

Chaotic Analysis on Human Gait Time-Series Signals

D. Gomez Rivera, A. D. Palomino Merino, M. A. D. Vargas Treviño, and G. Etcheverry

Abstract—Human Gait analysis is an important subject given its application to the study of pathologies of the human locomotor system. The study of the chaotic behavior of this complex system can help to understand in deep the variability of the human gait patterns. This work explains how to develop an acquisition and analysis tool in a twofold manner: first, a simple and practical setup is implemented in order to achieve the measurement of a person Center of Mass (CoM) when walking; second, an improved method for estimating Lyapunov exponents is described in order to analyze the recorded time-series chaotic behavior.

Index Terms—Chaotic time-series, human gait, Lyapunov exponents.

I. INTRODUCTION

The dynamics of the human gait has been studied in order to establish its chaotic behavior based on simple nonlinear time-series analysis methods [1]. This analysis is performed in order to study early diagnose common gait pathologies through unconstrained slow, normal, and fast paces [2], [3].

The importance of having an acquisition system for measuring the human gait becomes important at elder people when walking needs assistance for falling injury avoidance [4]. Therefore in this work, a simple and straightforward wireless setup is developed in order to log data into a personal computer.

A common manner to analyze human gait nonlinear and chaotic behavior is through Lyapunov exponents computation. An improved and simple method developed by K. Briggs is hereby implemented to show that the lateral walking movement is responsible for the aforementioned chaotic pattern [5].

II. LATERAL WALKING TIME-SERIES AND PHASE PLOT

The lateral time-series $x_t, x_{t+1}, \dots, x_{t+i}$ are responsible for 38-40% of gait cycle (swing) [2], which is shown in Fig. 1. This time-series was obtained from experimental data from an accelerometer unit placed at a person waist in order to obtain the Center of Mass (CoM) and therefore, capture the human gait system dynamic behavior. The finding of a positive Lyapunov coefficient means that the system is chaotic; see Fig. 2 where the phase plot shows a moderated chaotic behavior [5].

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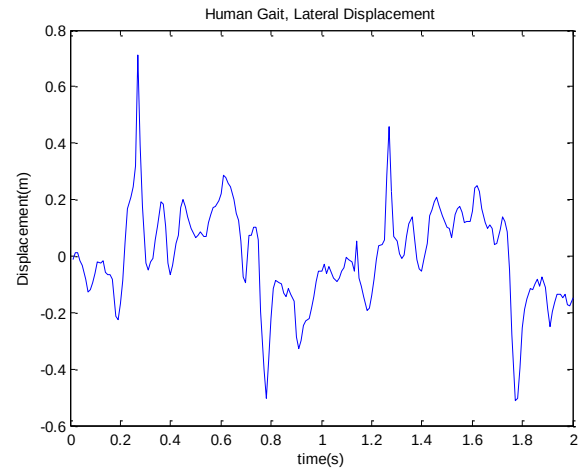


Fig. 1. Gait cycle.

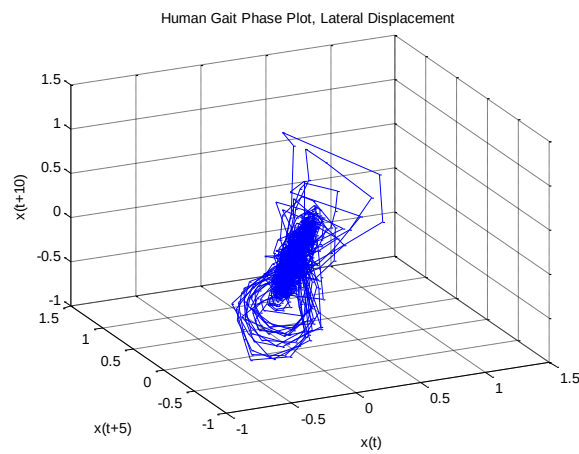


Fig. 2. Human gait phase plot.

III. THE LYAPUNOV EXPONENT

In order to compute the Lyapunov exponent, two points are considered within the phase plane: X and X_f , such as [2]:

$$\frac{\|X_f\|}{\|X\|} = e^{\lambda_i t} \quad (1)$$

In this manner, λ_i is obtained from expression:

$$\lambda_i = \lim_{t \rightarrow \infty} \left(\frac{1}{t} \log \frac{\|X_f\|}{\|X\|} \right) \quad (2)$$

If any of the Lyapunov exponents is positive, the system is said chaotic. This means that any pair of neighbor points within initial state separate abruptly and the system is sensitive to initial conditions, which is one of the main aspects of a chaotic system.

A negative exponent implies that the orbits approach a common fixed point. These systems are non-conservative. The degree of stability is measured by the absolute value of the exponent.

A zero exponent means the orbit maintain its relative position on a stable attractor. These kinds of systems are conservative and in a steady state mode.

The Lyapunov exponent is also used to differentiate between periodic signals and chaotic dynamics, because it is a measure of the rate at which the trajectories separate one from another and the trajectories of chaotic signals follow typical patterns in phase space. Another use for this exponent (λ) is to characterize the average rate of divergence on neighboring trajectories, with this it can be know the sensitivity to initial conditions on dynamical systems.

IV. METHODOLOGY

A. Measurement Module and Implementation

In order to obtain the CoM movement information, an MMA7361 accelerometer is used plus an Arduino nano board; besides it, a bluetooth HC-06 is adapted to the nano board to transmit information wireless to a PC as it is shown in Fig. 3.

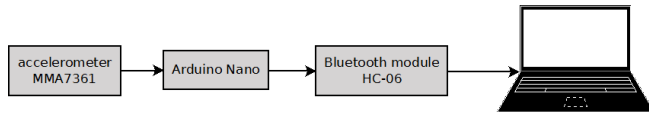


Fig. 3. Measurement module block diagram.

MMA7361 sensor [6] is a triaxial accelerometer with analog output, low current and high sensitivity between 1.5 g and 6 g.

Data obtained from this device are the following: gravity force and x, y and z axis acceleration. The principal measurement variable is the device inclination with respect to the gravity force related to the acceleration components on x and y axis; from this information and by using trigonometric functions, the inclination angles are obtained.

In order to perform the aforementioned task, an arduino code is developed to log data from the accelerometer and process them to obtain the device inclination. This procedure is shown in Fig. 4.

Finally, the bluetooth HC-06 module [7] is adapted to sent data wirelessly to a PC to make data logging more comfortable during measurements, a real device is placed on a person waist to simulate the CoM and perform several walks to record them. The first measurement prototype is shown in Fig. 5.

Fig. 6 shows the device axis orientation x, y and z when placed on a person waist in order to perform data logging.

The experimental device was placed on a person waist with axis oriented in the -g direction as shown in Fig. 7.

In order to obtain the experimental data over the PC, the client program for various network protocols PuTTY is used. The program is set to work with the Bluetooth module HC-06. The window for this setup is shown in Fig. 8.

In order to start communication between the measurement set and the computer, the open button is pressed and the sensor data is obtained in real-time and saved as a text file to

future processing.

The window where the information can be seen is shown in Fig. 9.

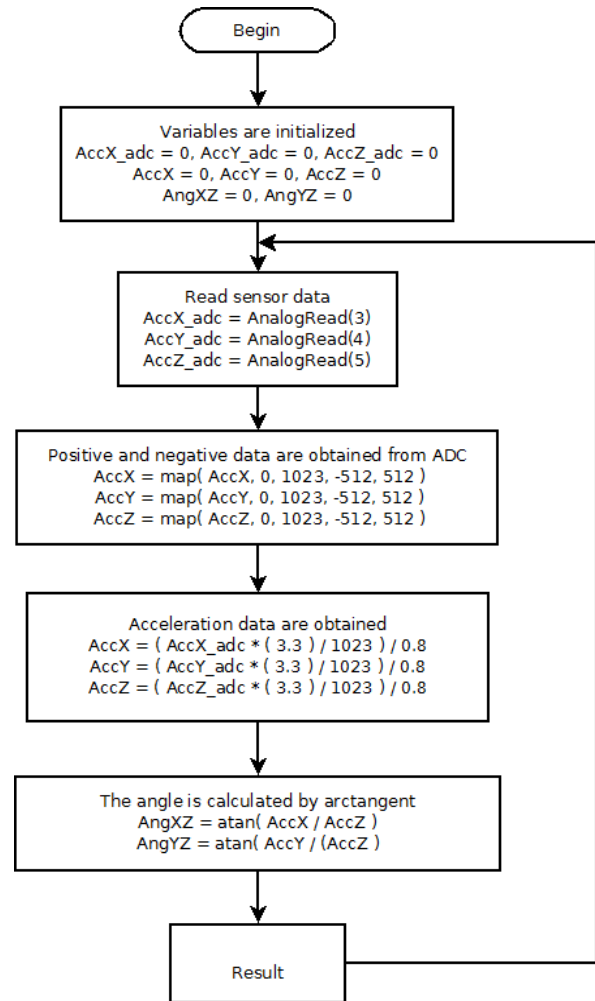


Fig. 4. Arduino program flowchart implementation.

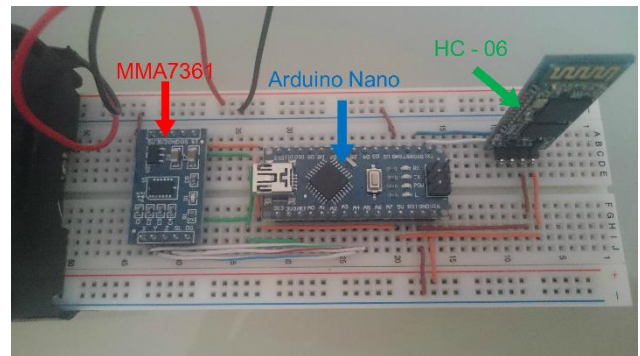


Fig. 5. Measurement prototype set.

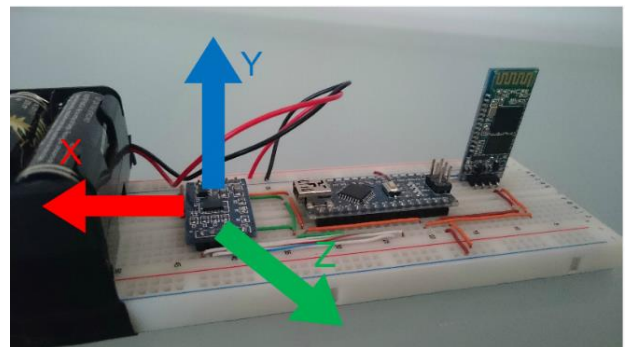


Fig. 6. Device axis orientation.

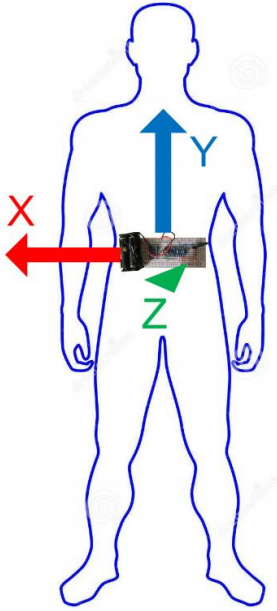


Fig. 7. Module on the person waist.

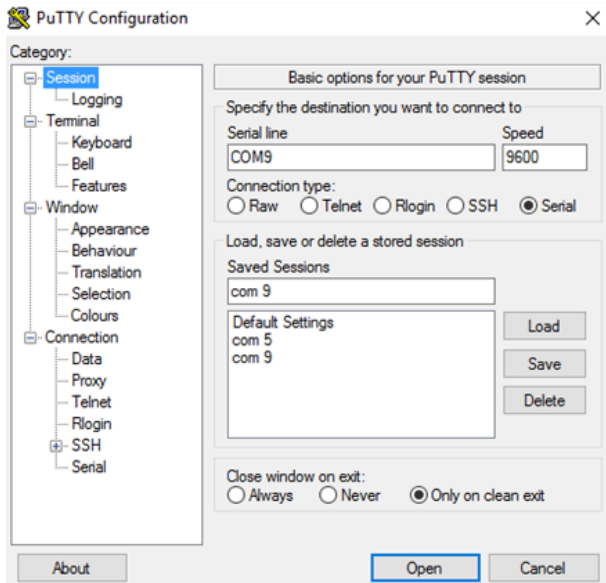


Fig. 8. PuTTY window setup.

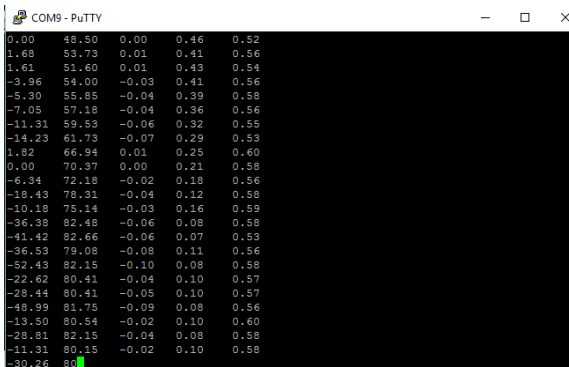


Fig. 9. Real-time data acquisition.

B. Lyapunov Exponents Estimation Algorithm

A chaotic system nature can be derived from the Lyapunov exponent value. This problem is stated in the beginning from real data logging of a supposed linear system behavior in order to establish its chaotic degree if present.

A MATLAB algorithm is developed in order to compute de

Lyapunov exponents; the procedure is the following:

- 1) The following constants are defined: embedding dimension m , samples number n , and time delay del .
- 2) Vectors $X \in \mathbb{R}^{n \times m}$ and $X_f \in \mathbb{R}^{n \times m}$ are defined from experimental data and have dimension $n \times m$:

$$X(i, b) = y(i + (b - 1) \times del) \quad (3)$$

$$X_f(i, b) = y(i + td + (b - 1) \times del) \quad (4)$$

where td is the neighbor distance (cycle period) and i varies from 1 to n and b from 1 to m .

- 3) Difference vectors $dX \in \mathbb{R}^{n \times m-1}$ and $dX_f \in \mathbb{R}^{n \times m-1}$ are defined as:

$$dX(:, bd) = X(:, bd + 1) - X(:, 1) \quad (5)$$

$$dX_f(:, bd) = X_f(:, bd + 1) - X_f(:, 1) \quad (6)$$

where bd varies from 1 to $m-1$.

- 4) $T_i = dX_f \cdot \text{pinv}(dX)$ is computed.
- 5) T_i is factorized through QR decomposition, where Q is an orthogonal matrix and R is a superior triangular matrix with non-negative diagonal elements.
- 6) The Lyapunov exponents are computed from:

$$Lyap = \log(\text{diag}(R)) \quad (7)$$

- 7) All the positive exponents are shown.

V. RESULTS

In this section the algorithm results from the human gait lateral displacement obtained from the measurement set are shown. The human gait cycle t_d was approximately of a hundred samples ($n=100$) and an embedding dimension of 3 ($m=3$) was chosen based on [5] for the torus case when time-series are not highly chaotic. The resulting Lyapunov exponent is reported on Table I.

TABLE I: THE ARRANGEMENT OF CHANNELS

Human Gait Data	Parameters		
	N	M	Lyapunov exp. λ_1
Experimental data, axis x	100	3	0.0927

VI. CONCLUSIONS

- 1) Based on the Lyapunov exponent λ_1 value obtained, it is clear that the human walk is chaotic in nature to a low degree,
- 2) Using a simple set-up and a few seconds recording, it is possible to obtain a high quality data-set,
- 3) Developing nonlinear analysis of human gait signals is the first required step for studying gait pathologies, and modeling and control gait support applications

afterwards. Analyze different patterns from a variety of persons is therefore important, since the gait patterns vary on different people. For instance, Fig. 10 shows a gait pattern from one person and Fig. 2 from another one.

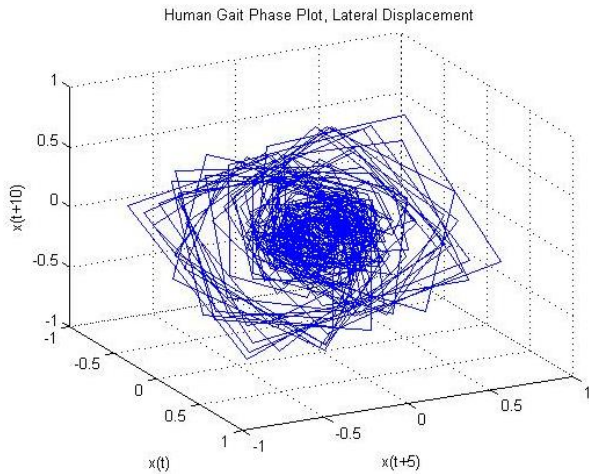
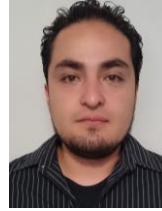


Fig. 10. Human gait phase plot from a different person.

- 4) A problem with the MMA7361 accelerometer is that it's very sensitive to vibration and mechanical noise, but the output signal could be improved using a digital filter.

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Dr. Vargas is member of the National System of Researchers (SNI) level I, she has 70 indexed articles, 50 papers in congress and has supervised 20 master thesis.



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