras or ultrasonic receivers must be set to ceilings or walls, environments are limited to measure orientations by using these motion captures. Therefore it is difficult to measure daily life activities with them. Mechanical motion tracking systems do not restrict measurement environment. However mechanical systems are not suited for a long time measurement since it requires an exoskeleton measuring device, which is attached to human joints.

This paper presents a realization method of an orientation estimation device which is small enough to attach humans or objects in daily life and contains wireless networking functions to connect multiple sensors to each others. Figure 1 shows a realized orientation estimation device next to a wristwatch for scale.

This paper is organized as follows. Section 2 provides the orientation estimation algorithm. Section 3 presents the realized orientation estimation device. Section 4 provides experimental results using the realized orientation device. Section 5 will give the conclusions and future works.

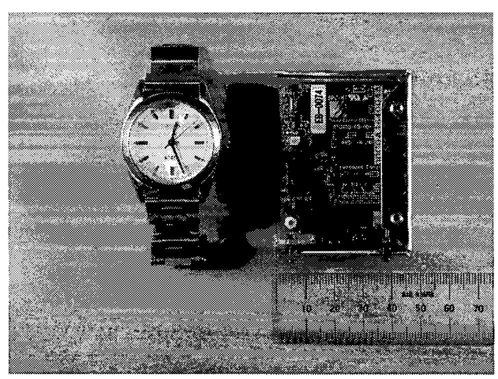

Figure 1: Realized orientation estimation device next to a wristwatch for scale

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## 2 Portable Orientation Measuring Device for Sensor Network

### 2.1 Realization Method

In order to realize an orientation estimation device that can be utilized in the daily life environment, the realized device must consist of only internal sensors. Moreover the device needs small and compact so that it can be attached to the human body without constraint.

Orientation can be determined by utilizing the direction of the magnetic field of the earth and the gravity direction. Magnetometers are employed to detect the magnetic field of the earth. Accelerometers are used to detect the gravity direction. However, accelerometers also measure the acceleration of the motion in addition to the gravity. Magnetometers, in general, show poor performance dynamic responses. Gyro sensors measure angular velocities and have the high performance dynamic responses. However gyro sensors cannot measure the absolute orientation. Of course, by summing the angular velocities measured by the gyro sensors over the time, the absolute orientation can be calculated, if the initial orientation is known. This method has a weak point that calculated accuracy goes down as time passes, since errors are accumulated through summing processes.

In order to complement each other's weak points, accelerometers, magnetometers and gyro sensors are integrated. Firstly the absolute orientation is measured using the accelerometers and magnetometers. Secondly, by integrating the measured absolute orientation with the local angular velocity by applying the Unscented Kalman Filter [9], the stability and the robustness of estimating the absolute orientation are improved over either sensor alone. Finally the estimated orientations are transmitted to the host computers through wireless networks.

Following subsections describe the absolute orientation measuring method by using accelerometers and magnetometers, the system model and the orientation estimation method with Unscented Kalman Filter.

### 2.2 Orientation Measurement using Accelerometers and Magnetometers

#### 2.2.1 World and Body Frame

Figure 2 shows coordinates that are used in this paper. The world frame is fixed to the earth. $X_w, Y_w$ and $Z_w$ correspond to north, west and up respectively. This world frame is the coordinate frame with respect to which the orientation of the device needs to be estimated. The body frame represented by the orthogonal axis $X_b, Y_b, Z_b$ is attached to the device.

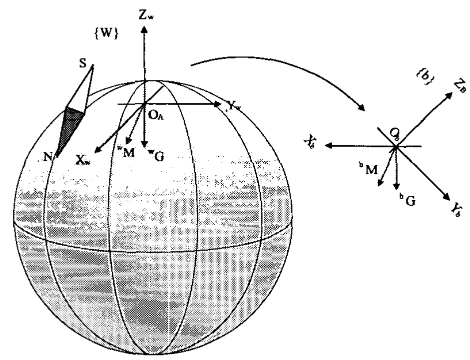


Figure 2: Definition of the world and the body frame

#### 2.2.2 Measurement of Gravity Direction

The acceleration vector in the body frame ${}^b\boldsymbol{g}$ measured by the accelerometers contains the gravity and the acceleration caused by motions. In order to remove the acceleration caused by motions from ${}^b\boldsymbol{g}$, the measured acceleration is filtered through the linear-phase FIR low pass filter. Since linear-phase FIR filters do not distort the phase of the input signal, it is suitable to integrate the filtered outputs of the accelerometers. The cut off frequency is determined as 1 [Hz]. The filtered acceleration is normalized and redefined as ${}^b\boldsymbol{g}$.

#### 2.2.3 Measurement of Magnetic Field of Earth

The magnetic field of the earth in the body frame ${}^b\boldsymbol{m}$ is measured by the magnetometers. This vector is normalized and redefined as ${}^b\boldsymbol{m}$.

#### 2.2.4 Orientation Calculation with Gravity and Magnetic Field of Earth

The orientation in the world frame fixed to the earth can be calculated by combining the gravity direction in the body frame ${}^b\boldsymbol{g}$ and the magnetic field of the earth in the body frame ${}^b\boldsymbol{m}$. This orientation can be obtained by solving the following non-linear simultaneous equation,

$$
\begin{aligned}
{}^w\boldsymbol{g} &= {}^w_bR\,{}^b\boldsymbol{g} \quad (1)\\
{}^w\boldsymbol{m} &= {}^w_bR\,{}^b\boldsymbol{m} \quad (2)
\end{aligned}
$$

where ${}^w_bR$ is the target orientation represented by the three Eular angles, yaw$\psi$, pitch$\theta$ and roll$\phi$.

$$
{}^w_bR = \begin{bmatrix} \theta_c\psi_c & -\phi_c\psi_s + \phi_s\theta_s\psi_c & \phi_s\psi_s + \phi_c\theta_s\psi_c \\ \theta_c\psi_s & \phi_c\psi_c + \phi_s\theta_s\psi_s & -\phi_s\psi_c + \phi_c\theta_s\psi_s \\ -\theta_s & \phi_s\theta_c & \phi_c\theta_c \end{bmatrix}
$$

where the subscripts $s$ and $c$ refer to sine and cosine. There are two methods of solving the non-linear simultaneous equation (1), (2). One is using some optimization methods like Gauss-Newton method, the other is using geometrical constraints. In this paper, the latter method is utilized to solve the orientation.

The magnetic field of earth direction and the gravity direction in the world frame are given by

$$\begin{aligned} {}^w\boldsymbol{m} &= \begin{bmatrix} a, & 0, & b \end{bmatrix}^T & (3)\\ {}^w\boldsymbol{g} &= \begin{bmatrix} 0, & 0, & -1 \end{bmatrix}^T & (4) \end{aligned}$$

where $a, b$ are the normalized horizontal and vertical component of the magnetic field of the earth vector respectively.

Rotations from the Body frame to the World frame are given by

$$\begin{aligned} {}^b\boldsymbol{m} &= {}^b_wR\,{}^w\boldsymbol{m} & (5)\\ {}^b\boldsymbol{g} &= {}^b_wR\,{}^w\boldsymbol{g} & (6) \end{aligned}$$

where ${}^b_wR$ is the transpose matrix of ${}^w_bR$. Components of ${}^b\boldsymbol{g}$ become

$${}^b\boldsymbol{g} = \begin{bmatrix} \sin\theta, & -\sin\phi\cos\theta, & -\cos\phi\cos\theta \end{bmatrix}^T. \quad (7)$$

Therefore we can obtain

$$\theta = Atan2({}^b\boldsymbol{g}(1), \sqrt{{}^b\boldsymbol{g}(2)^2 + {}^b\boldsymbol{g}(3)^2}). \quad (8)$$

Using equation (7) and (8), we obtain

$$\phi = Atan2(-{}^b\boldsymbol{g}(2)sign(\cos\theta), -{}^b\boldsymbol{g}(3)sign(\cos\theta)). \quad (9)$$

Rotation matrix from the body frame to the world frame is given by

$${}^w_bR = R(z,\psi)R(y,\theta)R(x,\phi) \quad (10)$$

where $R(z,\psi)$ is a rotation about the z-axis in a clockwise angle $\psi$, $R(y,\theta)$ is a rotation about the y-axis in a clockwise angle $\theta$ and $R(x,\phi)$ is a rotation about the x-axis in a clockwise angle $\phi$. The magnetic field of the earth in the body frame is written as

$${}^b\boldsymbol{m} = R^T(x,\phi)R^T(y,\theta)R^T(z,\psi)\,{}^w\boldsymbol{m} \quad (11)$$

Using the above equation, we obtain

$$\begin{aligned} R^T(z,\psi)\,{}^w\boldsymbol{m} &= R(y,\theta)R(x,\phi)\,{}^b\boldsymbol{m} & (12)\\ &= \begin{bmatrix} a\cos\psi, & -a\sin\psi, & b \end{bmatrix}^T & (13) \end{aligned}$$

Now $\psi$ is obtained by

$$\psi = Atan2(-\boldsymbol{v}(2)/a, \boldsymbol{v}(1)/a) \quad (14)$$

where $\boldsymbol{v} = R(y,\theta)R(x,\phi)\,{}^b\boldsymbol{m}$.

### 2.3 System Model of Orientation Estimation Device

The state equation and the observation equation for the orientation estimation device in this paper is written as

$$\begin{aligned} \dot{\boldsymbol{q}} &= \frac{1}{2}U({}^b\boldsymbol{\omega} + \boldsymbol{\nu}) & (15)\\ \boldsymbol{z} &= \boldsymbol{q} + \boldsymbol{\mu} & (16) \end{aligned}$$

where the state vector $\boldsymbol{q} = [\eta, \epsilon_1, \epsilon_2, \epsilon_3]^T$ is a quaternion of the device, ${}^b\boldsymbol{\omega} = [{}^b\omega_x, {}^b\omega_y, {}^b\omega_z]^T$ is an output of the gyro sensor in the body frame, $\boldsymbol{z} = [s, w_1, w_2, w_3]^T$ is an observation quaternion which is calculated by using the accelerometers and the magnetometers, $\boldsymbol{\nu}$ is the system noise, $\boldsymbol{\mu}$ is the measurement noise and $U$ is the $4\times 3$ matrix which converts the angular velocity in the body frame to the world frame

$$U = \frac{1}{\parallel \boldsymbol{q} \parallel}\begin{bmatrix} -\epsilon_1 & -\epsilon_2 & -\epsilon_3 \\ \eta & -\epsilon_3 & \epsilon_2 \\ \epsilon_3 & \eta & -\epsilon_1 \\ -\epsilon_2 & \epsilon_1 & \eta \end{bmatrix}, \parallel \boldsymbol{q} \parallel = \sqrt{\boldsymbol{q}\boldsymbol{q}^T}. \quad (17)$$

Using calculated Eular angles $\phi, \theta$ and $\psi$ from equations (8), (9) and (14), components of the observation quaternion $\boldsymbol{z}$ in the world frame can be obtained as

$$\begin{aligned} s &= \cos\frac{\phi}{2}\cos\frac{\theta}{2}\cos\frac{\psi}{2} + \sin\frac{\phi}{2}\sin\frac{\theta}{2}\sin\frac{\psi}{2} & (18)\\ w_1 &= \sin\frac{\phi}{2}\cos\frac{\theta}{2}\cos\frac{\psi}{2} - \cos\frac{\phi}{2}\sin\frac{\theta}{2}\sin\frac{\psi}{2} & (19)\\ w_2 &= \cos\frac{\phi}{2}\sin\frac{\theta}{2}\cos\frac{\psi}{2} + \sin\frac{\phi}{2}\cos\frac{\theta}{2}\sin\frac{\psi}{2} & (20)\\ w_3 &= \cos\frac{\phi}{2}\cos\frac{\theta}{2}\sin\frac{\psi}{2} - \sin\frac{\phi}{2}\sin\frac{\theta}{2}\cos\frac{\psi}{2}. & (21) \end{aligned}$$

### 2.4 Orientation Estimation

Kalman filter is the optimal quantities estimator with respect to the process noise and sensor noise. Unscented Kalman Filter is also optimal quantities estimators but is augmented by using the Unscented Transformation. This filter is more suitable for the non-linear systems than Extended Kalman Filter.

The state equation, obtained by the discretization (15), is

$$\boldsymbol{q}_t = \boldsymbol{f}(\boldsymbol{q}_{t-1}, \boldsymbol{\omega}_{t-1}, \boldsymbol{\nu}_{t-1}) \quad (22)$$

The discrete time version of the observation equation obtained from (16)

$$\boldsymbol{z}_{t-1} = \boldsymbol{h}(\boldsymbol{q}_{t-1}, \boldsymbol{\mu}_{t-1}) \quad (23)$$

where $t$ is the time step.

The state estimate $\bar{\boldsymbol{q}}_t$ and the corresponding state estimate covariance $\boldsymbol{P}_t$ are updated using UKF according to

$$\bar{\boldsymbol{q}}_t = \bar{\boldsymbol{q}}_{t|t-1} + \boldsymbol{K}_t(\boldsymbol{z}_t - \bar{\boldsymbol{z}}_{t|t-1}) \tag{24}$$
$$\boldsymbol{P}_t = \boldsymbol{P}_{t|t-1} - \boldsymbol{K}_t \boldsymbol{P}_{\tilde{\boldsymbol{y}}_t \tilde{\boldsymbol{y}}_t} \boldsymbol{K}_t^T \tag{25}$$

where $\bar{\boldsymbol{q}}_{t|t-1}$ is the prediction of $\bar{\boldsymbol{q}}_{t|t-1}$ at time t, $\boldsymbol{K}_t$ is Kalman gain, $\boldsymbol{z}_t$ is observed value from the accelerometers and the magnetometers, $\bar{\boldsymbol{z}}_{t|t-1}$ is the prediction of $\bar{\boldsymbol{q}}_{t|t-1}$ at time t and $\boldsymbol{P}_{\tilde{\boldsymbol{y}}_t \tilde{\boldsymbol{y}}_t}$ is the covariance matrix of the measurement vector using sigma points. The Kalman gain $\boldsymbol{K}_t$ is given by

$$\boldsymbol{K}_t = \boldsymbol{P}_{\boldsymbol{x}_t \boldsymbol{y}_t} \boldsymbol{P}^{-1}_{\tilde{\boldsymbol{y}}_t \tilde{\boldsymbol{y}}_t} \tag{26}$$

where $\boldsymbol{P}_{\boldsymbol{x}_t \boldsymbol{y}_t}$ is the covariance matrix between the state vector and the observation vector using sigma points.

# 3 Realization of Orientation Estimation Device

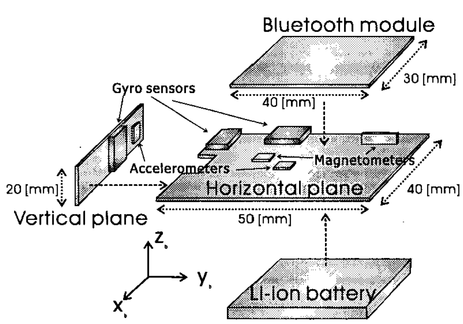


Figure 3: Configuration of the realized orientation estimation device

The realized device consists of accelerometers, magnetometers, gyro sensors, a microprocessor, a bluetoorh network module and a Li-ion battery. Figure 3 shows the configuration of the realized device. Figure 4 shows the vertical and the horizontal planes of the realized device. This device has four-layer planes. The size is $40mm \times 50mm \times 20mm$. The weight including the Li-ion battery is about 65 [g].

## 3.1 Sensors

We use popular sensors by considering the size, weight and performance of sensors. Details of sensors are described as follows:

**Accelerometer** ADXL202JE (Analog Devices) is used as the accelerometers. This sensor measures accelerations of 2-axes. In order to measure 3-axes accelerations, we use two ADXL202JEs. The size is $5.0 \times 5.0 \times 1.8[mm]$. The measurement range is $\pm 2[g]$. The sensitivity is $167[mV/g]$ at 3 [V] supply.

**Gyro sensor** GyroStar (Murata) is used as the gyro sensor. This sensor measures the angular velocity of one axis. In order to measure 3-axes angular velocities, we use three GyroStars. The size is $15.4 \times 8.0 \times 4.3[mm]$. The measurement range is $\pm 300[degree/s]$. At 3 [V] supply, the sensitivity is $0.67[mV/degree/s]$ .

**Magnetometer** HMC1051Z (Honeywell) is used to measure the z-axis of the magnetic field of the earth. HMC1052 (Honeywell) is used to measure the x and y axes. The size of the HMC1051Z is $3.9 \times 10 \times 1.5[mm]$. The HMC1052 is $3.0 \times 3.0 \times 1.1[mm]$. The measurement range is $\pm 6[gauss]$. The sensitivity is $1.0[mV/V/gauss]$.

## 3.2 Microprocessor

H8S2633F (Hitachi) is used as the microprocessor considering the channels of analog inputs, the size of memories and the supply voltage. The memories of processor are 256 kByte ROM and 6 kByte RAM. The analog inputs of this processor are $10bit \times 16ch$. The clock speed is at 16 MHz. This microprocessor digitized all outputs of sensors and estimates the orientation by using the above algorithm. The estimated orientation (quaternion) is transmitted to the host computer through the Bluetooth wireless network. In order to accelerate calculation time of estimation, we use the trigonometric function table and modify the equation of the covariance matrix in UKF when we implement the algorithm to the microprocessor.

## 3.3 Wireless Network

In order to construct the wireless network, we use a Bluetooth network module. The bluetooth has the following nice features: 1) the throughput of bluetooth is up to 1Mbps, 2) the power consumption is about 25mW, 3) wireless sensor network can be constructed by using a piconet and a scatternet. PF-6070 (Canon i-tech, Inc.) is used in this device. The microprocessor and the sensors are run at 3.7 [V]. However the bluetooth module should be run at 3.0 [V]. The supply voltage of this module is regulated to 3.0 [V] through two diodes.

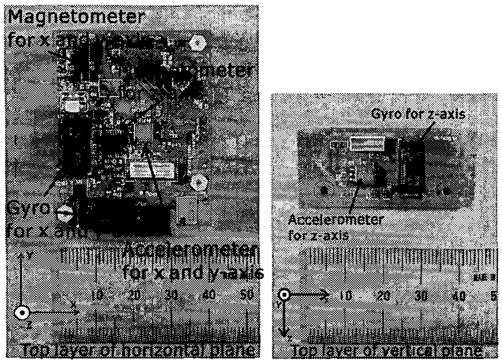


Figure 4: Top layer of horizontal plane (left). Top layer of vertical plane (right).

## 4 Experiment

In order to examine the accuracy of the orientation estimation, experiments are performed by using the realized device. The device is fixed to a tripod of a camera. Since this tripod has three way panhead, we can set Eular angles of the device by using the tripod. Estimated quaternions are converted to the Eular angles and evaluated comparing with the reference Eular angles of the tripod. Eular angles of the device in the body frame are changed as follows:

1. $\phi$ is fixed to $0°$. $\theta$ is fiexed to $0°$. $\psi$ is rotated from $0°$ to $360°$ in $45°$ degree increments.
2. $\phi$ is fixed to $0°$. $\theta$ is fiexed to $30°$. $\psi$ is rotated from $0°$ to $360°$ in $45°$ degree increments.
3. $\phi$ is fixed to $0°$. $\theta$ is fiexed to $60°$. $\psi$ is rotated from $0°$ to $360°$ in $45°$ degree increments.
4. $\phi$ is fixed to $30°$. $\theta$ is fiexed to $0°$. $\psi$ is rotated from $0°$ to $360°$ in $45°$ degree increments.
5. $\phi$ is fixed to $30°$. $\theta$ is fiexed to $30°$. $\psi$ is rotated from $0°$ to $360°$ in $45°$ degree increments.
6. $\phi$ is fixed to $30°$. $\theta$ is fiexed to $60°$. $\psi$ is rotated from $0°$ to $360°$ in $45°$ degree increments.

Figure 5 shows the results of the experiment 3. The left graph of figure 5 is $\phi$. The center is $\theta$. The right is $\psi$. Solid lines are estimated orientations through the realized device. Dotted lines are measured orientations through the accelerometers and the magnetometers.

It is seen from figure 5 that $\theta$ of the estimated orientation vibrates less than $\theta$ of the measured orientation. $\psi$ of the estimate orientation can track motions faster than the measured orientation.

Table 1 shows means and standard deviations of the absolute value of errors. It is seen from table 1 that the maximum mean of error is $3.4[degree]$ and the maximum standard deviation of errors is $0.36[degree]$. This shows that the realized device can estimate the absolute orientation less than $4.0[degree]$ error.

Table 1: Means and standard deviations of the absolute value of errors

| | $\phi[degree]$ | $\theta[degree]$ | $\psi[degree]$ |
|---|---|---|---|
| mean | 3.4 | 2.1 | 3.2 |
| std | 0.17 | 0.21 | 0.36 |

Measured orientation data and estimated orientation data are gathered to the host computer through the bluetooth wireless network at 38,400bps. The sampling rate is 12 Hz, since it takes much time to calculate the covariance matrix in UKF.

We demonstrate to estimate the orientation of a teapot by using the device. The realized device was attached to the surface of the teapot. The estimated value was transmitted to the host computer through the bluetooth. The orientation was drawn using OpenGL. Figure 6 shows the demonstration results. From these results, the realized device is useful to estimate orientation.

## 5 Conclusion

In this paper, we developed a portable orientation estimating device equipped with the wireless network module. By using accelerometers, magnetometers and the kinematics constraints, orientations of the device in the world frame can be measured. However since the response of this measured orientation is slow, the measured orientation have many errors in quick motions. Gyroscope sensors measure angular velocities in the body frame. By integrating the measured orientation with the angular velocities in the body frame using Unscented Kalman Filter, orientations of the device can be estimated. Since integration of sensors and network will be necessary function in near future, we mount a bluetooth network module to the device. Experiments reveal that the stability and the robustness of estimating the absolute orientation are improved over either sensor alone.

In future, we must improve the estimation algorithm to increase the sampling rate. Quantitative analysis for dynamic response and the construction of wireless network such as a piconet are also future work.

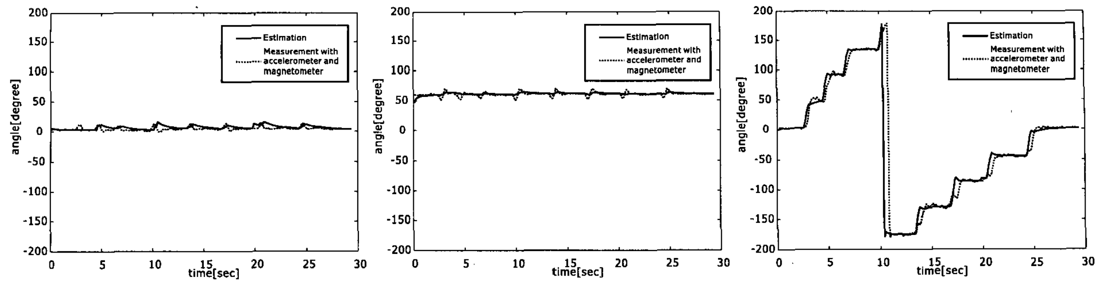


Figure 5: $\phi$ (left) is fixed to 0°. $\theta$ (center) is fiexed to 60°. $\psi$ (right) is rotated from 0 to 360 in 45° degree increments.

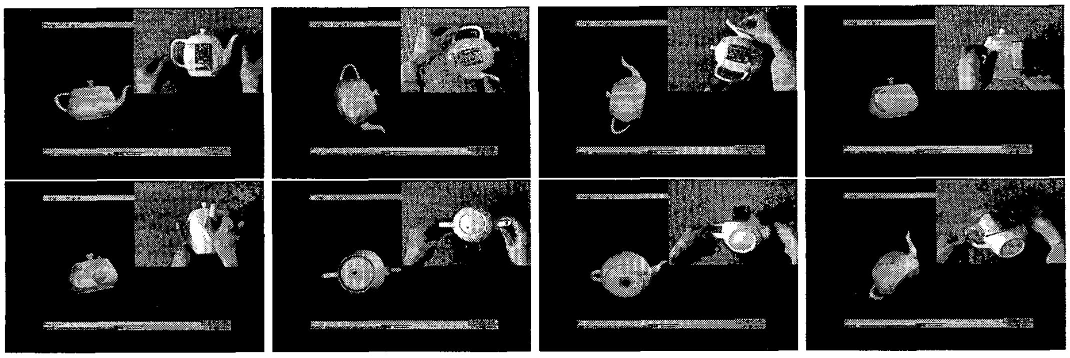

Figure 6: Demonstration results for the orientation estimation device using a teapot

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