Non-restricted measurement of walking distance

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Abstract

vertical walking distance is discussed. The horizontal distance is estimated by using three dimensional acceleration of subject's toe. The movement of the foot is assumed that only the pitch angle of the foot changes and the velocity of the foot is never negative. A three dimensional accelerometer is fixed at subject's toe and measures acceleration during swing phase of the foot. A piezoelectric gyro is used to estimate the angle of the foot and calculate the horizontal acceleration of the foot. The horizontal distance is obtained by integrating the horizontal acceleration twice every step. The vertical distance is calculated by integrating the change of atmospheric pressure during ascending or descending. A band pass filter is applied to reject natural change of the atmospheric pressure and sensor noise. The integration of the output of the filter produces a value corresponding to the vertical distance. Experiments were performed at a horizontal corridor and stairs. Experimental results show that the error of the horizontal distance estimated is 5.3 % maximumly and 0.0 % on average, and the vertical distance is 11.1 % maximumly.

1 Introduction

The information of the human behavior in daily life such as level walk, ascending, descending, walking speed and walking distance is very valuable for medical diagnosis of heart disease and senile dementia, progress of health motive, and estimation of consumed calorie. Pedometer and calorie counter are widely used recently to estimate the consumed calorie. Ino-Oka et al developed a measurement system which is composed of a pedometer and a Holter electrocardiogram recorder. The system was useful to evaluate daily activity and the function of heart and diagnose the effect of medical treatment[1]. The pedometer and the calorie counter, however, generate uncertain values since they are only available during level walk of normal velocity and are not able to identify the human behavior of going up the stairs that consumes the calorie twice as much as that of level walk. To solve these problems, Takahashi *et al* tried to classify the human walking patterns into level walk, ascending and descending by applying the acceleration to the clustering method[3]. Though the clustering method obtained good results, the method required high-performance computer because of the huge amount of calculation procedure. In addition, the estimation of the consumed calorie requires the walking velocity. To measure the walking velocity, Miyazaki developed a unrestricted measurement method of the walking velocity by using a piezoelectric gyroscope which senses angular velocity of leg[2]. He constructed a simple symmetric gait model applicable to normal walk and calculated the length of stride and walking velocity every step. Although the accuracy of estimated velocity was high, the method requires the relation between gait cycle and stride length of the subject prior to the experiment and is difficult to apply to the abnormal walk of disabilities or aged people.

In this paper, we propose a method for non-restricted measuring walking distance without subjects' features such as stride length or asymmetric walk. We measure three dimensional acceleration of subject's toe using a three dimensional accelerometer and a piezoelectric gyro. The acceleration is projected to the horizontal plane to produce the horizontal velocity and the horizontal distance. The gyro is used to compensate the rotation of the accelerometer. The vertical distance is estimated by using an atmospheric pressure sensor and a band pass filter which generates the change of the atmospheric pressure during ascending or descending. A definite integral of the output of the filter corresponds to the vertical distance. In the experiments, several subjects are asked to perform level walk and

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ascending/descending using the measurement system to investigate the effect of the proposed method.

2 Horizontal distance

2.1 Estimation of swing phase

It is considered that the horizontal distance is calculated by integrating horizontal acceleration twice that is measured by using a three dimensional accelerometer attached to the subject's body. As the axis of the accelerometer pitches, rolls and yaws during walk, the measured acceleration data are affected by the gravitational acceleration and cause numerical error of the integration. Precise calculation of the horizontal distance, therefore, requires the angle of the attached accelerometer during the walk. A piezoelectric gyro senses the angular velocity and estimates the angle of the accelerometer by the integration of the output of the gyro. However, the output of the gyro which includes sensor drift will affect the integration of the angular velocity. Long-term integration of the angular velocity, therefore, causes large error of the estimated angle. Moreover, the calculation of the angle requires the initial angle of the accelerometer. The initial angle can be estimated by using the component of the gravitational acceleration when the accelerometer remains stationary. However, the accumulation of the integral error is hardly avoided during long-term walking, for example, if the accelerometer is installed at the subject's waist. Therefore, in this paper, we pay attention to the movement of the toe and deal with the acceleration data of the swing phase which lasts about 1 second at most. It is necessary to estimate the swing phase from the measured data. We utilize the angular velocity of foot to define the swing phase. Figure 1 show the angular velocity during level walk. It is obvious that the angular velocity is almost steady at 0 [deg/s] during the stance phase. On the contrary, the angular velocity fluctuates during the swing phase. The definition of thresholds θ_{max} and θ_{min} enables us to distinguish the swing phase from the gait cycle. The angles θ_{max} and θ_{min} are defined as 30 [deg/s] and -30 [deg/s], respectively, based on the preliminary experimental results. However, there is a possibility that the angular velocity remains within the thresholds during the swing phase. Therefore, we assert that the swing phase should continue for more than 150 [ms] in which the angular velocity is within $\pm$ 30 [deg/s]. These criteria will result in reliable detection of the swing phase.

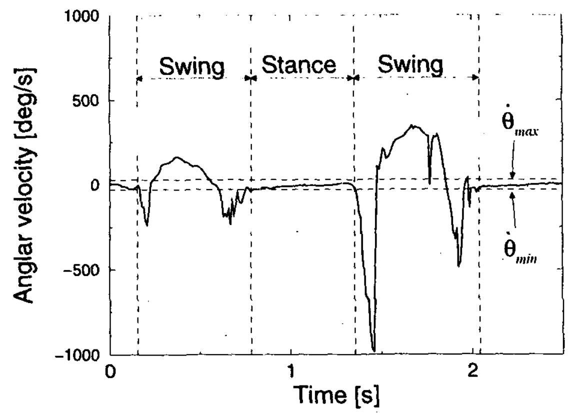

Figure 1: Phase detection during walk using angular velocity

2.2 Calculation method

We measure the acceleration of the toe to estimate the horizontal distance during level walk. The toe vertically and horizontally moves during swing phase which continues for about 1 second at most and is steady during stance phase. The angle of the toe during the stance phase can be estimated by the component of the gravitational acceleration which is measured by the accelerometer attached to the toe. Figure 2 shows axis coordinate of the sensor system attached on the foot. Accelerations in the direction x, y and z are denoted as α_x, α_y and α_z, respectively. To minimize the number of the sensors, we assume that the pitch angle of the foot varies while the rolling and yawing angles are almost steady during swing phase and the x axis is assumed to be parallel to the horizontal plane. We use a three dimensional accelerometer to measure the three dimensional acceleration of the toe and a piezoelectric gyro to sense the angular velocity of pitch angle of the accelerometer during the swing phase.

At first, three dimensional acceleration of the toe is projected to the horizontal plane to estimate the horizontal velocity. The horizontal component of the acceleration projected to the yz plane is calculated as

$$\alpha_{yz} = \alpha_y \cos\theta_y - \alpha_z \sin\theta_y. \quad (1)$$

The pitch angle of the sensor system θ_y is calculated by the integration of the angular velocity

$$\theta_y(t) = \int_0^t \dot{\theta}(\tau)\mathrm{d}\tau + \theta_{init}, \quad (2)$$

where θ_{init} is the initial angle of the sensor system at

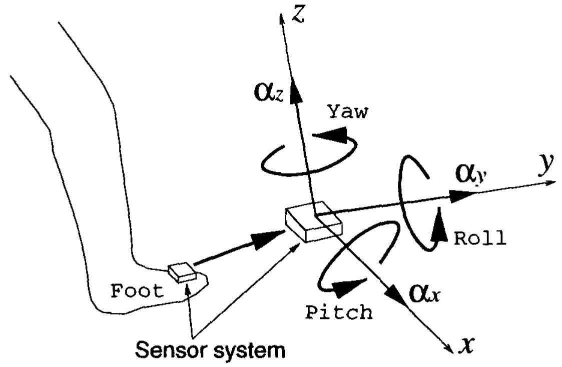

Figure 2: Axis coordinate of the sensor system attached on the foot

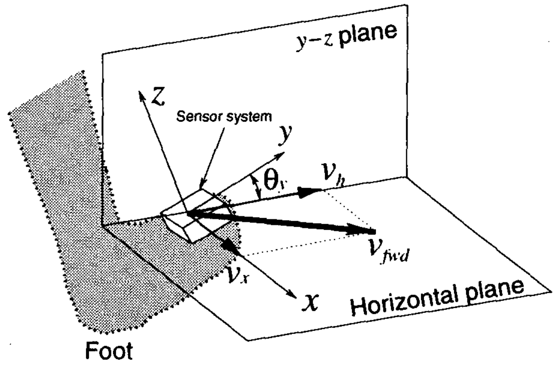

Figure 3: Estimation of horizontal velocity v_{fwd}

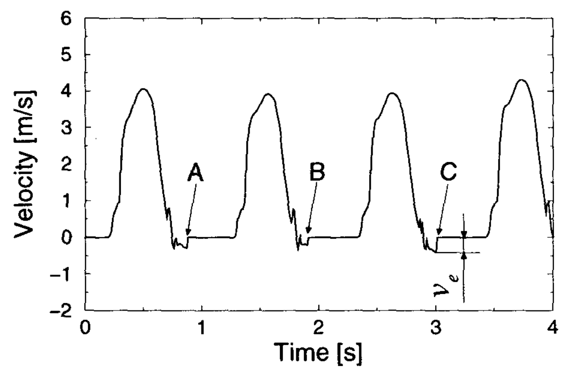

Figure 4: Calculated horizontal velocity. Points A, B and C show the end of the swing phase

the beginning of the swing phase. The initial angle θ_{init} is calculated as

$$\theta_{init} = \sin^{-1}\frac{\alpha_y}{g}, \qquad (3)$$

where g is the acceleration of gravity. The integration of α_{yz} gives the horizontal velocity of yz plane v_{yz} as follows,

$$v_{yz}(t) = \int_0^t \alpha_{yz}(\tau)\mathrm{d}\tau. \qquad (4)$$

The horizontal velocity v_x in the direction of the x axis is easily calculated by

$$v_x(t) = \int_0^t \alpha_x(\tau)\mathrm{d}\tau. \qquad (5)$$

As shown in Figure 3, the horizontal velocity v_{fwd} projected to the horizontal plane and the horizontal distance l during the swing phase are formulated as

$$v_{fwd}(t) = \sqrt{\{v_{yz}(t)\}^2 + \{v_x(t)\}^2} \qquad (6)$$

$$l(t) = \int_0^t v_{fwd}(\tau)\mathrm{d}\tau. \qquad (7)$$

2.3 Modification of integrated values

An example of the horizontal velocity v_{fwd} calculated by the proposed method is illustrated in Figure 4. The horizontal velocity repeatedly returns zero since the foot stands still on the ground during the stance phase. However, the v_{fwd} at the end of the swing phase (A, B and C) is not zero while the actual velocity is zero. This is caused by the measurement error of the accelerometer and the gyro due to electrical noise or sensor drift. To perform precise calculation of the horizontal distance, we have to reject the measurement error from the measured data. It is, however, difficult to identify the occurrence of the error. Therefore, we assume that the measured acceleration $\alpha(t)$ contains constant error α_e and is expressed by the following equation,

$$\alpha(t) = \alpha_a(t) + \alpha_e \qquad (8)$$

where $\alpha_a(t)$ is the actual acceleration of the toe. The actual velocity $v_a(t)$ of the toe is derived by

$$v_a(t) = \int_0^t \alpha(\tau)\mathrm{d}\tau - \alpha_e t. \qquad (9)$$

If the horizontal velocity derived at the end of the swing phase is v_e, the actual velocity is calculated as

$$v_a(t) = \int_0^t \alpha(\tau)\mathrm{d}\tau - \frac{v_e}{T} \times t, \qquad (10)$$

where T is the duration of the swing phase. The pitch angle of the toe can be modified in the same way. If the pitch angle of the toe at the end of the swing phase is calculated as θ_{ye} from Equation (2) and the actual pitch angle is derived as θ_a from Equation (3), the actual pitch angle $\theta_{ya}(t)$ during swing phase is modified as

$$\theta_{ya}(t) = \int_0^t \dot{\theta}(\tau)\mathrm{d}\tau - \frac{\theta_{ye} - \theta_a}{T} \times t. \qquad (11)$$

The angle $\theta_y(t)$ is modified by Equation (11) to derive α_{yz}, then the horizontal velocity v_{yz} and v_x are compensated by using Equation (10).

3 Vertical distance

We have proposed a method to classify the human walking pattern into level walk and going up/down the stairs by using an atmospheric sensor[4]. In this paper, we apply the method to estimate the vertical distance. As the atmospheric pressure slightly changes during ascending/descending, the output of the pressure sensor will be amplified exceedingly. Moreover, it is considered that the output of the pressure sensor includes disturbances such as natural change of the pressure in weather condition and electrical noise. The former changes very slowly and can be rejected by a high pass filter. The frequency of the latter is considered to be high. Moreover, we define the vertical movement that continues for more than 1.5 [s] as going up/down the stairs, since two or three steps may take about 1.5 [s]. We constructed a band pass filter (BPF) which passes the signal of around 0.3 [Hz] and an amplifier which magnifies the output of the sensor 1000 times. A transfer function of the BPF $G(s)$ is formulated as

$$G(s) = \frac{-1000\omega^2 s}{s^2 + 2\zeta\omega + \omega^2}, \qquad (12)$$

where damping factor ζ and natural frequency ω are set to $\sqrt{2}/2$ and 0.6π, respectively. Negative magnification of $G(s)$ generates positive output from the sensor when the subject goes up the stairs. The output of the BPF is related to the vertical velocity because it performs like a differentiator. A definite integral of the output of the BPF brings about a numerical value which is equivalent to the vertical distance. Derivation of the actual distance requires calibration.

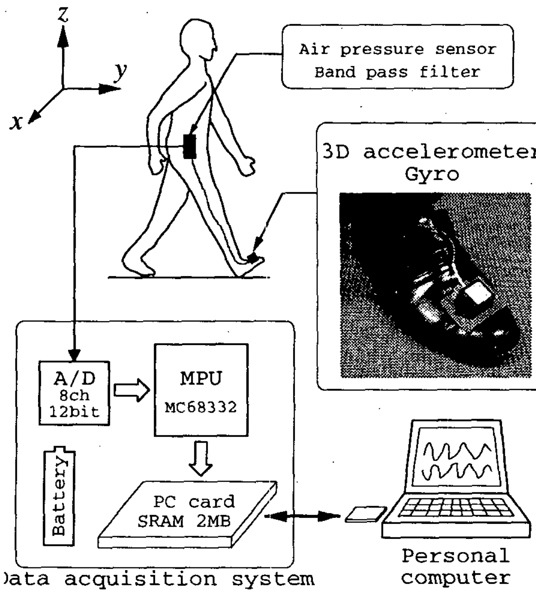

Figure 5: Experimental equipment

4 Experiment

4.1 Equipment and Method

A sensor system constructed by a three dimensional accelerometer and a piezoelectric gyro is attached to the subject's toe and is fixed by an adhesive tape on the right shoes. The atmospheric pressure sensor and the BPF are installed in a small box with a data acquisition system which is composed of a 12 bit analog-to-digital converter, an MPU (Motorola MC68332), a 2 mega bytes memory card and a dry cell battery. The subjects fixed the data acquisition system at their waist. The measured data are recorded in the memory card with the sampling period of 10 [ms]. After the experiments, the memory card is inserted to a computer to derive the walking distance off-line.

Experiments were performed at a horizontal corridor which is 30 [m] in length and the stairs which is 10.8 [m] in height. Eight subjects were asked to walk on the the horizontal corridor with normal, fast and slow speed. Similarly, seven subjects ascended and descended the stairs normally and fast. The subjects wore usual shoes. To confirm the effectiveness of the proposed method, the subjects performed the same experiment twice.

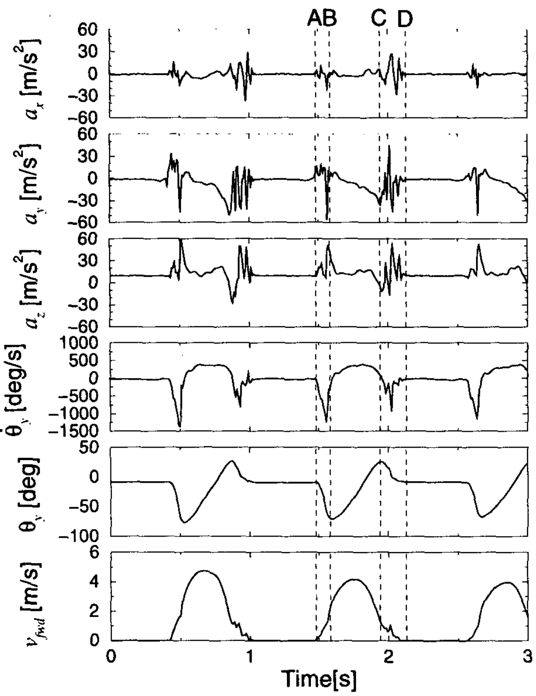

Figure 6: Experimental results of acceleration α_x, α_y, α_z, angular velocity $\dot{\theta}_y$, pitch angle θ_y and horizontal velocity v_{fwd} during level walk

4.2 Results

Figure 6 illustrates the time trajectories of the change of the three dimensional acceleration α_x, α_y, α_z, the angular velocity $\dot{\theta}_y$, the pitch angle θ_y, and the horizontal velocity v_{fwd}. Time interval from A to D corresponds to the swing phase. The toe leaves from the floor and the horizontal velocity begins to increase at the moment A. We can see that the ankle stretches from A to B, then bends until C from the change of θ_y. It is considered that the heel contacts on the floor at C since there are rapid increases in α_y and α_z. After C, the toe gradually approaches to the floor and the horizontal velocity reaches zero at D.

Figure 7 shows the changes of the horizontal distance of a subject who walked normally, fast and slowly. Each line features wavy increases which result from the horizontal distance of the toe during the swing phase and reachs 30 [m] finally. Slope of each line corresponds to the walking velocity. Table 1 shows the estimated horizontal distance of eight subjects. Average value and standard deviation are 30.0±0.8 [m] and the error is 5.3 [%] maximumly.

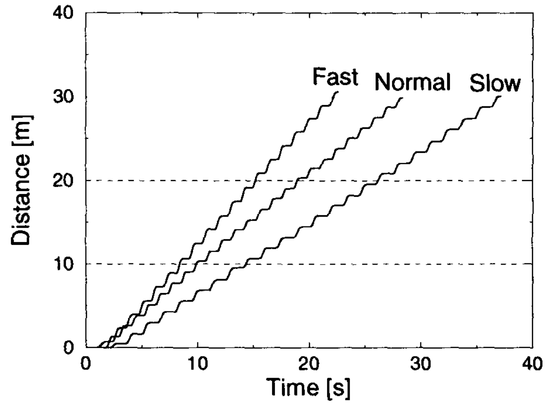

Figure 7: Experimental result of time trajectories of the horizontal distance

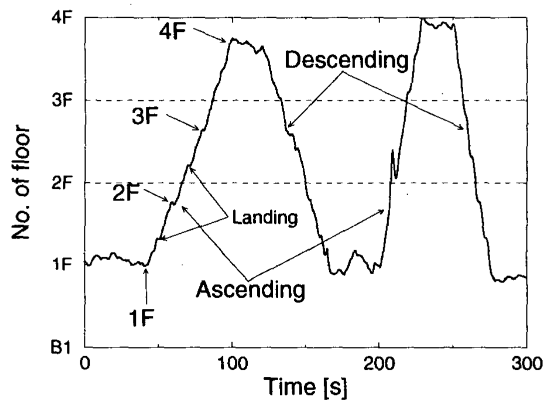

Figure 8: Output of the BPF applied to the air pressure sensor during ascending/descending

Let us turn to the estimation of the vetical distance. Figure 8 shows the change of the estimated vertical distance of a subject who normally and rapidly went up/down the stairs. Vertical axis, which denotes the number of the floor, is derived by integrating the output of the BPF and calibrating it using a mean value of the estimated vertical distances of seven subjects. During ascending/descending, the estimated vertical distance increases/decreases and roughly reaches the fourth floor and the first floor, respectively. We can identify that the vertical distance remains still when the subject walked each floor and each landings. Ta-

Table 1: Estimated horizontal distance

No. of Subject	Estimated distance [m]					
	Normal		Slow		Fast	
1	30.0	30.6	30.4	30.4	29.1	28.9
2	29.5	29.8	29.6	29.6	29.5	29.2
3	29.8	31.1	30.2	29.6	30.7	29.9
4	30.9	31.2	30.3	30.7	31.3	30.7
5	31.5	31.3	31.3	31.0	31.3	31.6
6	30.4	29.6	29.7	29.9	29.9	30.2
7	29.0	29.0	29.3	29.0	29.3	28.9
8	30.0	28.7	29.6	29.1	30.0	29.3
Ave.	30.0±0.8					

Table 2: Estimated vertical distance

No. of Subject	Estimated distance [m]			
	Normal		Fast	
	Up	Down	Up	Down
1	9.8	9.9	10.9	11.4
	11.3	11.4	9.6	10.2
2	11.1	10.9	10.9	10.6
	10.8	11.0	10.9	10.7
3	10.8	10.9	10.9	10.7
	10.5	11.0	11.2	10.4
4	11.2	10.9	11.3	10.9
	10.7	10.5	10.7	10.5
5	10.9	10.3	10.2	10.3
	10.8	10.5	10.8	10.2
6	11.1	11.0	10.5	10.6
	11.3	11.1	11.3	10.7
7	10.5	11.5	11.4	11.4
	10.7	10.9	11.1	10.8
Ave.	10.8 ± 0.4			

ble 2 shows the estimated horizontal distances of seven subjects. Average value of the estimated distance is equal to 10.8 [m], since each values are calibrated to the height by using their own average value. The estimation error is within 11.1 [%].

It is confirmed that the precise estimation of the horizontal distance can be performed by utilizing the three dimensional acceleration of the toe. The filtering and the integrating the time change of the atmospheric pressure enables us to make a rough estimation of the vertical distance.

5 Conclusions

A non-restricted measurement method for measuring walking distance has been proposed. The horizontal distance is derived by the integration of the three dimensional acceleration of the subject's toe each step. Numerical error accumulated by the integration of the measured data is linearly rejected to perform precise estimation of the distance.

Vertical distance is estimated by using the change of the atmospheric pressure. The BPF is used to generate only the change of the air pressure during ascending/descending related to the vertical velocity. The vertical distance is derived by the integration of the output of the BPF. The experimental results show that the proposed method enables us to obtain the precise estimation of the horizontal distance within the error range of 0.0±2.7 [%] on average. The error of 11.1 [%] seems to be unavoidable on the estimation of the vertical distance because of utilizing the atmospheric pressure. We confirm that the proposed method can estimate the horizontal and vertical distance during walk unrestrictedly.

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