# Experimental Evaluation of the Gyroscope Sensor used in a New Gait Phase Detection System

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## ABSTRACT

*This paper focuses on the experimental evaluation of a gyroscope sensor used in a new gait phase detection system, which has previously been presented in [1]. The system distinguishes four phases during walking (stance, heel-off, swing and heel-strike) and consists of three force sensitive resistors, a gyroscope and a processing unit. The system has been successfully tested by subjects with normal and pathological gait styles. Further, it has been verified that the system works with very high reliability even on irregular ground surfaces and varying ground inclinations. The contribution of this paper lies in the in-depth analysis of the processing of the gyroscope signal. Miniaturized gyroscopes have recently been used also in other biomedical applications, for which the presented results are of particular interest.*

## INTRODUCTION

In a previous paper [1] we presented a new gait phase detection system which distinguishes four phases during gait: stance, heel-off, swing, heel-strike. The system, as shown in Figure 1, consists of three force sensitive resistors (FSR), which measure the applied weight pressure in three areas of the sole and a piezoelectric gyroscope which is inserted in the shoe heel and which measures the rotational velocity of the foot (about the y-axis) with respect to an inertial system. In previous publications [1], [2] we have claimed that the combined use of the FSRs and the gyroscope together with a intelligent rule based detection algorithm leads to a very robust gait phase detection system. The performance of the system has been validated by healthy and walking-impaired subjects on irregular and inclined ground surfaces and even on stairs. A key role for this highly reliable performance is played by the gyroscope sensor which provides information about the foot's momentary angular velocity, which the FSRs can not provide. Based on this information we are able to estimate in real-time the angular inclination of the foot $\theta(k)$ with respect to the ground and thus distinguish between a true heel-off event and a simple unloading of the foot (for instance due to weight shifting from one leg to the other during stance without and actual lifting of the heel). The gyroscope is also used to detect the beginning of the swing phase, which is characterized by a change of the foot rotation from clockwise direction to counter-clockwise (viewed from the right hand lateral side). The gait phase detection system shall be used to trigger the onset of stimulation sequences in functional electrical stimulation (FES) systems for walking.

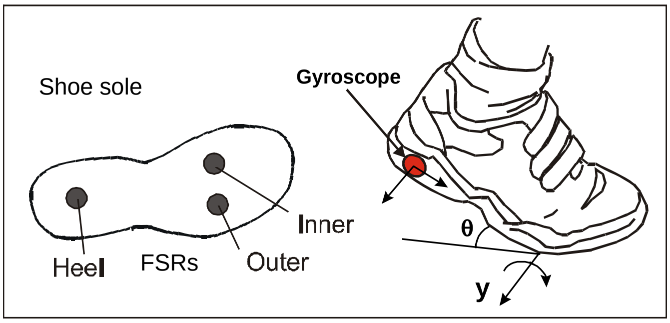

***Figure 1** Placement of the force sensitive resistors (FSR) and the gyroscope used for the gait phase detection system.*

In the last years, miniaturized gyroscopes have been used for several purposes in the field of biomedicine and rehabilitation. J. R. Henty [3], for example, placed a gyroscope on the foot above the metatarsals in order to distinguish two phases in the gait cycle, the swing phase and the stance phase. Further, he calculated the hip, knee and ankle flexion angles during the gait cycle by placing a gyroscope at the thigh, at the shank and at the foot and by integrating the differences of the gyroscope signals. In another application, Thomas Fuhr in [4] placed a gyroscope on the thigh of his subjects in order to estimate the angular velocity of the knee flexion during the standing-up phase. In spite of the above mentioned works and the multiple use of the same gyroscope device[1], no detailed analysis of the gyroscope signal has been reported yet. Therefore, in the following, we present results obtained from the experimental analysis of the gyroscope sensor and discuss the consequences for the gait phase detection application. The analysis does not include the FSR sensors, because they are used as simple switches, i.e. they determine whether weight is applied to the respective area of the foot sole or not.

## THEORETICAL ASPECTS OF GYROSCOPE SIGNAL ANALYSIS

During rotations the gyroscope senses the mechanical deformation of an internal vibratory prism caused by the coriolis force. It delivers an output voltage $g(k)$ which is proportional to the rotational velocity $\dot{\theta}(k)$, as expressed by Equation 1. The parameters $a$ and $b$ are the gain and offset values and $v(k)$ is the measurement noise which includes round-off errors and disturbances. The angular excursion $\theta(n)$ can be estimated by integrating the gyroscope signal, according to Equation 2. The estimation error committed by the integration of the noisy gyroscope signal is given by $\varepsilon_\theta$. Under the assumption that the measurement noise $v(k)$ is random, white and zero mean with standard deviation $\sigma_v$, the standard deviation $\sigma_\theta(n)$ of the estimation error $\varepsilon_\theta(n)$ increases with time according to a random walk law, see Equation 3 and Figure 2. However, this is a conservative estimate, since in reality the measurement noise may not be white or zero-mean. For time critical systems (such as the gait phase detection system), the following question is of interest: How accurately can the time point $t_{th}$ be determined at which the angular excursion reaches a given threshold value $\theta(t_{th}) = \theta_{th}$ ? Given the uncertainty in the estimation of $\theta(n)$ (standard deviation $\sigma_\theta(n)$), the standard deviation $\sigma_{th}$ on the estimation of $t_{th}$ is given by Equation 4.

*Equation 1* $$g(k) = a\dot{\theta}(k) + b + v(k)$$

*Equation 2* $$\hat{\theta}(n) = T \cdot \sum_{k=0}^{n} \tfrac{g(k)-b}{a} = \theta(n) + \varepsilon_\theta(n)$$

*with* $\varepsilon_\theta(n) = \tfrac{T}{a} \cdot \sum_{k=0}^{n} v(k)$ *and T=sampl. period*

*Equation 3* $$\sigma_\theta(n) = \sigma_v \cdot \tfrac{T}{a}\sqrt{n}$$

*Equation 4* $$\sigma_{th} = \frac{\sigma_\theta(t_{th})}{\dot{\theta}(t_{th})}$$

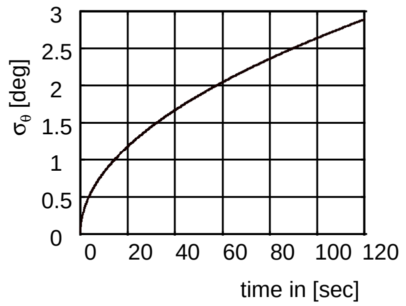

***Figure 2*** *Illustrates Equation 3 for $a$=3.8mV/deg/sec, $T$=10ms, $\sigma_v$=10mV*

## EXPERIMENTS

In order to validate the theoretical predictions of the error committed by the integration of the gyroscope's signal the following experiment was performed. The gyroscope was mounted on an articulated arm which was rotated repetitively by 45 degrees. The average rotational velocity was

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[1] Gyrostar, Murata Electronics, Kyoto, Japan

approximately $\omega = 22\,\mathrm{deg/sec}$ (very slow for walking purposes, taken as worst case). Figure 3a shows recordings of the gyroscope signal during the first 4 trials.

**Random Errors:** The random measurement noise amounts to $\sigma_v = 10mV$ and the signal to noise ratio at these slow rotational velocities is at an approximate level of ≅30dB. Figure 3b shows estimates of the angular excursions $\theta(k)$ obtained by the integration of the gyroscope signal. The deviation of the final angle estimate amounts to $\varepsilon_\theta = 1.5\,\mathrm{deg}$ and is due to the integration of the random measurement noise. This measured error is in good agreement with the theoretical standard deviation of $\sigma_\theta \cong 0.6\,\mathrm{deg}$ calculated by Equation 3 (with $a = 3.8mV/\mathrm{deg}/s$, $n = 500$, $T = 0.01s$). The uncertainty with which we can determine the time point at which $\theta(k)$ crosses the threshold of e.g. $40°\,\mathrm{deg}$ is given by Equation 4 and amounts approximately to: $\sigma_{th} = \sigma_\theta(t_{th}) / \omega = 26ms$. A large portion of the measurement noise is due to disturbances in the signal transmission through the long wires and to the round-off errors of the employed 10bit resolution A/D converter. In order to reduce the relative importance of the measurement noise shielded wires were employed and the gyroscope signal was amplified using the circuit displayed in Figure 4b (amplification factor = 3.3).

**Offset Drift:** The Figure 3c and 3d, show the integration results for the same experiment as above carried out at different temperatures (18.7°, 20.4°C). The integrated signals exhibit a significant *systematic* error which is due to an offset drift caused by the temperature variations. This systematic error can be eliminated by re-calibrating the gyroscope signal before each trial. The Figure 3e and 3f show the same data as the Figure 3c and 3d but with a software offset correction.

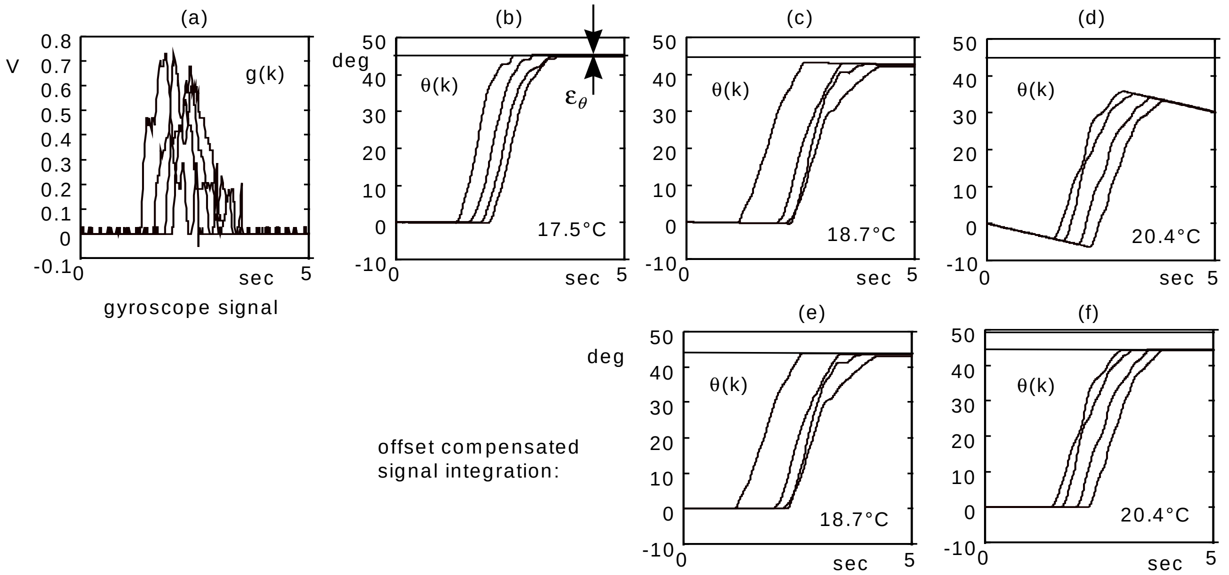

*__Figure 3__ The experiment shown in this figure consisted of repetitive rotations of the gyroscope of 45 degrees. (a) shows the gyroscope signals for the first set of 4 trials. (b) shows the angular excursion $\theta(k)$ obtained by integration of the gyroscope signals shown in (a). The final integration error is $\varepsilon_\theta$=1.5 degrees, which is due to the integration of the random measurement noise. (c) and (d) show integration results of the same experiment repeated at different temperatures. The large error is due to a temperature drift. In (e) and (f) the same data as in (c) and (d) are shown, but with a software offset correction.*

To evaluate the influence of the temperature on the offset drift of the gyroscope signal the above experiment was repeated at different temperatures ranging from 5 to 50°C. In Figure 4c the measured offset values are shown as function of the temperature. In the same temperature range, the gain factor $a$ varied within a range of ±5%, which results in a less important error as compared to the offset drift.

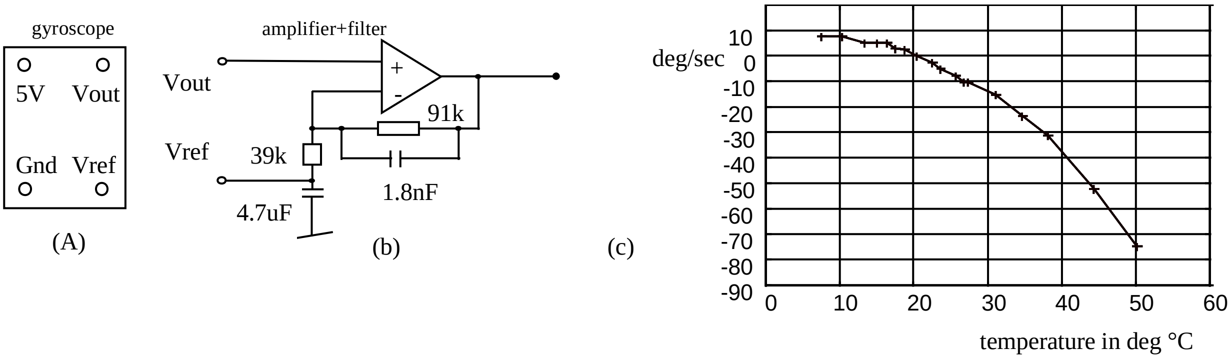

**Figure 4** *(a) shows the gyroscope connections and (b) the amplifying circuit used in the experiments. (c)Shows the offset drift of the measured gyroscope signal as a function of the temperature. The offset at 20°C is set to zero and the deviations are scaled to equivalent [deg/sec] units.*

## DISCUSSION

The main conclusion from the above experiments is that the gyroscope sensor can provide very valuable information if its signal is processed appropriately. First, a compensation of the gyroscope's temperature drift is absolutely necessary in order to obtain quantitative measurements. If the drift is (computationally) compensated the gyroscope signal can be used to measure rotational velocity or angular excursions (by integration of the gyroscope signal). Integration of the gyroscope signal should be limited to short time periods (depending on the required precision), in order to maintain an approximately constant temperature and in order to avoid the integration error which increases with the number of integrated samples according to Equation 3 and Figure 2. In the case of the gait phase detection system the signal offset is re-calibrated once in every walking cycle during the stance phase (rotational velocity $\dot{\theta} = 0$). However, at fast walking speeds (>7km/h) the stance phase becomes shorter and shorter and does not satisfy the condition of rotational velocity $\dot{\theta} = 0$ anymore, because the foot rolls from heel-strike to heel-off continuously on the ground without a pause. Thus at these speeds, it is impossible to compensate for the temperature drift. We have shown that the timing uncertainty in the detection of the gait phases is affected by the errors in the estimation of the angular inclination. Based on the presented (worst case) experiments this error should be smaller than 26*ms*, which is sufficiently accurate for a FES walking application. Finally, in a future design it would be desirable to develop for the gyroscope a temperature compensating electronic circuit or to actively regulate the temperature of the gyroscope to a constant value.

## REFERENCES

[1] I. Pappas, "A Novel Gait Phase Detection System" presented at AUTOMED'99, Darmstadt, Germany, 1999.

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[3] J. R. Henty and D. J. Ewins, "Applications of gyroscopic angular velocity sensors in FES systems" presented at 6th International Workshop on Functional Electrostimulation, Vienna, Austria, 1998.

[4] T. Fuhr and G. Schmidt, "Autokalibrierungsverfahren für ein patientenfixiertes Goniometer-Gyroskop-System zur Bewegungsmessung" presented at AUTOMED '99, Darmstadt, 1999.

NOTES:

Figures 1-4 where edited in the files final figs.ppt

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