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Analysis and Comparison of Low Cost Gaming Controllers for Motion Analysis

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Abstract— **Gaming controllers are attractive devices for research due to their onboard sensing capabilities and low cost. However, a proper quantitative analysis regarding their suitability for motion capture has yet to be conducted. In this paper, a detailed analysis of the sensors of two of these controllers, the Nintendo Wiimote and the Sony Playstation 3 Sixaxis is presented. The acceleration data from the sensors were plotted and compared with computed acceleration data derived from a high resolution encoder, then correlated to determine the performance of the gaming controllers. The results show high correlation between the acceleration data of the sensors and the computed acceleration, and more consistency in the sensors of the Sixaxis. The applications of the findings are discussed with respect to potential research ventures.**

I. Introduction

Video game controllers such as Nintendo's Wii remote and Sony's Playstation controllers have revolutionized how we interact with games by enabling intuitive motion sensing and interpretation rather than relying on keyboard, mouse, or button clicks. As Gams and Mudry noted, recent developments in the field of Micro Electro Mechanical Systems (MEMS) have made it possible to develop high precision and high performance sensors for a nominal cost [1]. The availability of such sensors within these gaming controllers, and the wide range of tools available for open-source development with these devices, makes devices such as the Wiimote and Sixaxis potential platforms for low-cost motion capture.

In this paper, we analyze two of these low cost gaming devices, the Nintendo Wiimote and the Sony Playstation 3 (Sixaxis), pictured in Fig. 1, in terms of their accuracy and resolution. We discuss in detail the sensors on each controller, and compare recorded accelerations in a variety of controlled conditions to computed accelerations from a high resolution encoder. Finally, we discuss the comparative performance of the gaming controllers, and the viability of these devices as low-cost motion capture systems for research.

While we have explored the utility of two particular gaming devices in this paper, the broader use of commercial gaming devices for applications such as rehabilitation is not new (see [2], [3] for examples). Low-cost gaming interfaces are also applicable to a number of other domains, such as collaborative music creation and navigation. For example, in [4], Nakaie et al. used the Wiimote to create sounds in a collaborative way. They tracked and projected the acceleration and the 3D spatial data of a few moving Wiimotes on a "Sound Table" which had 16 speakers. This produced a mixture of sounds corresponding to the movement of the different controllers. Schlömer et al. used the Wiimote to recognize 3D hand gestures [5], where the Wii's accelerometer data recorded during hand motion were fed to a hidden Markov model for training and recognition. In [6], Castelluccci and MacKenzie used the Wiimote as a tool for text entry by mapping the hand gestures obtained from the Wii's accelerometer data to predefined characters. In a somewhat similar manner, Gallo et al. used the Wiimote to interact with a virtual environment [7]. With this approach, they were able to create a more natural environment for clinicians to interact with human anatomy. Finally, Bradshaw and Ng used the Wii Fit Balance Board and the Wiimote accelerometers plus camera to track a conductor's hand motion [8].

Common in all of these studies is an approach where patterns of motion are extracted from the measured data. This pattern or gesture recognition is easily achieved with low cost devices despite lower resolution or drift compared to more expensive systems since only patterns must be recognized, eliminating dependence on raw motion data. Other

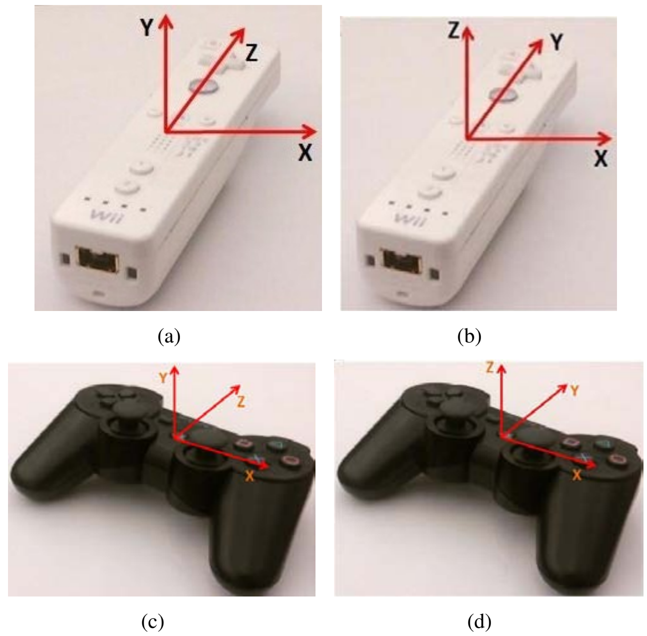

Fig. 1. (a),(c) show the coordinate system used by GlovePIE and (b), (d) show the local coordinate systems of the controllers

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groups have used the motion data of the gaming devices more directly, either for teleoperation of a robotic device for human-robot interaction research [9], or for assessing rehabilitation outcomes by tracking wrist motion or patient balance [10]–[12]. Absent from many of these studies is explicit information on the performance capabilities of these gaming devices as motion sensors.

Despite their broad appeal, the utility of low-cost input devices is potentially limited due to a lack of published data regarding their performance compared to more traditional sensors used in the research domain. While information on "hacking" the Wiimote is widely available [13], there have only been a few studies to directly report the performance of any specific controllers, and fewer still that compare devices.

In [14], Ardito et al., compared the mouse plus keyboard, the Wiimote, and the Xbox 360 on the basis of their performance and ease of use during three 3D tasks. Participants were asked to carry a "Utah teapot" from one table to another table in a certain orientation in two of the three tasks and move the teapot through hoops in the other task. All three tasks were designed to be performed in virtual environments. During these tasks all three input devices were compared in terms of the ease, accuracy and time taken for maneuvers, but no sensor data was reported showing how reliable the sensors on these devices are and whether they could be used as high precision tracking devices. In another study, Attygalle et al. used the infrared cameras of two Wiimotes to track hand motion during physical therapy, later comparing the tracking results with those obtained from a 10 camera motion capture system (Motion Analysis) [15]. Although it was evident from their results that the performance of the Wii was reliable for motion capture, one of the main drawbacks of this system was that the Wii's infrared camera had to be pointed at the patient's arm at all times as the sensors were not used for motion tracking. Natapov et al. compared the standard mouse with the Wiimote and Nintendo's Classic Controller in terms of tracking and pointing, though no quantitative performance results related to the Wiimote's onboard sensors were reported [16]. In another study, Gams et al. used two Wiimotes to map hand movements of a drummer to a robot playing a drum [1]. While the paper discussed the acceleration data acquired by the Wiimote devices, the authors did not compare these data with any other means of tracking motion data, therefore the accuracy of the sensors could not be judged. Finally, Xie et al. compared 24 dimensional data captured from 8 Wiimote controllers to data captured by an 8 camera motion capture system (Vicon) [17]. They carried out a Principal Component Analysis on the collected data and used a motion recognition algorithm, confirming that the Wiimote data compared well to the Vicon data. No details regarding the accuracy, resolution, sensitivity or reliability of the Wiimote sensors were reported.

This paper is organized as follows: Experimental Methods are discussed in Section II, followed by Results and Discussion in Section III and Conclusions in Section IV.

II. Experimental Setup And Methodology

Prior to using the gaming controllers in research, it is necessary to determine the accuracy, resolution, and suitability of gaming devices for motion capture. In this work, we compare accelerations recorded from two different low cost gaming controllers, the Wiimote and the Sixaxis, to computed acceleration data from a high-resolution linear optical encoder. The recently released Motion Plus module for the Wiimote contains gyroscopes useful for tracking rotational motion; however, an investigation of the performance of the Wiimote Motion Plus module as compared to the Sixaxis rotational measurements will be the subject of future planned experiments, and is not discussed in this paper.

A. Nintendo Wiimote controller

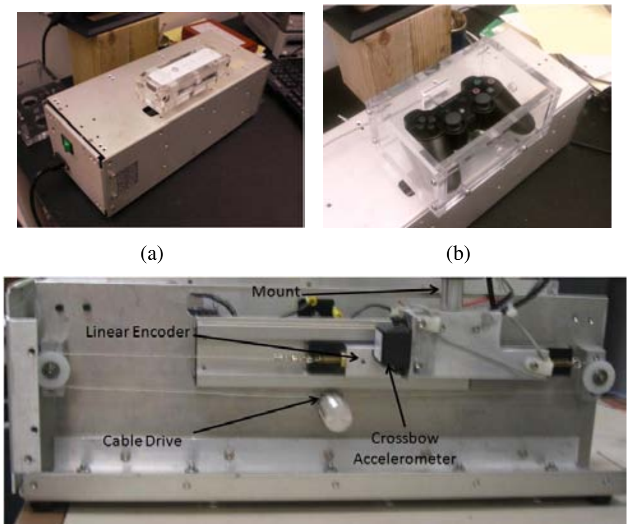
The Wiimote has two sensing elements: a 3-axis linear accelerometer and an infrared digital camera. The controller communicates with the console over a wireless Bluetooth interface (BCM2042 chip from Broadcom) [1]. The camera has a resolution of (1024 X 768) [8] with more than 4 bits of dot size and a 45° horizontal field of view [13] . The accelerometer (Analog Devices ADXL 330) has a range of +/- 3g and a bandwidth from 0.5 Hz to 1600 Hz on the X and the Y axes and a bandwidth from 0.5 Hz to 550 Hz on the Z axis [18]. The device has a sensitivity of 10% and 10 bits of precision on the X axis as opposed to 9 on the Y and the Z. However, the different axes are all assumed to have a 10-bit range and the Least Significant Bit (LSB) is always set to zero for Y and Z [19].

B. Sony Sixaxis controller

The Sixaxis controller is able to sense accelerations along its 3 axes with its accelerometers. In addition to the accelerometers, the Sixaxis has a gyroscope for measuring the yaw. The Sixaxis communicates with its console through a Bluetooth link or USB cable. Due to the lack of availability of technical details in the literature, no further specifications of the Sixaxis are included in this section.

C. Mechatronic Test Bed

To test the sensors on each gaming controller, each device was separately mounted on a moving one degree of freedom mechatronic test bed as shown in Fig. 2. The test bed is activated by a DC motor (Faulhaber, 3557K024C) that serves as an actuator of the device. The output voltage of the digital-to-analog converter (DAC) is passed through a voltage-to-current amplifier (Advanced Motion Controls, model 12A8M) to drive the motor. The amplifier gain is selected such that 1 Volt at the DAC corresponds to 8 mNm of torque applied by the motor. The motor is mounted on a cable drive with a radius of 10 mm. The mount is driven by a cable-and-pulley drive system and translates on a ball-slider (Del-Tron Precision Inc., model S2-6) with low friction. High stiffness fishing wire (American Fishing Wire, grade 26 lbs nylon coated 7 X 7 stainless steel, 16 N/mm stiffness) is used to connect the moving mount assembly with the cable drive, as shown in Fig. 2c. The motor has



(a) (b)

(c)

Fig. 2. One degree of freedom mechatronic test bed with (a) the Wii and (b) the Sixaxis controllers mounted for acceleration measurement comparisons. (c) Components of the one degree of freedom mechatronic testbed

small friction torque, and the pulleys are mounted on high performance bearings to reduce the effects of friction. The bandwidth of the device is determined to be about 30 Hz. A high precision optical linear position encoder (Renishaw RGH24X) and an accelerometer (Crossbow Technology Inc., model CXL02LF1Z) are mounted on the mount assembly to measure the assembly's instantaneous states of position and acceleration, which are then compared with those of the controller's.

D. Experiment Design

The test bed was commanded to produce and track sinusoidal input signals of 1 Hz and 4 Hz at amplitudes of 0.7 cm and 4.9 cm. These values were chosen to be within the actual range of frequencies of human motions. The controllers were oscillated using the test bed. Concurrently, acceleration data were recorded from the controllers while position, velocity, and acceleration data were recorded from the test bed. Data collection was performed using GlovePIE, MATLAB and QuaRC on a Windows based PC.

GlovePIE (Glove Programmable Input Emulator) was originally developed as a system for emulating joystick and keyboard input using the essential reality P5 Glove. It now supports emulating different kinds of inputs, from a number of devices. During the data collection, the acceleration data read from the sensors of the gaming controllers were sent through GlovePIE [20] to a virtual joystick PPJoy [21]. Data from the virtual joystick were read through a QuaRC block in Simulink and sent to the MATLAB workspace. QuaRC, developed by Quanser, is a real time software environment that can be used with Simulink for rapid controls prototyping and hardware-in-the-loop testing [22].

To obtain quantitative results regarding the performance of the two gaming devices, the controllers were mounted on the test bed in three different orientations. By changing the orientation of the controller, data were gathered from each axis independently. The measurements were then compared and correlated with those obtained from the test bed's sensors. The computed acceleration was determined by double differentiating the position encoder values from the test bed.

E. Data Acquisition

During the experiment, the acceleration data from the Wiimote and the Sixaxis were collected using GlovePIE and sent to a text file, which was later imported to MATLAB for analysis. Concurrently, acceleration, position and velocity data were collected from the test bed sensors using QuaRC and MATLAB. The test bed sensor data were acquired at a rate of 1000 Hz, while the Wiimote was sampled at approximately 100 Hz and the Sixaxis controller was sampled at approximately 75 Hz. Because multiple processes were running on the computer during data acquisition, the sampling rate of the Wiimote and the Sixaxis controllers were lower than the sampling rate specified in GlovePIE (200 Hz).

Initially, we attempted to collect data from the controllers using GlovePIE, and then pass the data to a virtual joystick created with PPJoy [21]. The data from virtual joystick were then sampled at 1000 Hz using the QuaRC Host Game Controller block for the Sixaxis and the QuaRC Host Wiimote block for the Wiimote. However, the preliminary results showed that both the QuaRC Host Wiimote and the QuaRC Host Game Controller blocks were unable to sample the data at 1000 Hz. Due to this discrepancy, and the sampling issue with the QuaRC Host, this method was aborted and the lower sampling rate data acquisition architecture described above was used.

F. Post Processing

In post processing, the sampled data from both the encoder and accelerometer of the test bed, and the accelerometers of the controllers, were filtered with a 6^{th} order Butterworth filter with a cutoff frequency of 2 Hz for the experiments run at 1 Hz and a cutoff frequency of 8 Hz for the experiments run at 4 Hz. A Butterworth filter was chosen because of its maximally flat pass band. The filter order was chosen as 6 to ensure that the filter gain was 1 for the entire pass band and for a sharper transition band. The data was filtered both in the forward and the backward directions to compensate for phase lag. The double differentiated encoder data was filtered after each differentiation step to compensate for the noise introduced due to the digital differentiation. Once all the data were collected, the double differentiated encoder data, which is hence forth referred to as computed acceleration, was resampled at the sampling frequency used by GlovePIE to acquire data and then cross correlated with the acceleration data from the controllers. The correlation coefficient was computed at the point where the maximum value of the cross correlation sequence occurred.

III. Results and Discussion

In Figs. 3-6, data sets represented by thick grey dotted lines indicate computed accelerations, thin light grey continuous lines indicate raw unfiltered acceleration data from the controllers, and thick black continuous lines indicate filtered acceleration data from the controllers. As the resolution of the Sixaxis controller is the same in all three axes, plots for only the X axis are shown.

Preliminary experiments were conducted prior to mounting the controllers on the test bed. In these tests, data from the sensors were collected manually and the resolution was determined. Results showed that the accelerometers of the Sixaxis controller are slightly higher resolution than those of the Wiimote. The Sixaxis controller's accelerometers can measure up to 0.905% of gravity as compared to 1.05%, 1.98% and 2.13% of gravity by the Wiimote's X, Y and Z accelerometers. The differing resolutions across the axes may be due to different levels of precision on the internal variables used to report the sensor data. It could also be due to the analog filter bandwidth at X_{OUT}, Y_{OUT} and Z_{OUT} [18], which are the acceleration values along the X, Y and Z axes from the accelerometer chip. The working details of the Wiimote's accelerometer chip along with the functional block diagram can be found in [18], [23].

Table I shows that the acceleration data from the controllers have a high correlation with the computed acceleration at the test frequencies and amplitudes. As the resolution of the Sixaxis controller is the same in all three axes, correlation coefficients for only the X axis are shown. The high correlation coefficients suggest that the sensors in both gaming controllers are well suited to operate in that range as motion tracking devices. This can be further verified from Fig. 3-6, where the data sets in thick black are seen to track the data sets in thick dotted grey with high accuracy. The phase lag may be due to delay in transmission of the data from the sensors of the controllers to the console. Differences in the correlation coefficients for the Z axis compared to the X and Y axes could be attributed to the differences in their dynamic range as discussed in Section II A.

When compared with each other, the sensors of the Sixaxis are more consistent those of the Wiimote. At frequencies around 1 Hz, the accelerometers of the Wiimote are less accurate at detecting small accelerations, thus resulting in the smaller correlation coefficients. Increasing the amplitude increases the correlation coefficients. When compared to the Wiimote, the Sixaxis controller displays a smaller variation in sensitivity across the tested range. The reason for the better results of the Wiimote at low frequencies and higher amplitudes may be because of the stiffness of the spring mass system of the accelerometers. The accelerometers in the Sixaxis controller do not have such issues, which can possibly be because they are more sensitive, have better resolution and have lesser spring stiffness effects than the accelerometers in the Wiimote. Therefore, for very slow motions which include abrupt changes in direction, the Sixaxis controller would be a better choice. For motions with higher frequencies and amplitudes, both controllers perform well. In addition, at higher frequencies and amplitudes both devices exhibit low noise in the sensor data. When used for slow and low amplitude applications, adequate noise filtering is required.

TABLE I

Correlation between the acceleration from the controllers and the Computed Acceleration at different frequencies and amplitudes. As the resolution of the Sixaxis controller is the same in all three axes, correlations for only the X axis are shown

Frequency	**Amplitude**	**Correlation Coefficients of Controllers**			
		Wii			Sixaxis
Hz	cm	X	Y	Z	X
1	0.7	0.86	0.81	0.97	0.94
4	0.7	0.97	0.96	0.97	0.98
1	4.9	0.98	0.98	0.99	0.97
4	4.9	0.98	0.98	0.99	0.91

For Figs. 3-6 it is also noted that filtered data often overshoots the raw unfiltered acceleration data from the controllers. This is because of noise components in the raw unfiltered controller data. From the Fourier series, it can be shown that the first harmonic of the unfiltered data is equivalent to that of the filtered data.

IV. Conclusions

The use of low cost gaming controllers is attracting attention in research domains where human-scale motions are of interest. This paper has presented a detailed comparison of dynamic sensor data of the Wiimote and Sixaxis controllers and computed acceleration data from a high-resolution digital encoder. The Wiimote is best suited for applications with fewer jerks and fast prolonged motions. In contrast, the Sixaxis is best suited for both slow and abrupt motions. The overall performance of these gaming controllers was comparable to the computed acceleration data, therefore these low-cost controllers should provide reliable data for gross human motion capture at a fraction of the cost of camera based systems.

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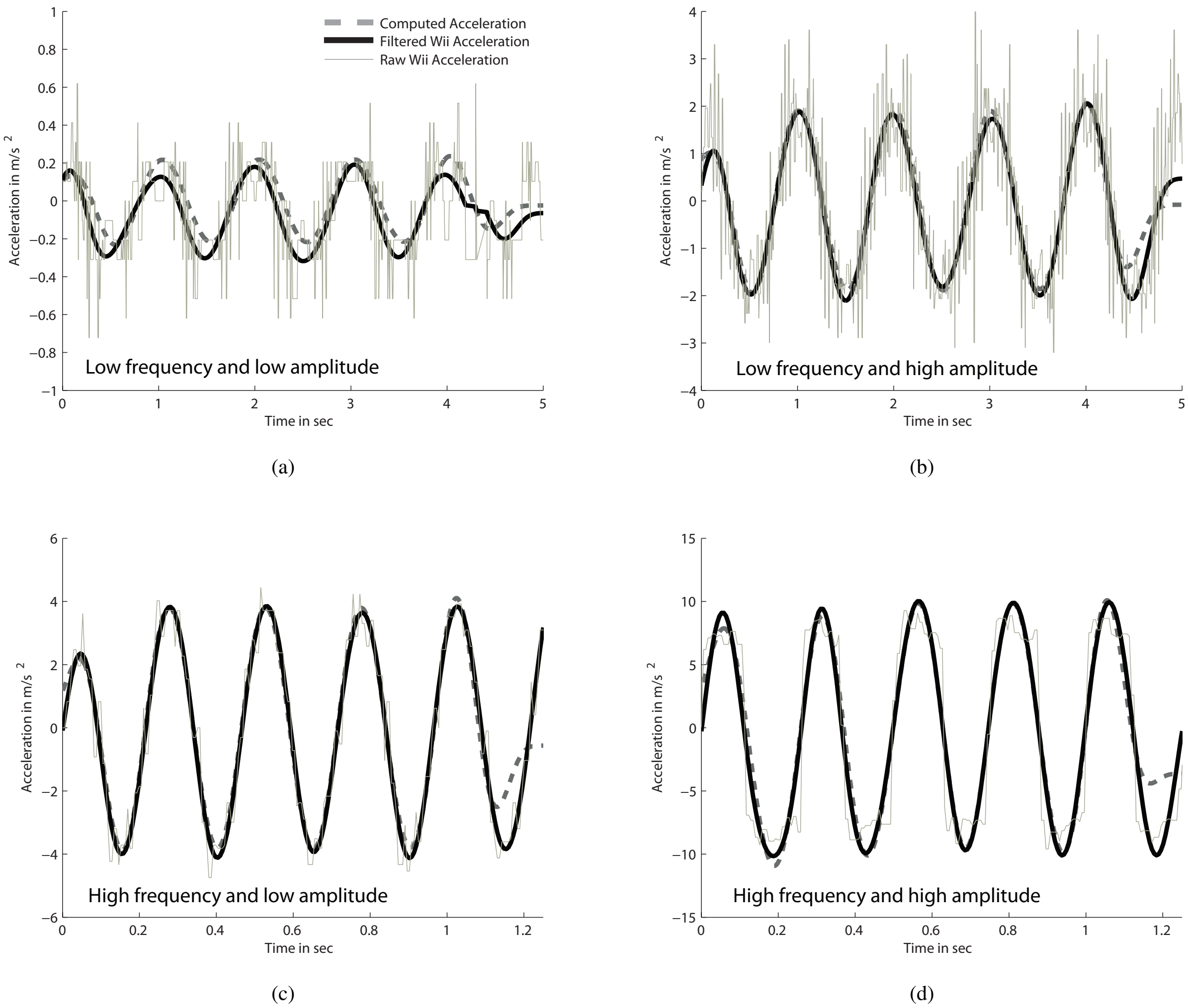

Fig. 3. Performance of the Wii's X-axis accelerometer at different frequencies and amplitudes, (a) 0.7 cm amplitude at 1 Hz, (b) 4.9 cm amplitude at 1 Hz, (c) 0.7 cm amplitude at 4 Hz, (d) 4.9 cm amplitude at 4 Hz

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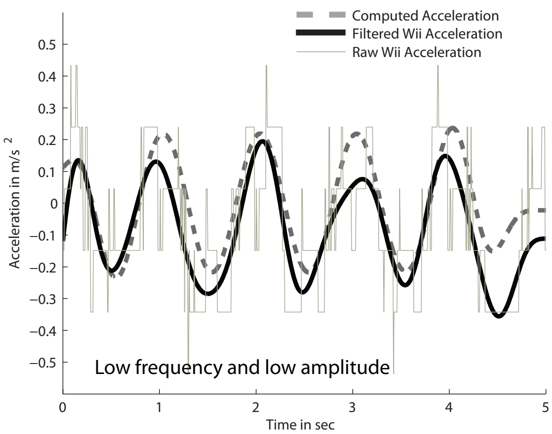
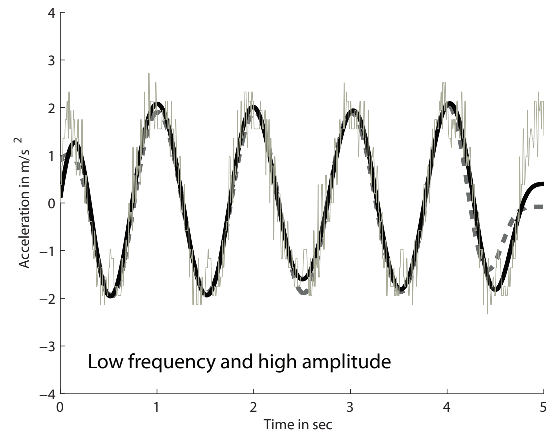


(a)



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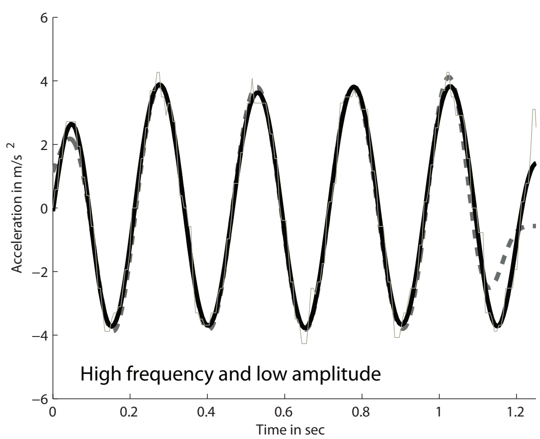

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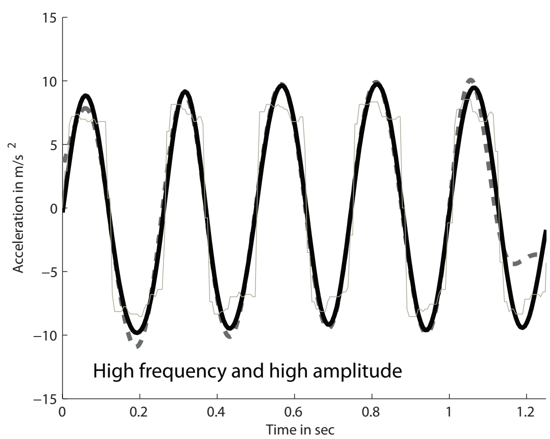


(d)

Fig. 4. Performance of the Wii's Y-axis accelerometer at different frequencies and amplitudes, (a) 0.7 cm amplitude at 1 Hz, (b) 4.9 cm amplitude at 1 Hz, (c) 0.7 cm amplitude at 4 Hz, (d) 4.9 cm amplitude at 4 Hz

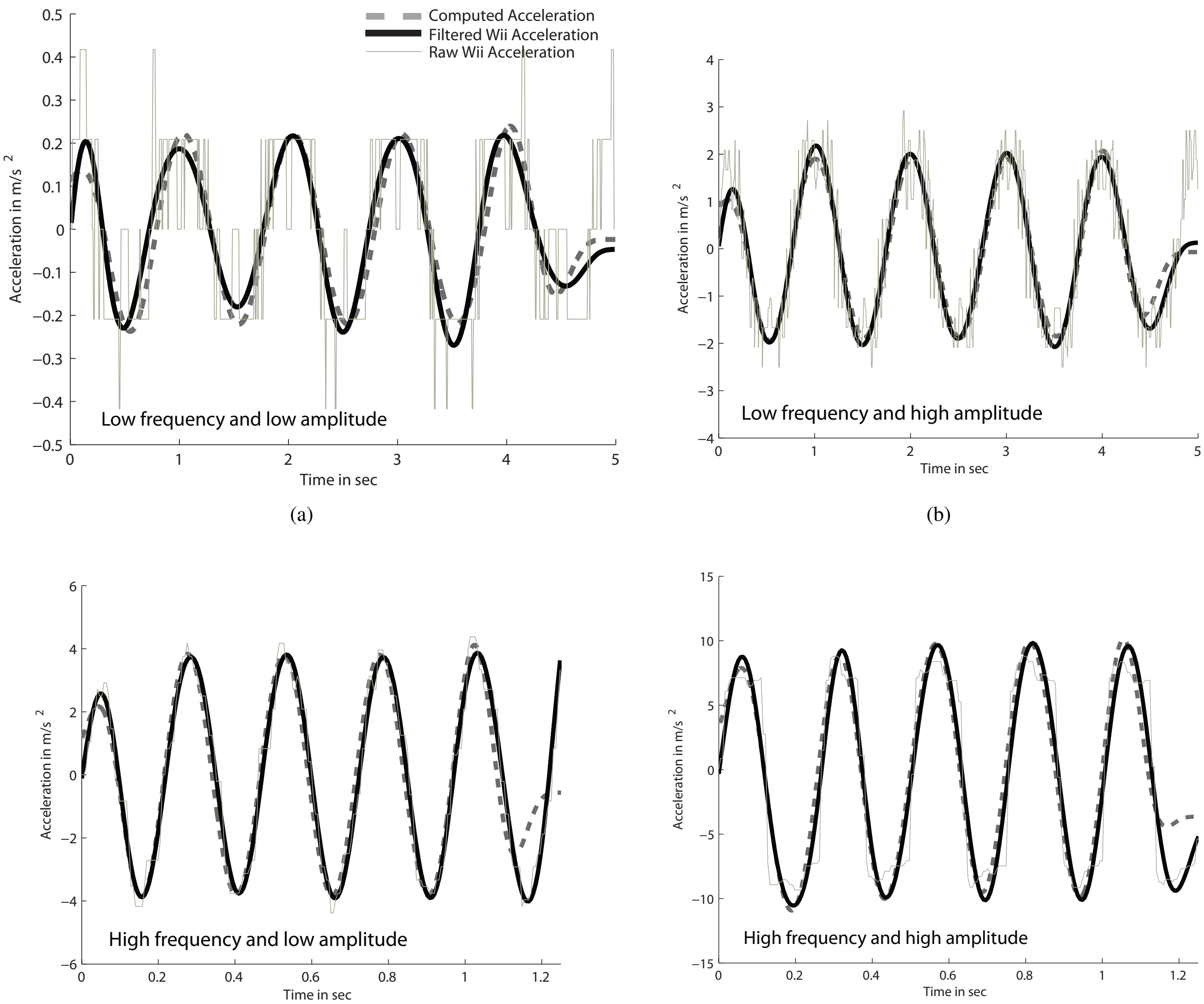
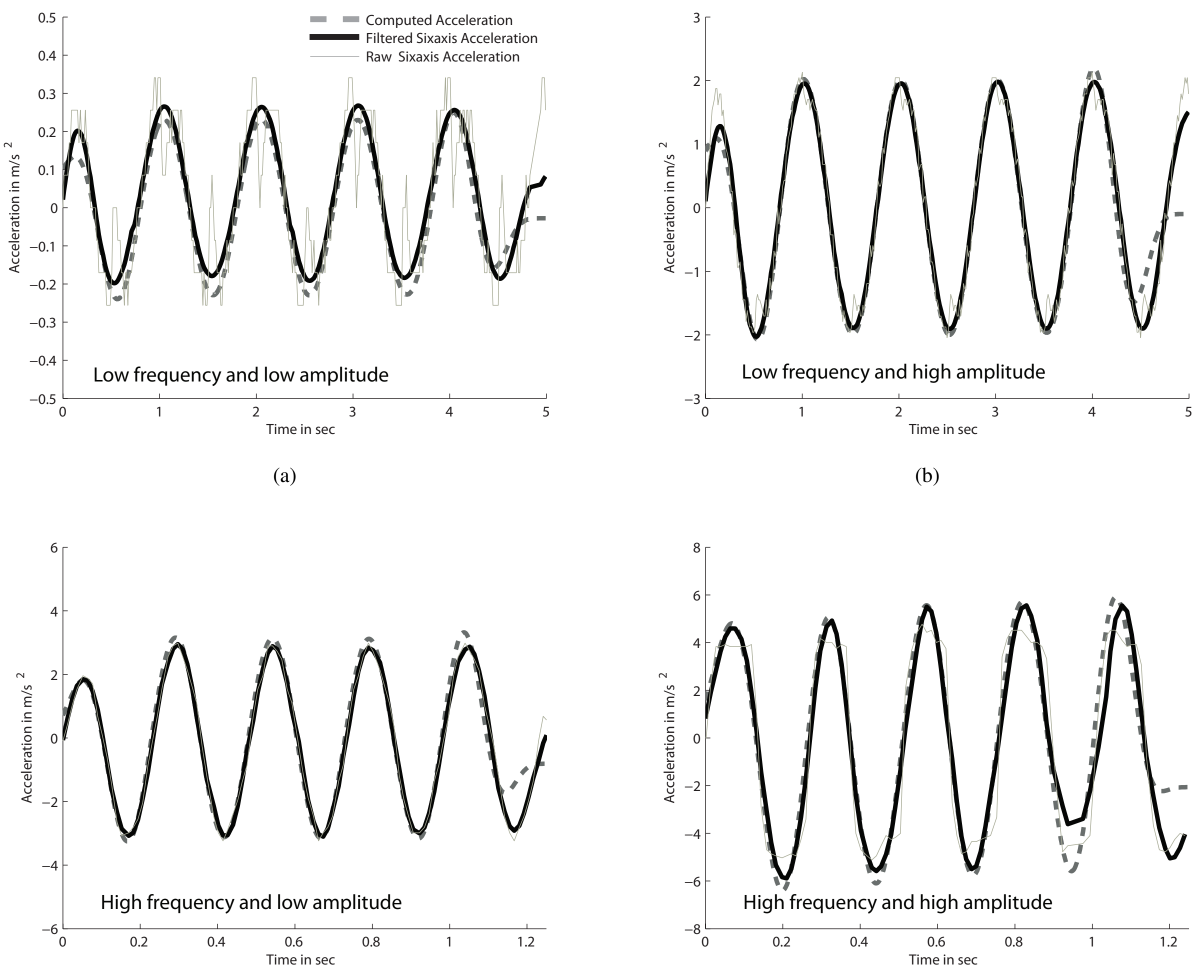


Fig. 5. Performance of the Wii's Z-axis accelerometer at different frequencies and amplitudes, (a) 0.7 cm amplitude at 1 Hz, (b) 4.9 cm amplitude at 1 Hz, (c) 0.7 cm amplitude at 4 Hz, (d) 4.9 cm amplitude at 4 Hz



(a) (b)

(c) (d)

Fig. 6. Performance of the Sixaixs controller's X-axis accelerometer at different frequencies and amplitudes, (a) 0.7 cm amplitude at 1 Hz, (b) 4.9 cm amplitude at 1 Hz, (c) 0.7 cm amplitude at 4 Hz, (d) 4.9 cm amplitude at 4 Hz