Gait detection and sonification based on angular rate sensors

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1. INTRODUCTION

This project is concerned with the acquisition, analysis, and visualization of *gyroscopic data* produced by motion tracking sensors, in particular with the objective of *step detection and sonification* applied in the context of post-stroke and Parkinson's patients physiotherapy. Audio feedback, useful for the patient, is produced immediately after each step is taken. The application can simultaneously acquire, record, and visualize motion data, it triggers personalized audio samples sequentially (in a circular fashion) while the subject is moving.

2. SENSORS AND DATA

Xsens MTw Awinda motion sensors are used to acquire motion data.
The setup consists of:

- 2x Xsens MTw Awinda motion trackers
- 1x USB Master dongle
- 2x Body straps

Mtw Awinda motion tracker

USB Master dongle

The two motion trackers are placed on the velcro straps that are wrapped on the ankles of the subject, the sensors are equipped with a 3-axial gyroscope and a magnetometer to detect orientation. The data is produced with a maximum sample rate of 120Hz and and transmitted wirelessly to the master device (USB dongle) with a maximum latency of 30ms.
The packets produced by the motion trackers are sent to the USB Master dongle via the Awinda patented wireless protocol, with a maximum guaranteed range of communication of 10 meters (in an office space). Orientation information contained in each packet is described as the three Euler angles (Roll, Pitch, Yaw).

3. APPLICATION OVERVIEW

The application accesses data produced by the two sensors via a simplified Python interface that relies on the Xsens device API, a library with classes to communicate with Xsens devices on a basic level. It is structured in an object oriented fashion with 3 main components:

MTw class This class implements the setup of the master device, motion trackers detection and pairing, data acquisition, recording and proper closing of resources. The class exposes one public method `mtwRecord()` as the only entry point to the application. Such method has a mandatory `duration` argument that specifies the duration of the recording in seconds and two optional flags:

- plot

- analyze

The two flags specify if the data has to be plotted and/or analyzed, the plotter and analyzer are spawn as child processes (daemons) and can read the data -while it is received- from shared memory. The data is put into shared memory by the MTw object after extracting the useful angle information.

Analyzer class This class implements the step detection algorithm and triggers sound samples from a specified sample library. The data is read from shared memory while being produced by the sensors and after being processed by the MTw object. An object of this class is created by the MTw object if the relative flag is given as argument to the `mtwRecord()` method, this object code runs separately as a daemon.

Plotter class This class implements the real-time visualization of the data produced by the sensors, it is created by the MTw object if the relative flag is given and runs as a separate daemon.

4. STEP DETECTION AND SONIFICATION

Step detection is performed using pitch angle retrieved from each of the two sensors mounted on the ankles of the subject. The algorithm follows the idea in [1], without relying on initial calibration to find thresholds for steps validation. Step detection code is ran in the Analyzer process, a separate process is spawn for each leg. The member function `stepDetector()` is called every 3ms and it is responsible to detect a step as soon as it's movement is completed, each time a step is detected an audio sample is reproduced from the given sample library. The analyzer process returns the total number of steps counted for each leg.

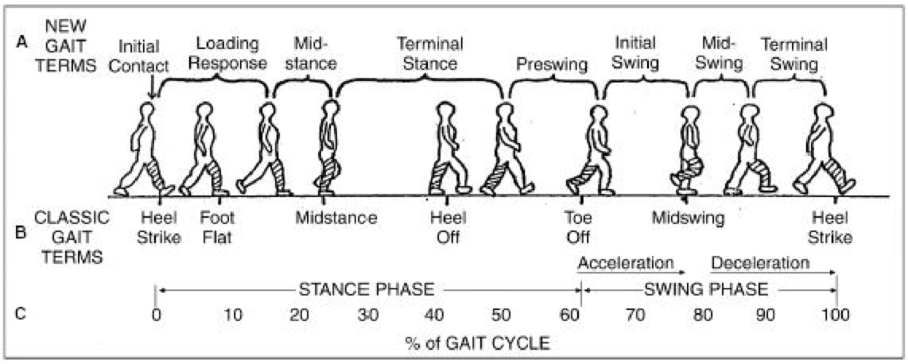

Figure 2: Gait cycle

4.1 Leg movement and sensor reading

Gait cycle is measured from the Initial Contact of one heel to the next Initial Contact of the same heel to the ground, during this cycle the pitch angle between the leg and ground varies from positive to negative and from negative to positive (view figure 3). A step can be therefore identified by observing two successive negative gradient zero crossings in the pitch signal from the same leg. The zero crossing happens slightly after the Initial Contact of the heel, (in Mid Stance, view figure 2) when the leg is perpendicular to ground. (view subsec 6.2)

4.2 Calibration

Before starting the recording while sensors are attached to the subject an *orientation reset* is performed. The frame of reference of the motion trackers is transformed to a new frame which is the one of the object they are attached to, this ensures that a zero crossing will be encountered only when the leg where the sensor is mounted is perpendicular to ground, regardless of the orientation of the sensor with respect to such leg.

4.3 Zero-Crossing detector

Gyroscopic signal generated from the motion trackers attached to the legs takes a sinusoidal behaviour. As previously mentioned a step is characterized by two zero crossings with alternating polarity, therefore it can be identified by detecting these consecutive zero crossings. The first *negative gradient* zero crossing is encountered after Initial Contact during Mid Stance, and the second *positive gradient* zero crossing is encountered during the swing phase (end of Mid-swing) where the tibia is again perpendicular to ground (view figure 2).

The aforementioned `stepDetector()` function analyzes the content of a small buffer containing the last 15 readings from the motion tracker attached to one leg. A zero crossing is detected counting the number of positions in witch the buffer changes from positive (zero included) to negative. The count of positions in witch this happens must not be more than one in such a small window (roughly corresponds to 125ms), more frequent changes in polarity must be considered noise.
Polarity of the zero crossing is determined computing the gradient at the position where the zero is found.
A step is detected as follows:

- A *negative gradient* zero crossing marks the end of the previous Swing phase and the beginning of the Stance phase that has just begun after Initial Contact
- A following *positive gradient* zero crossing must be detected meaning the foot is in Swing phase again (this happens during Terminal Swing at the end of the Swing phase)
- Another *negative polarity* zero crossing is encountered, at this instant a step is counted and an audio sample is reproduced.

Figure 3 shows a signal with two labeled cycles where the area between two downward pointing triangles represents a step.

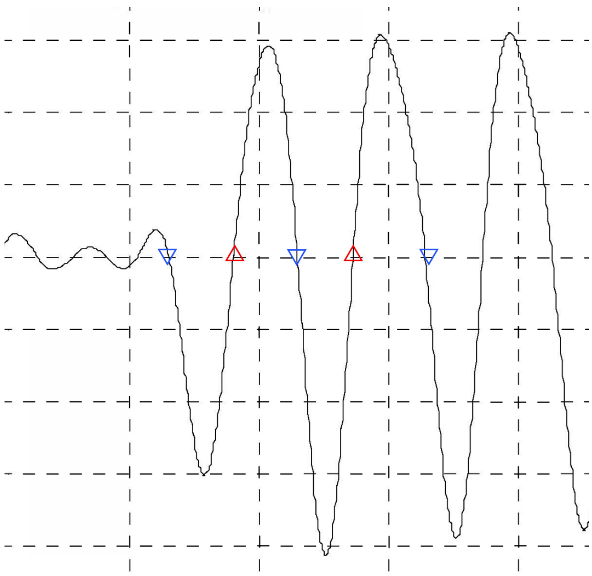

Figure 3: Step detection through zero crossings

4.4 Avoiding false detections

A gyroscope signal may cross zero with a negative gradient for more than one time during the period from Initial Contact to Loading Response, this period corresponds to 0-10% of the gait cycle [1].
A timeout method is used to avoid false detections. The timeout is set to 100ms, this time corresponds to 7% of the average fast gait of 1.5 steps per second (reffered to a single leg). During the timeout period all encountered zero crossings are rejected, the timeout is reset after the first *valid* negative gradient zero crossing is encountered. The waveform in figure 4 shows an example of step rejection, the first cycle marked with the red segment represents a step that will be rejected due to its period being shorter than the threshold (indicated by the green segment). The cycle marked by the blue line will be considered valid

4.5 Adaptive threshold validation

An adaptive peak threshold is used to validate steps. Threshold peak detection helps to avoid recognising instantaneous and small movements of the device as false positives. A step is considered valid only if the positive peak encountered before the negative gradient zero crossing is above such threshold.

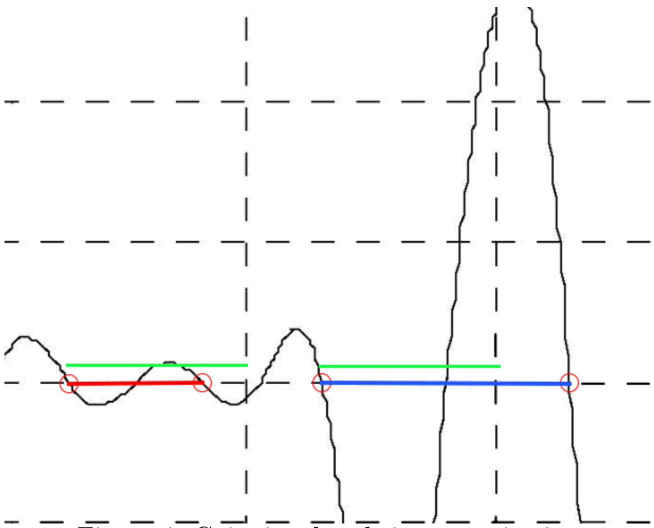

Figure 4: Gait signal and timeout rejection

The threshold value is initially set to its minimum of 2.0 deg to ensure that steps are not detected while subject is standing still (due to noise in the signal), and gradually updated as the subject is walking.
The threshold is updated computing the minimum positive peak of the last 10 steps. Negative zero crossings preceded by a peak below the threshold are ignored. As can be viewed in figure 5 the first negative gradient zero crossing is preceded by a peak below the threshold (indicated by the red line) and will be rejected, the two following steps will be detected correctly as they both have a peak over the validating threshold. Steps with peak threshold 3.0 deg below the margin are allowed to let the threshold gradually vary depending on subject gait during the same walking session. Hence the minimum value of the peak can also slowly decrease over time.

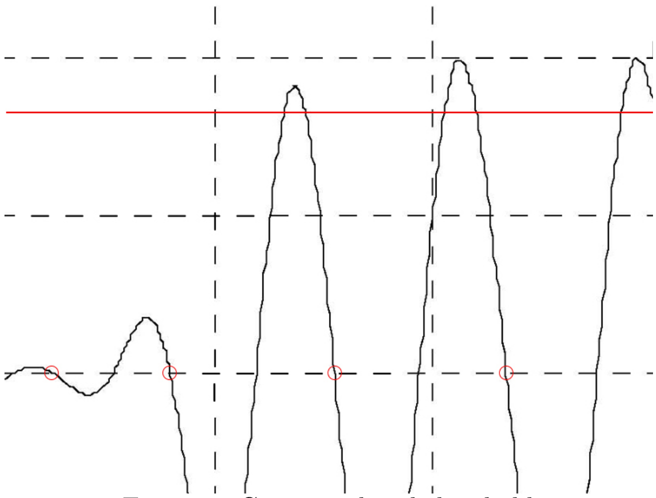

Figure 5: Gait signal and threshold

5. RESULTS

The use of gyroscopes for gait detection provides a series of advantages, they represent a portable and non-invasive solution and offer good performance in detecting steps at slow speeds.
Performance is measured on 30 trials carried out by several (healthy) subjects. Tests are performed at different walk speeds on level ground and have a duration of 1 minute. During the test, subjects walk back and forth, approximately 2 to a maximum of 5 meters from the "Master device". Subjects are also free to change walking speed as they like, the total number of steps taken is then divided by the duration of the test to find the mean

velocity, measured in steps/min. Test results are grouped by walk speed in three speed intervals corresponding to "slow" , "medium" and "fast" walking speeds. Results are reported in table 1.

Table 1: Test results

Speeds	Actual steps	Detected steps	Accuracy
$\leq$ 60 steps/min	47	45	95.7%
	48	48	100%
	54	54	100%
	58	57	98.2%
	58	58	100%
60-80 steps/min	65	65	100%
	75	74	98.6%
	71	69	97.1%
	68	65	95.5%
	75	73	97.3%
$\geq$ 80 steps/min	92	90	97.8%
	95	89	93.6%
	95	91	95.7%
	92	90	97.8%
	90	87	96.6%

Overall performance of the algorithm is above 93%. The primary source of errors arises from steps that have positive peaks that fall below the threshold. This happens when steps are very short and the movement's angle is too minimal to be recognised as a valid step, or when the subject rotates in place. As speed increases, the number of times the subject rotates in place also increases, as the subject goes back and forth more frequently. The algorithm performs poorly in all conditions where the angle described by the movement of the leg is not changing polarity, e.g. stepping in place, or swinging in place without forward advancement.

6. FUTURE WORK

6.1 Initializing thresholds through a calibration phase

As mentioned in subsection 4.5, threshold peak detection is useful to avoid detecting false positives. These validating thresholds for step detection can be acquired for each patient by means of a *calibration phase*. During this phase the subject is asked to walk for a certain period during which motion data is acquired. After such period, peaks preceding negative zero crossings are detected. The minimum peak value can be used as validating threshold in the actual walk experiment performed on the subject. This method can be tested as a substitute of the current adaptive threshold validation, or it can be used in conjunction with it.

6.2 Triggering feedback sounds earlier

As mentioned above, zero crossing happens slightly after the Initial Contact of the heel, in Mid Stance when the leg is perpendicular to ground. This "delay" between the instant when the heel is placed on the ground (Initial contact) and the moment when the zero crossing is detected can be perceived when the audio sample is reproduced. The subject has to shift his weight forward and receives the feedback of a completed step when the other foot is already in Pre-swing. The "delay" can get larger or shorter depending on walking speed. This effect could cause the subject to fail to associate the sound reproduced to the actual step taken. To avoid this, the playback of a sound could be anticipated to an instant preceding the moment when the zero crossing is detected in the gyroscopic data.

One way to do this ensuring no false positives are detected is to use an additional sensor that provides acceleration data (or a device integrating both). The accelerometer signal can be used to detect the instant in which the heel contacts the ground and trigger the sound immediately, while ensuring that the step is valid relying on gyroscopic information.

6.3 Monitoring patient stress and fatigue

When faced with environmental changes, we tend to keep our internal state constant. This mechanism is called homeostasis. Stress can be defined as a state disharmony or threatened homeostasis [2].

Measures like the level of psychological stress and physical fatigue in patients can be used as indicators of how well the patients are responding to the physical task to which they are subjected. These could be used as a reference measure to adjust the load to the specific patient and to assess over time if the patient is getting used to such task.
Stress monitoring can be achieved by analyzing different signals produced from wearable devices like: PPG (photoplethysmogram), GSR (Galvanic skin Response), HRV (Heart rate variability) [3]. A number of time-domain, frequency-domain and non-linear features can be extracted from such signals [4]. Machine learning models such as k-NN1, k-NN3, SVM, LDA can be a simple and effective way to infer the level of stress from such feature vectors as shown in [3][4].

REFERENCES

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[4] Heo, S., Kwon, S., and Lee, J., "Stress detection with single ppg sensor by orchestrating multiple denoising and peak-detecting methods," *IEEE Access* **9**, 47777–47785 (2021).