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# Physical and digital architecture for collection and analysis of imparted accelerations on Zip Line attractions

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## Abstract

The accelerations experienced by riders of Zip Line attractions is an underexplored area of public safety assurance. These amusement devices require complex processes to collect and analyze acceleration data. Highly versatile and effective rider-worn and ride-carried devices are necessary to collect acceleration and velocity data without affecting the integrity of the ride. This paper introduces the use of a sensor device for collecting Zip Line acceleration data in the form of a *Trailing Trolley*. This architecture extends the work of Sicat et. al.'s which proposed the use of a *Sensor Vest* and *Headwear* to collect linear and rotational accelerations of a Zip Line rider. We investigate the logistics of combining the two sensor platforms and formulate a procedure to post-process and analyze the data. Techniques to extract, filter, and process the accelerations recorded is discussed and the potential for the synthesis of positioning linear and rotational data is described. Additional testing of data collection and analysis is necessary to prove the viability of these techniques and apparatuses as potential parts of a standardized test method for measuring rider experienced g-forces on Zip Lines.

**Keywords:** Zip Line; acceleration; g-force; wearable; data collection and processing

## 1. Introduction

Zip Line technology is rapidly spreading throughout major tourist destinations. As Zip Lines become ubiquitous it is critical that a high degree of public safety assurance be maintained through vigilance against unintended acceleration due to collision events. However, the ability to accurately collect and process acceleration data is hampered by the wide array and complexity of Zip Line systems. Therefore, we describe a procedure, proposed architecture, and filtering process for the collection of acceleration data on Zip Line systems.

Current international standards present an imprecise description of Zip Line acceleration limits. ASTM standards do not describe limits on accelerations, nor do they describe the process for collecting or analyzing acceleration data. However, ASTM's Aerial Adventure Attractions Standard (F2959) provides a basis for this study. Standards from the Association for Challenge Course Technology also do not address the collection or analysis of acceleration data. Consequently, the lack of defined design and safety processes could lead to patron injuries if accelerations become

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too great. Therefore, we aim to provide a proactive and strategic procedure and sensor architecture to assist in defining limits of rider-experienced accelerations. Determining limits on acceleration can also help guide the design of future Zip Line attractions, leading to safer entertainment facilities around the world. This paper presents an iterative procedure for the collection of acceleration data on a Zip Line attraction. It also provides suggestions for post-processing techniques and provides evidence that suggests where sensor technology can be further implemented to improve Zip Line attraction experiences.

## 2. System Requirements

### *2.1 Trailing Trolley specification*

Accelerations due to collisions between the main trolley system and braking blocks can exceed 80g's. Therefore, collecting velocity data directly from the main trolley system is difficult. The intent of introducing the *Trailing Trolley* is to provide an alternative surface to record velocity data without impeding or adding weight to the main trolley. Although it does not directly measure data from the rider-harness system, it is mechanically linked to the main trolley and will mimic the velocity of the Zip Line-rider system.

The *Trailing Trolley* is designed with an additional mass beneath its center of gravity in order to stay upright throughout the duration of the line. While this extra mass does affect the shape of the line's catenary during the ride, it does not result in drastic changes that would significantly alter ride experiences. The *Trailing Trolley* uses a deformable coupler, adapted from the suspension system of a mountain bike, to avoid collision with the main trolley. Translating the energy through the suspension prevents the extra mass of the *Trailing Trolley* from affecting the collision between the main trolley and the brake system while it continues in its intended line of motion. Data collected from the *Trailing Trolley* is then used as surrogate data to analyze the motion of the main trolley prior to the collision event.

### *2.2 Sensor Wearable specification*

The *Sensor Wearable* has two components, a *Sensor Vest* and *Headwear*. The *Sensor Vest* houses the shoulder, heart and center of mass (COM) sensors while the *Sensor Headwear* houses the head and neck sensors. The garment's main design priority is to adequately address sensor displacement while ensuring flexibility for body shape and size of a test participant. For both components, we created custom-made pockets out of polyester material lined with fusible interfacing to tightly house the sensors. Each pocket-front utilized a mesh fabric to allow the test participants and administrators to visually check if the accelerometers were turned on and in the correct position before and after launch. A number of 1-inch hook and look H&L tape straps were kept on the *Sensor Vest* in case the accelerometers needed extra reinforcement.

The *Sensor Vest* is made up of a tactical vest waistcoat, commonly used in military field training. The material is made of a sturdy 600D oxford fabric and insulated with foam boards, maximizing wear-resistance to endure long and hard use. The surface of the *Sensor Vest* is covered with H&L tape allowing it to accommodate a wide range of body shapes and sizes. Additionally, the shoulder and waist include modular plastic buckles, and a durable H&L tape strap system. The *Sensor Headwear* utilizes a leather suede lined cap--commonly used in aviation apparel. The structure is sturdy and shaped snugly for the head. Given that Zip Line riders must wear safety helmets, we chose a base that is thin, comfortable and snug to wear underneath a protective helmet. An H&L tape strap is mounted along the back of the head where the head and neck sensors were attached.

### *2.3 Accelerometer specification*

The *Sensor Vest* utilized four HAM-IMU and HAM-IMU-alt, while the *Trailing Trolley* utilized a ±16g HAM, and a ±200g impact accelerometers supplied by Gulf Coast Data Concepts. Each accelerometer had available options to record several sensor variants (specifically acceleration, gyroscopes, and quaternions). While the *Sensor Wearable* is required to consider linear and rotational movement of the Zip Line rider, the accelerometer model used includes quaternion capability. On the other hand, a standard ±16g accelerometer is utilized on the Trailing Trolley as it does not have to consider rotational values. To complement the ±16g HAM, a ±200g impact accelerometer increased frequency and expanded range of the impact. The more extreme and instantaneous accelerations directly experienced by the Trailing Trolley during brake collision.

The form factor is 2.21L x 1.55W x 0.60H inch weighing at 0.9oz, keeping it compact and light-weight. Data from the digital sensors are time stamped using a real-time clock with data recorded on a microSD memory card in simple text format. When connected via a USB cable to a personal computer, the HAM appears as a standard mass storage device containing the comma delimited data files and the user setup file. In our experiments, the accelerometer was set to the 16g range, gyroscope was set to the default 2000 °/sec, and sampling rate of 200 Hz.

## 3. Validation Protocol

### *3.1 Procedure for data capture*

The test subject was selected from the research group and donned the *Sensor Wearables*. The sensors were adjusted within the garments to establish a common set of axes. Once the telemetry gathering components were on the rider, they were fitted with the corresponding Zip Line equipment including safety harness, main trolley attachment, and helmet. In addition to the garment sensors, two additional sensors were added to the *Trailing Trolley*. The equipped rider was placed into the Zip Line ride following regular procedures. The rider was instructed to maintain a normal rider pose during all phases of the ride including launch, sliding and braking. A timer was designated who would measure the time between launch and final braking.

### *3.2 Procedure for data filtering and post-processing*

Post collection, data was filtered using multiple methods available in common MatLab libraries. The data was sent through two Butterworth filters in separate instances.

First, in compliance with ASTM F2137, the data was fed through a single pass, four-pole Butterworth filter with a cutoff frequency of 5 Hz. The filter frequency response for this filter as used with the 200 Hz collection rate can be seen in **Figure 3.1**. The fourth order Butterworth falls steeply upon reaching the cutoff frequency and minimizes signal response beyond the cutoff frequency. **Figure 3.2** provides an example of the response of collected Zip Line data after being fed through a single pass four-pole Butterworth filter. While the entirety of the data still appeared chaotic, conducting a frequency analysis and selection process allows noise in the data to be reduced. **Figure 3.3** shows the normalized frequency prior to filtering while **Figure 3.4** shows post filtering frequencies. Compared to the responses of other filter types, the single pass Butterworth filter created a simplified view of the data. However, erratic features within the filtered data persist.

A second Butterworth filter was used with nearly identical results. This filter was identical to the F2137 filter but used two passes (forward and backward) to eliminate phasing in the results. While the filter had point differences in maximums and minimums, post-cut time alignment, and slope trends, the general frequency response was incredibly similar to the single pass Butterworth filter. It is important to note that dual pass Butterworth filters are generally not used by national standards due to their unpredictability in their interactions with each unique data set.

### *3.3 Data response*

By cross referencing quaternion data with the corresponding instantaneous acceleration at time of impact, the propagation of impact can be traced down the body. **Figure 3.4** presents the impact with a friction break (a popular Zip Line brake where a high friction block is placed on the line and used to slow down riders). **Figure 3.4** demonstrates the complexity of the relationship between *Trailing Trolley*-experienced accelerations and rider-experienced accelerations. Most importantly, the collected data demonstrates that rider's weight, height, and orientation all affect the propagation of g-forces through the rider-harness system. This multitude of confounding variables prevents the establishments of defined limits on *Trailing Trolley* accelerations.

*Trailing Trolley* accelerations reach an astounding maximum – often exceeding ±16g on the HAM accelerometers. During a collision with a friction brake, the impact accelerometer measured a maximum acceleration of approximately 80 g's. If this acceleration were to be analyzed via existing ASTM F2291 limits, it would fail. Almost all the brake collision when analyzed directly from the *Trailing Trolley* fail existing g-force limits, particularly when one considers that the rider could be in any number of positions.

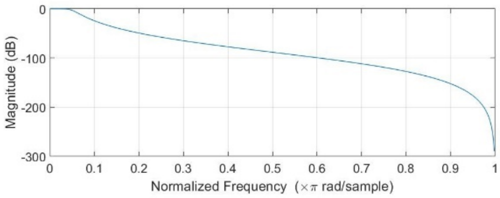

*Figure 1 Frequency Response of 4 Pole Butterworth Filter*

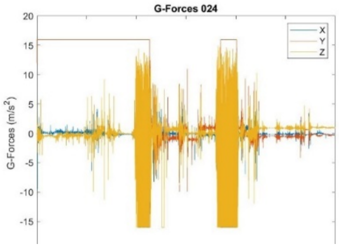

*Figure 2 Example of Filtered Acceleration Data*

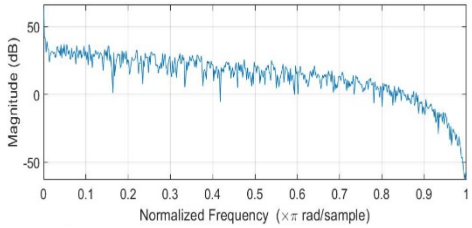

*Figure 3 Frequency of Unfiltered Data*

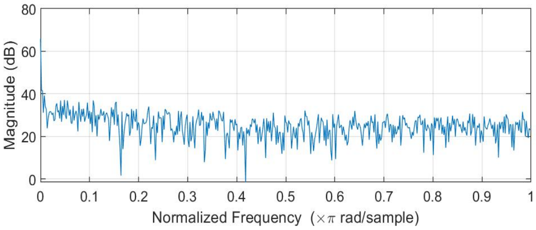

*Figure 4 Frequency of Filtered Data*

We found that the time-based analyses of group data were difficult, particularly in the impact moments. Thus, the versatility of the HAM becomes paramount. The Gulf Coast HAM collects quaternion positioning data. Utilizing this metric allows for the translation of the time-based impact accelerations into position-based impacts. By transitioning into the position-based data, the movement of the rider becomes the object of differentiation, creating the ability to analyze how internal rider reactions counteract the force of the impact. This analysis is in progress, with preliminary results showing the translation of the impact through the rider clearly.

## 4. Discussion

Summarized, we contribute a validation protocol and post-processing procedure that will evaluate the reliability and validity of a *Trailing Trolley* and *Sensor Wearable* combined system used to measure acceleration of a Zip Line rider. While this study provides a model for exploration, there exists several assumptions and areas for improvement which require future investigation and evaluation.

Due to the complexities involved in the interaction between the rider and the impact forces, a live human test subject is necessary in these early stages. As such, a garment designed to allow a rider to interact freely with the system was created to contain accelerometers. Further, data post-processing techniques were used to into consideration the unique complexities of the system by utilizing filters specifically for input frequencies in order to achieve maximum resolution. Through this work it was realized that with the collection of quaternions, analysis of the data may be moved outside of time-space and into position-based analyses to allow for a more precise analysis of split-second collisions.

Additional data collection is crucial to test the viability of the collection and processing methods. The current sample size of Zip Lines used is small, whereas the spread of Zip Lines is quickly growing. The more data that is collected from a diverse set of rides and geographic areas, the better we will understand how the data gathering garment can be more effectively used and will aid in determining what data is reliable. By continuing data collection and investigating the effect of positioning data, the rider experienced g-forces in Zip Line braking may be further quantified.

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