



## A pen-shaped data input device

### Field of the invention

The present invention relates to a pen-shaped data input device.

### Background of the invention

5     Currently, there are four main types of pen-shaped device used to input information from users for output information to computing devices.

The most popular method is to use an electronic surface, such as a digital white board, a digitising tablet, a touch screen and so on. A pen or any other hand held pen-like tool could be used to write on the electronic surface. The  
10     electronic surface will output information about the pen's movements to a computing device to which the electronic surface is connected. As the pen's movements on the surface are monitored by means of detection mechanisms built into the surface, such techniques are called the Surface Digitiser Approach. The portability of such an electronic surface, as compared to simply  
15     carrying a pen, is limited. Various technologies, e.g. capacitive plates, resistive plates, electric field surfaces, electromagnetic surfaces etc. have been used to develop such equipment.

A second approach is to use a pen-like device comprising a digital camera and an image processor for optical recording. Unique patterns on a specially  
20     designed surface are captured by the camera as the pen moves over the surface. One example of such predetermined patterns is a lattice structure of invisible pre-designed dots [1]. Such a dot pattern is used for tracing the locus of hand writing strokes. The pen-like device itself contains the mechanisms for the detection of the tip's position, but the specially designed surface is necessary to  
25     provide a passive reference. This is the major drawback in the portability and simplicity of this approach. Furthermore, as a huge number of images have to be continuously captured for accurate image processing, the device requires large memory and a high precision imaging system. Additionally, this kind of optical recording is very sensitive to optical disturbances. Pixel noise, shadows,  
30     and occlusions in the optical field may easily cause errors.



A third approach is based on tracking and sensing the motions of the pen by employing “externally referenced” motion-sensing devices such as stationary infrared, ultrasonic or video cameras [2, 3]. Such external sensing techniques have limitations due to occlusions, interference and noise, and also require  
 5 many expensive and complex additional devices.

The fourth approach is to use an Inertial Measurement System (IMS) [4]. IMSs detect the motion of pen-like devices by inertial sensors which are attached directly to the devices. The sensors give output signals indicative of the motions of such a device. Two types of sensors are essential for inertial measurement:  
 10 accelerometers and gyroscopes.

An accelerometer detects the force ( $F$ ) a small mass ( $m$ ) applies to a pressure sensitive device; the acceleration is simply obtained as:

$$a = \frac{F}{m}$$

along an axis, based on the fundamental mechanical principle, Newton's  
 15 Second Law.

A gyroscope is a device which measures a rotational angular velocity that causes a Coriolis Force effect according to the Coriolis Equation:

$$F_{Coriolis} = -2m(\omega \times v_r)$$

where

20  $\omega$  denotes the angular velocity of the rotating frame of reference; and

$v_r$  denotes the velocity in a rotating frame; and

$m$  denotes the mass.

This force is measured, and the angular velocity is then obtained by calculating  $\omega$  from the equation. To detect angular velocities around dual axes or triple  
 25 axes, it is necessary to use more than one gyroscope.

The working principles of accelerometers and gyroscopes are well known and are not repeated in this text.

Many researches have been conducted in study of pen-like IMS, some are described in US patent [5] and Japanese patent applications [6-10].

5 There are six degrees of freedom, consisting of 3 translational degrees of freedom and 3 rotational degrees of freedom, which completely describe the movement of a pen shaft. In order to keep the structural design simple, some of the patented methods [6-9] did not measure all the required information, so the resultant simulated handwriting was mathematically incorrect and practically  
10 inapplicable. US patent No. 6,229,102 [5] and Japanese patent application No. 7-294240/1995 [10] used sufficient accelerometers and gyroscopes to sense all six parameters of a pen's movement, but the structural design was too complex to be implemented in a hand held pen-like device, especially because three single-axis gyroscopes were used.

#### 15 Summary of the invention

The present invention aims to provide a new and useful pen-shaped data input device.

In general terms, the invention proposes a data input device comprising a shaft, exactly one gyroscope which measures an angular velocity of a rotation of the  
20 shaft, and two accelerometers which respectively measure the accelerations of two spaced apart portions of the shaft.

The two spaced-apart portions are typically a top-end portion and a bottom-end portion of the shaft when the shaft is upright.

The gyroscope is preferably arranged to be sensitive to rotations about the  
25 longitudinal axis of the shaft.

The two accelerometers measure at least five (preferably exactly five) acceleration degrees of freedom. These, and the one rotational degree of freedom measured by the gyroscope, together completely describe the motion

of the shaft. Thus, the present invention makes possible a complete tracking of the shaft's movement using only one gyroscope.

#### Brief description of the figures

Preferred features of the invention will now be described, for the sake of illustration only, with reference to the following figures in which:

Fig. 1 is a perspective view of an embodiment of the invention; and

Fig. 2 is a flowchart of a general tracking system of the embodiment of Fig. 1; and

Fig. 3 is the definition of a Pen Coordinate System (PCS) used by the embodiment of Fig. 1; and

Fig. 4 is the definition of a Gravity Coordinate System (GCS) used by the embodiment of Fig. 1; and

Fig. 5 is the definition of a Writing Coordinate System (WCS) used by the embodiment of Fig. 1; and

Fig. 6 illustrates the PCS of Fig. 3 in relation to the GCS of Fig. 5; and

Fig. 7 illustrates the initial relationship of the GCS and PCS of Fig. 3 and Fig. 5; and

Fig. 8 illustrates the relationship between the rotation angles defined in Fig 7. and measurement values of the static accelerations at an initial stage; and

Fig. 9 illustrates translation and rotation of the pen shaft from time  $t$  to time  $t+\Delta t$  in the PCS of Fig. 3; and

Fig. 10 illustrates the rotation of the pen shaft of the embodiment from  $\mathbf{p_P}$  to  $\mathbf{p_{P1}}$ .

### Description of the preferred embodiment

The present embodiment is designed to use more accelerometers and fewer gyroscopes as compared to existing prior arts while keeping accurate trajectory tracking.

5 Fig. 1 illustrates a pen-shaped input device which is an embodiment of the invention. It includes a shaft 1 and three sensors: one 2D accelerometer 3, one 3D accelerometer 5 and one single-axis gyroscope 7. One end of the shaft is tapered in the present embodiment to give the feel of a pen. The device shall be referred to as a "pen" in what follows.

10 The procedure for tracking movements of the pen is to continuously convert the measurements by the sensors 3,5,7 in Fig. 1 into data representative of the six degrees of freedom of movement of the pen. The measurement mechanism can be divided into two sub-components:

(i) sensing of movements in terms of continuous accelerations and angular  
15 velocities; and

(ii) calculating the trajectories of the pen's tapered end based on these sensor measurements.

The triple-axis accelerometer 5 of Fig. 1 is located at Point A towards the tapered end of the pen 9, having the Z-axis along the longitudinal axis 2 of the  
20 pen shaft 1 pointing towards the tail 8 of the pen shaft 1. The X-Y plane of the triple axis accelerometer 5 is perpendicular to the pen's longitudinal axis 2. The dual-axis accelerometer 3 is located at Point B towards the end of the pen shaft 1. The X-Y plane of the accelerometer 3 is oriented parallel to that of the triple-axis accelerometer 5 and the origin is also located on the longitudinal axis 2 of  
25 the pen shaft 1. The gyroscope 7 at Point C is also aligned to the longitudinal axis 2 of the pen shaft 1. All sensors are placed along the longitudinal axis 2 of the pen shaft 1 to ensure a sensing structure compact in size. These sensors produce six measurement outputs, five accelerations along the  $X_A$ ,  $Y_A$ ,  $Z_A$ ,  $X_B$  and  $Y_B$  axes, and one angular velocity around the  $Z_A$  axis. From these six  
30 sensing parameters, the trajectory of pen's tip-end 9 at the Point P in the

drawing can be derived, preferably by a calculation unit 4 integrated into the pen as shown in Fig. 1.

To facilitate the trajectory calculation, three coordinate systems are defined in this embodiment: a Pen Coordinate System (PCS) shown in Fig. 3, a Gravity  
 5 Coordinate System (GCS) shown in Fig. 4, and optionally a Writing-surface Coordinate System (WCS) as illustrated in Fig. 5:

1. The pen and the sensors contained in the pen shaft 1 define the PCS as shown in Fig. 3. The origin, denoted as P, represents the tip-end 9 of the pen shaft 1. The  $Z_P$ -axis represents the longitudinal axis 2 of the pen shaft 1,  
 10 which is aligned to the  $Z_A$  axis of the triple-axis accelerometer 5 and to the longitudinal axis 2 of the gyroscope 7. The  $X_P$  and  $Y_P$  axes have the same directions as the respective X and Y-axes of the two accelerometers 3,5. The PCS is also denoted by three unit-vectors  $\mathbf{p}_P$ ,  $\mathbf{q}_P$  and  $\mathbf{r}_P$ , corresponding to  $Z_P$ ,  $X_P$  and  $Y_P$  axes respectively, all shown in Fig. 3.
- 15 2. The GCS, Fig. 4, is fixed at the initial stage of a tracking process. The origin, denoted by G, is defined by the initial position of the PCS's origin, P. The  $Z_G$  axis always points to the direction opposite to gravitational pull. The  $X_G$  and  $Y_G$  axes are defined according to the Pen's orientation at the initial stage so that the Pen's longitude axis  $Z_P$  is lying at the positive quadrant region of the  
 20  $Y_G$ - $Z_G$  plane, as shown in Fig. 4.
3. If the information concerning a writing surface on which the pen moves is known to the system, a fixed WCS denoted by the origin W and the axes  $X_W$ ,  $Y_W$  and  $Z_W$  is defined with relation to the GCS. It is shown in Fig. 5.

Please note that, in this mathematical representation, the scalars are denoted in  
 25 normal case, e.g. x, r1, while vectors are denoted in lowercase boldface, e.g.  $\mathbf{p}_P$ , and matrices in uppercase boldface, e.g.  $\mathbf{T}$ . The subscripts of P, G and W denote the vectors in the PCS, GCS and WCS, respectively.

Tracking the position and orientation of the PCS in the GCS as shown in Fig. 6  
 is the key objective in this system. The translation of the PCS relative to the  
 30 GCS represents the trajectory of the pen's tip-end 9 and is denoted by the

displacement between the origins of PCS and GCS,  $\mathbf{t}_G$ . The orientation of the pen shaft is denoted by the coordinates of the unit-vectors  $\mathbf{p}_P$ ,  $\mathbf{q}_P$  and  $\mathbf{r}_P$  and their relative locations in GCS which is represented by  $\mathbf{p}_G$ ,  $\mathbf{q}_G$  and  $\mathbf{r}_G$ . As shown in Fig. 6, the solid-line pen image indicates the actual pen shaft at some time in the tracking process, and, by removing the displacement of the PCS origin from the GCS origin, the dashed-line pen image indicates the orientation of the PCS in the GCS.

The movement of a rigid body, like the pen shaft in the present embodiment, can be decomposed into two types of transformations, a translational and a rotational. The coordinate transformation can be mathematically expressed by multiplying a 4×4 matrix, representing translation by the first three elements of the fourth column and rotation by the top-left 3×3 matrix, with a 4×1 vector formed by the 3D coordinate and a dummy fourth element “1”, as shown in Eq.(1).

$$\begin{pmatrix} v_1' \\ v_2' \\ v_3' \\ 1 \end{pmatrix} = \begin{bmatrix} r_1 & r_2 & r_3 & t_1 \\ r_4 & r_5 & r_6 & t_2 \\ r_7 & r_8 & r_9 & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{pmatrix} v_1 \\ v_2 \\ v_3 \\ 1 \end{pmatrix} = \mathbf{M} \times \begin{pmatrix} v_1 \\ v_2 \\ v_3 \\ 1 \end{pmatrix} \quad (1)$$

where  $v_1$ ,  $v_2$  and  $v_3$  are the 3D coordinate s to be transformed; and

$v_1'$ ,  $v_2'$  and  $v_3'$  are the transformed 3D coordinates; and

the 4×4 matrix contains 9 elements,  $r_1$  to  $r_9$ , for rotation; and

3 elements,  $t_1$  to  $t_3$ , for translation.

The transformation matrix,  $\mathbf{M}$ , shown in equation (1), can be separated into a translation matrix,  $\mathbf{T}$ , and a rotation matrix,  $\mathbf{R}$ , i.e.  $\mathbf{M}=\mathbf{T} \times \mathbf{R}$ . In the case of the actual pen shaft in GCS defined by  $\mathbf{t}_G$ ,  $\mathbf{p}_G$ ,  $\mathbf{q}_G$  and  $\mathbf{r}_G$ , the conversion of coordinates from the PCS to the GCS is defined by

$$\mathbf{T}_{P \rightarrow G} = \begin{bmatrix} 1 & 0 & 0 & \cap \\ 0 & 1 & 0 & \mathbf{t}_G \\ 0 & 0 & 1 & \cup \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$\mathbf{R}_{P \rightarrow G} = \begin{bmatrix} \cap & \cap & \cap & 0 \\ \mathbf{q}_G & \mathbf{r}_G & \mathbf{p}_G & 0 \\ \cup & \cup & \cup & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

where the form  $\cap$   
 $\mathbf{t}_G$  denotes a column vector with three elements, similarly  
 $\cup$

applied to other column vectors. Additionally, the orientation of the actual pen  
 5 shaft in GCS is defined by the rotational angles,  $\phi$ ,  $\varphi$  and  $\theta$ , around axes in  
 terms of the right hand rule. The rotational matrix conversion matrix from the  
 PCS to the GCS is defined by

$$\mathbf{R}_{P \rightarrow G} = \mathbf{R}_{X_G}(\phi) \times \mathbf{R}_{Y_G}(\varphi) \times \mathbf{R}_{Z_G}(\theta) = \quad (4)$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi & 0 \\ 0 & \sin \phi & \cos \phi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos \varphi & 0 & \sin \varphi & 0 \\ 0 & 1 & 0 & 0 \\ -\sin \varphi & 0 & \cos \varphi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos \theta & -\sin \theta & 0 & 0 \\ \sin \theta & \cos \theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Additionally, the transformation from the GCS to the PCS is just the inverse of  
 10 these matrices,  $\mathbf{T}_{G \rightarrow P} = \mathbf{T}_{P \rightarrow G}^{-1}$  and  $\mathbf{R}_{G \rightarrow P} = \mathbf{R}_{P \rightarrow G}^{-1}$ .

Having a transformation matrix,  $\mathbf{M}$ , is theoretically equivalent to knowing the six  
 parameters, three-dimensional translation values (x, y, z) and three-axis rotation  
 angles, but more computationally tractable because all calculations can be done  
 in matrix multiplication.

15 The entire procedure of tracking the trajectory of the pen's tip-end in GCS is  
 shown as a flowchart in Fig. 2. From the system point of view, it is to convert the

six sensing measurements into the actual movements of the pen's tip-end by a series of calculations and conversions.

It is assumed that the pen keeps in the static state at the starting point of the movement trajectory. The pen's initial position, in other words, the position of the PCS and the orientation of its three axes in the GCS are shown in Fig. 7. Both origins coincide at the initial stage, therefore the translation matrix is an identity matrix initially:

$$\mathbf{T}_{P \rightarrow G}(0) = \mathbf{T}_{G \rightarrow P}(0) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

When the pen is stationary at the initial stage, the accelerometer measures the 3D accelerations in the PCS's axes pointing to the negative direction of the  $Z_G$  axis as gravity is the only force acting on the pen. In other words, it gives the projection of the unit vector  $\mathbf{p}_G(0)$  in the PCS's  $X_P$ ,  $Y_P$  and  $Z_P$  axes as

$$\left( -\frac{x(0)}{v(0)}, -\frac{y(0)}{v(0)}, -\frac{z(0)}{v(0)} \right),$$

where

$x(0)$ ,  $y(0)$  and  $z(0)$  are the measurement of static accelerations in the accelerometers at the initial stage; and

$$v(0) = \sqrt{x(0)^2 + y(0)^2 + z(0)^2}.$$

Because the  $Z_P$  is assumed to be lying at the  $Y_G$ - $Z_G$  plane initially, the rotation, representing the orientation, can be decomposed into rotating  $\theta$  degree around the  $Z_G$  axis, then rotating  $\phi$  degree around the  $X_G$  axis in the right-hand rule. Based on the relationship of  $\theta$ ,  $\phi$ ,  $x(0)$ ,  $y(0)$ ,  $z(0)$ ,  $u(0)$  and  $v(0)$  shown Fig. 8, it has the following equations:

$$\cos \theta = \frac{y(0)}{u(0)} \quad ; \quad \sin \theta = \frac{x(0)}{u(0)} \quad ;$$

$$\cos \phi = -\frac{z(0)}{v(0)} \quad ; \quad \sin \phi = -\frac{u(0)}{v(0)} \quad ;$$

$$\text{where } u = \sqrt{x(0)^2 + y(0)^2}.$$

Therefore, the rotation matrix converting coordinates from the PCS to the GCS becomes

$$\begin{aligned} \mathbf{R}_{P \rightarrow G} &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi & 0 \\ 0 & \sin \phi & \cos \phi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos \theta & -\sin \theta & 0 & 0 \\ \sin \theta & \cos \theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} \frac{y(0)}{u(0)} & -\frac{x(0)}{u(0)} & 0 & 0 \\ -\frac{x(0)z(0)}{u(0)v(0)} & -\frac{y(0)z(0)}{u(0)v(0)} & \frac{u(0)}{v(0)} & 0 \\ -\frac{x(0)}{v(0)} & -\frac{y(0)}{v(0)} & -\frac{z(0)}{v(0)} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{aligned}$$

The rotation matrix from the GCS to the PCS is its inverse:  $\mathbf{R}_{G \rightarrow P}(0) = (\mathbf{R}_{P \rightarrow G}(0))^{-1}$ . These transformation matrices fully define the PCS in GCS at the initial stage.

- 10 When the tracking process starts, the six sensors measure the accelerations and angular velocity at regular intervals, the times being denoted as  $t$  and the interval as  $\Delta t$ . The gyroscope 7 measures the angular velocity as  $\omega_{z_p}(t)$ . The acceleration sensors 3,5 measure the acceleration values in five directions, including the gravitational pull on the pen at the initial static state,  $g_P(t)$ , and the
- 15 dynamic accelerations due to pen's movements,  $a_P(t)$ . As the system continuously monitors the orientations of PCS axes in the GCS, represented by the rotation matrix  $\mathbf{R}_{G \rightarrow P}(t)$ , the effect of constant gravitational pull on the sensors can be calculated by multiplying  $\mathbf{R}_{G \rightarrow P}(t)$  with the universal constant  $\mathbf{g}$ . Then, the five dynamic accelerations,  $a_P(t)$ , can be separated from the
- 20 gravitational effect on the sensor measurements. Note that the accelerations

along the Z-axis of both accelerometers 3,5 are the same, because both Z-axes are aligned along the longitudinal axis. Therefore, five acceleration values are sufficient to represent the 3D dynamic accelerations experienced by both accelerometers 3,5.

- 5 It is assumed that the accelerations and angular velocity remain at constant values between time  $t$  to the next sampling time  $t+\Delta t$ . The new PCS locations of Point A and B after moving the pen can be obtained by integrating the acceleration values in the time interval  $\Delta t$  by following the equations:

$$\begin{aligned}
 x_{\text{new}} &= x_{\text{old}} + \frac{1}{2} a_{x_p} \Delta t^2 + v_{x_{\text{old}}} \Delta t & v_{x_{\text{new}}} &= v_{x_{\text{old}}} + a_{x_p} \Delta t \\
 y_{\text{new}} &= y_{\text{old}} + \frac{1}{2} a_{y_p} \Delta t^2 + v_{y_{\text{old}}} \Delta t & v_{y_{\text{new}}} &= v_{y_{\text{old}}} + a_{y_p} \Delta t \\
 z_{\text{new}} &= z_{\text{old}} + \frac{1}{2} a_{z_p} \Delta t^2 + v_{z_{\text{old}}} \Delta t & v_{z_{\text{new}}} &= v_{z_{\text{old}}} + a_{z_p} \Delta t
 \end{aligned} \tag{5}$$

- 10 Similarly, the angle of rotation around the longitudinal axis 2 as shown in Fig. 1 of the pen is calculated based on the angular velocity obtained from the gyroscope 7:

$$\theta = \omega_{z_p} \Delta t \tag{6}$$

- As illustrated in Fig. 9, this translational and rotational movement can be  
 15 decomposed into a rotation matrix  $\mathbf{R}_p(t \rightarrow t + \Delta t)$  and a translation matrix  $\mathbf{T}_p(t \rightarrow t + \Delta t)$  in the PCS:

- The pen, at all times represented by  $\mathbf{p}_p$  which describes the shaft's longitudinal axis, is first rotated around the  $Z_p$  axis by the  $\theta$  degrees calculated from the gyroscope. Then it is rotated around the  $Y_p$  axis by  $\varphi$  degree, then around  $X_p$   
 20 axis by  $\phi$  degrees to the orientation represented by the vector  $\mathbf{p}_{p1}$ . Finally it is translated to the position of vector  $\mathbf{p}_{p2}$ . Since the old positions A and B as shown in Fig. 9 at time  $t$  and the new positions  $A_2$  and  $B_2$  as shown in Fig. 9 at time  $t+\Delta t$  are all known, the unit vector  $\mathbf{p}_p$  is (0, 0, 1) and the  $\mathbf{p}_{p2}$  is equal to :

$$\left( \frac{x_{B_2} - x_{A_2}}{|AB|}, \frac{y_{B_2} - y_{A_2}}{|AB|}, \frac{z_{B_2} - z_{A_2}}{|AB|} \right)$$

which is also equal to the unit vector  $\mathbf{p}_{P1}$  with the same orientation, where

$|AB|$  denotes the Euclidean distance between A and B.

Rotating  $\theta$  degrees around the  $Z_P$  axis can be simply represented by

$$\mathbf{R}_{Z_P}(\theta) = \begin{bmatrix} \cos \theta & -\sin \theta & 0 & 0 \\ \sin \theta & \cos \theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

5

Rotating the unit vector  $\mathbf{p}_P$  to the  $\mathbf{p}_{P1}$  is illustrated in Fig. 10 if the coordinates of the unit vector  $\mathbf{p}_{P1}$  are denoted as  $(x, y, z)$ . The  $\mathbf{p}_P$  is first rotated to the  $\mathbf{p}_{P'}$  by  $\varphi$  degree around  $Y_P$ , then rotated to the  $\mathbf{p}_{P2}$  by  $\phi$  degree around  $X_P$ . Therefore, the

10 rotation matrix is obtained as

$$\mathbf{R}_{\mathbf{p}_P \rightarrow \mathbf{p}_{P2}} = \mathbf{R}_{X_P}(\phi) \times \mathbf{R}_{Y_P}(\varphi) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi & 0 \\ 0 & \sin \phi & \cos \phi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos \varphi & 0 & \sin \varphi & 0 \\ 0 & 1 & 0 & 0 \\ -\sin \varphi & 0 & \cos \varphi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where  $\cos \varphi = u$ ,  $\sin \varphi = x$ ,  $\cos \phi = \frac{z}{u}$ ,  $\sin \phi = -\frac{y}{u}$  and  $u = \sqrt{y^2 + z^2}$ .

Then, the complete rotation matrix is derived as

$$\mathbf{R}_P(t \rightarrow t + \Delta t) = \mathbf{R}_{\mathbf{p}_P \rightarrow \mathbf{p}_{P2}} \times \mathbf{R}_{Z_P}(\theta).$$

15 By having the position  $\mathbf{A}_1 = \mathbf{p}_{P1} \times |A_1P|$ , where  $|A_1P|$  is the Euclidean distance between  $\mathbf{A}_1$  and origin P, the translation vector can be determined as  $\mathbf{t}_P = \mathbf{A}_2 - \mathbf{A}_1$ . The translation matrix  $\mathbf{T}_P(t \rightarrow t + \Delta t)$  is formed as

$$\mathbf{T}_p(t \rightarrow t + \Delta t) = \begin{bmatrix} 1 & 0 & 0 & \cap \\ 0 & 1 & 0 & \mathbf{t}_p \\ 0 & 0 & 1 & \cup \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

Since the PCS vectors change during the measurement intervals, the velocity of the sensors in the new PCS is calculated as

$$\mathbf{v}_p(t + \Delta t) = \mathbf{R}_p^{-1}(t \rightarrow t + \Delta t) \times \mathbf{v}_{new},$$

5 where  $\mathbf{v}_{new} = (v_{x_{new}}, v_{y_{new}}, v_{z_{new}})$  is the velocity calculated in the current PCS.

As the position and orientation of the pen shaft are referenced to the global GCS during writing, the above translation and rotation matrices have to be converted from the PCS to the GCS. Based on the  $\mathbf{T}_{p \rightarrow G}(t)$  and  $\mathbf{R}_{p \rightarrow G}(t)$  calculated at time  $t$ , the final movement and rotation in the GCS from time  $t$  to  $t + \Delta t$  can be easily derived by multiplying the conversion matrices by the movements and rotations measured and expressed in PCS:

$$\mathbf{T}_G(t \rightarrow t + \Delta t) = \mathbf{T}_{p \rightarrow G}(t) \times \mathbf{T}_p(t \rightarrow t + \Delta t)$$

and

$$\mathbf{R}_G(t \rightarrow t + \Delta t) = \mathbf{R}_{p \rightarrow G}(t) \times \mathbf{R}_p(t \rightarrow t + \Delta t).$$

15 If the relationship between the WCS and the GCS, shown in Fig. 5, has been defined by the translation matrix  $\mathbf{T}_{G \rightarrow W}(t)$  and the rotation matrix  $\mathbf{R}_{G \rightarrow W}(t)$ , the pen-tip's movement in the WCS can be further obtained from the movement coordinates by multiplying these transform matrices.

With the movements,  $\mathbf{T}_G(t \rightarrow t + \Delta t)$ , and rotations,  $\mathbf{R}_G(t \rightarrow t + \Delta t)$ , of the pen in the GCS, the location of the pen's tip-end,  $\mathbf{t}_G(t + \Delta t)$ , and also the orientations of the moved PCS in the GCS at the next sampling time,  $\mathbf{p}_G(t + \Delta t)$ ,  $\mathbf{q}_G(t + \Delta t)$  and  $\mathbf{r}_G(t + \Delta t)$ , can be identified. The position and rotation of the moved PCS relative

to the GCS is redefined by  $\mathbf{T}_{P \rightarrow G}(t+\Delta t)$  and  $\mathbf{R}_{P \rightarrow G}(t+\Delta t)$  and are used for the calculation at next sampling time  $t+2\Delta t$ .

While tracking the pen's paths of trajectory, pen's writing movements must be differentiated from non-significant movements. This is preferably achieved by using a touch switch located at the pen tip. When the pen tip touches a solid surface, it is considered as the writing status, otherwise, the non-writing status.

The flow of the trajectory detection mechanism is outlined in Fig. 2:

(i) At an initial stage, the pen is stationary. By measuring the gravitational pull acting on the stationary pen, the initial state of the tracking system can be determined along with the pen's orientation. These are expressed with respect to both the GCS and a PCS.

(ii) When the pen moves, the dynamic states of the sensors are measured at regular intervals. The gyroscope produces a value representing the angular velocity of the shaft about longitudinal axis of the shaft. After compensating for the gravitational pull on the acceleration sensors, and by relating the orientations of the PCS vectors to the GCS, the accelerations due to writing motions can be obtained.

(iii) The velocities and translations of two accelerometers can be calculated by integrating their accelerations. When the pen shaft has been moved, the translations of the pen's tip-end and the rotations of the pen's pitch and yaw (rotation of the pen in axes other than the longitudinal axis) can be calculated by applying simple vector analyses. The rotational movement of the pen's roll (rotation around the longitudinal axis) is obtained directly from the measurement of the gyroscope.

(iv) By relating the movement vectors in PCS to the GCS, the movements of the pen's tip-end are, in one iterative step, obtained.

(v) A new location and a new orientation of the pen are calculated after every sampling interval, and are referenced to for the next set of calculations in the next sampling interval.

(vi) The writing or non-writing movements of the pen are differentiated by a touch switch located at the pen tip. The pressure exerted on the switch from the writing surface indicates a writing state, otherwise, a non-writing state.

By continuously repeating steps (ii) to (vi), the trajectories of the tip-end can be tracked and the orientations of the pen-shaft can be monitored. The above tracking procedure is repeated from one sampling to the next until the end of a writing process.

Some of the main advantages of the embodiment include:

(i) No specific types of paper, writing-tablets or external reference devices are needed.

(ii) This embodiment has a smaller size and costs less than those of prior art systems with similar designs because of the reduced number of gyroscopes, and yet it retains equivalent functionality.

(iii) Only six inertial sensor measurements are needed to represent the movements of a pen shaft, equivalent to the complete six degrees of freedom of a moving object.

(iv) The embodiment is able to track the movement of the pen's tip-end accurately.

(v) All coordinate transformations can be represented by a composite matrix multiplication.

(vi) The actual handwriting movements on solid surfaces can be distinguished from the non-writing movements of the pen by using a surface-touching switch.

## References

[1] Ericson Petter, Hugosson Ola and Faahraeus Christer, Device And Method For Recording Hand-Written Information, European Patent WO9960467 (November 25, 1999).

[2] Ehud Baron, Victor Korsensky and Omry Genossar, Method and system for digitizing handwriting, US Patent 5,977,958 (November 2, 1999).

[3] Nobuyasu Yamaguchi, Hiroshi Ishikawa, Yasuhide Iwamoto and Atsuo Iida,  
5 Ultrasonic coordinate input apparatus, US Patent 5,637,839 (June 10, 1997).

[4] C. Verplaetse, "Inertial Proprioceptive Devices: Self-Motion-Sensing Toys and Tools", IBM Systems Journal, vol. 35 (3,4), pp. 639-650, 1996.

[5] Yasuhiro Sato, Takao Inoue, Etsuko Fujisawa, Takashi Kitaguchi, Toshiyuki Furuta, Norihiko Murata and Mitsuru Shingyouchi, Pen-Shaped Handwriting  
10 Input Apparatus Using Accelerometers and Gyroscopes and An Associated Operational Device for Determining Pen Movement, US Patent 6,229,102 (May 8, 2001).

[6] Japanese Laid-Open Patent No.6-67799/1994.

[7] Japanese Laid-Open Patent No.6-230886/1994.

15 [8] Japanese Laid-Open Patent No.7-94716/1995.

[9] Japanese Laid-Open Patent No.7-200127/1995.

[10] Japanese Laid-Open Patent No.7-294240/1995.

Claims

1. A data input device comprising a shaft, exactly one gyroscope which measures an angular velocity of a rotation of the shaft, and two accelerometers which respectively measure the accelerations of two spaced-apart portions of  
5 the shaft.
2. A data input device according to claim 1 in which measurements of 5 accelerations and one rotational movement are indicative of the six degrees of freedom of motion of the shaft.
3. A data input device according to claim 1 or claim 2 further comprising  
10 calculation means for deriving movements and positions of the shaft.
4. A data input device which can differentiate writing movements from non-writing movements.
5. A data input device according to claim 1, claim 2, claim 3 or claim 4 further comprising a pressure sensitive tip at one end of the shaft, the tip  
15 providing an output indicative of the shaft's contact with a solid surface.
6. A data input device according to any preceding claim further including output means for outputting information representing on the movements and positions of the shaft.
7. A combination of a data input device according to claim 6 and a  
20 computing device arranged to receive the information output by the output means.