Virtual Reality Bicycle with Data-Driven Vibrotactile Responses from Road Surface Textures

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***Abstract*—In this paper, we proposed a data-driven vibrotactile rendering system for indoor exercise bicycles. The input of the data-driven model is described by a two-dimensional vector of cycling velocity and tire pressure. We designed a data-collection bike that captures vibrations induced at the handlebar and the cycling velocity for different tire pressures. The data were collected from four real cycling pavements. The level of the tire pressure was varied according to subjects' weight. Data-driven input-output based haptic modeling was adapted for generating road surface texture models. A rendering system was also developed and integrated into the stationary bicycle, and four virtual textures were evaluated by experienced cyclists. The results show that the participants were able to successfully discriminate and identify simulated virtual road surfaces.**

***Index Terms*—VR bicycle, vibrotactile responses, data-driven approach**

I. Introduction

Recently, indoor cycling systems have been widely disseminated in urban life due to the limited access to outdoor cycling facilities and inappropriate weather conditions. These training systems are considered to be good alternatives to the real bicycles from the fitness point of view. However, a pleasant effect of cycling in the real environment was missing, which makes the indoor training session tedious. To improve the effectiveness of the stationary bicycles, the researchers integrated the virtual reality (VR) technologies to the indoor training systems. Due to immersion and presence in the virtual environment, people find VR bicycles as more engaging which increases a user performance [1] and motivation to exercise.

The research on the VR bicycle started from a provision of visual feedback. Such simulators resemble computer games where the graphics scene is altered in accordance to the pedaling frequency. Hence, these VR systems evolved into exergaming, where the user participated in gaming quests [10] [9]. However, VR bicycle systems were still lacking an immersive experience due to the absence of proper haptic feedback. The haptic models which were integrated into VR bicycle simulators can be classified into two categories. The first group is related to macro features of the cycling environment such as pedal [2] and steering resistance [3], headwind [1], and turns [4]. The second class is devoted to modeling the micro-features of the road surfaces that provide vibration responses at contact points between a cyclist and bicycle, i.e., a handlebar [2] , pedals, and seat.

To produce realistic haptic feedback of the real road surfaces, we adapted and integrated a data-driven concept of vibrotactile haptic texture modeling and rendering into a VR bicycle simulator. Data-driven approach is an approximation technique that establishes the input-output mapping based on raw measurements collected during a real interaction. The model input dimension denotes the degree of freedom of the model where each input variable describes a particular characteristic of the interaction. For instance, a two-dimensional input space of the isotropic texture model produces feedback vibration based on the applied normal force and velocity magnitude [5]. The velocity magnitude can be decomposed into two lateral components to form a three-dimensional input vector for anisotropic haptic texture modeling [6].

In our case, we adopted a data-driven modeling [6] and rendering [7] algorithms with two-dimensional input space describing cycling velocity and tire pressure. The output is z-axis acceleration signals that represents vibration responses. The relationship between the model input and corresponding vibration responses is implemented by the RBFN-based computational formulation that was developed in [6].

For capturing data, we have developed data collection bicycle with sensors that record bicycle speed and vibration responses on the handlebar. Three experienced cyclists with different weights were involved in data acquisition process where bicycle tire pressure were inflated accordingly. The vibrotactile haptic rendering system of road surfaces was developed based on created models and integrated into stationary bicycle. In the rendering system, we have used vibrotactile motors to stimulate vibrations, i.e., according to interpolation model output. Furthermore, we have designed pedal resistance unit relying on eddy current phenomenon that avoids generating unacceptable vibrations while pedaling augmented stationary bicycle simulator. To evaluate our system we conducted a psychophysical experiment. The results and discussion of the experiment are provided, which showed promising performance for both road surface discrimination and identification.

We consider the work presented in [2] to be the most related to our research where the researchers rendered a simple background vibrations to the handlebar. However, their

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Fig. 1. Data Collection Bicycle: 1) ADXL 345 digital accelerometer; 2) Hall sensor; 3) Magnets; 4) Raspberry Pi.

work does not provide a realistic vibrotactile responses, since they did not directly measure vibrations in the handlebar, while riding a bicycle in different road surfaces. Additionally, their approach does not take into account many factors that affect induced vibrations while measuring road conditions. For instance, a cyclist can perceive a different level of vibrations depending on different inflated tire pressure. The weight and the grab on handlebar grip of the rider is another example that has to be considered. Our approach, in contrast, incorporates all counted above crucial factors while measuring vibrotactile responses.

II. Data Acquisition System

Fig. 2. Road surfaces for evaluation.

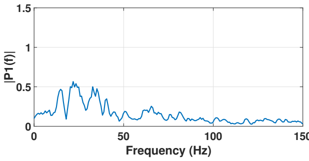
Our data acquisition system uses Flat-Bar Road Bicycle (sometimes it is called Performance Hybrid Bicycle) with a flat handlebar, which is considered to be efficient on pavement and also suitable for unpaved trails (See Fig. 1). The primary requirement for our data collection system was portability. Therefore small single-board computer (Raspberry Pi 3 Model B) was chosen to run a data collection software implemented in Python programming language. At the stem-handlebar connection, we mounted three-axis digital MEMS-based accelerometer (Analog Devices ADXL345) to the handlebar (see Fig. 1) which sends sampled data to Raspberry Pi. The accelerometer data were captured with a dynamic range of +/- 8 g and 10-bit resolution at a frequency of 1020 Hz. The velocity of the bicycle was captured based on Hall Effect. We attached Hall sensor to the front fork (see Fig. 1), and seven magnets to the spokes of the front wheel with 3D printed spoke magnet holders. The magnets were equally spaced along the wheel rim. When the magnets pass through the Hall sensor, the Raspberry Pi registers the tick. Taking into account the circumference of the tire and time interval between ticks, we calculated the velocity of the bicycle.

The vibrotactile responses induced to cyclist can vary due to many factors. For instance, [8] found that the wrist angle, a force on the stem, tire pressure, cycling velocity, and weight of the cyclist affect the vibrations induced to cyclist. The weight of the cyclist was implicitly defined in our model since the tire pressure is selected in accordance with his/her weight. The subject collecting the data was instructed to keep the arms straight and the wrist angle at zero-degrees, in order to keep the force on the stem as constant. We recruited three cyclists (2 years, four years, and more than ten years regular biking experience) with 54 kg, 76 kg and 90 kg weight and provided the data collection bicycle with 5.5 bar, 6.5 bar, and 7.5 bar inflated tires respectively. The tires were inflated according to tire manufacturer (Schwalbe North America Ferndale, United States) recommendations. Moreover, the participants were not allowed to change the gears during data acquisition process to avoid undesirable vibrations generated from mechanical parts of the data collection bicycle.

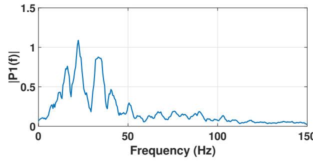
The roads with different characteristics were selected as the sample set (Fig. 2). Asphalt roadway has stochastic structure and is a typical bicycle pavement in South Korea. The brick and tile pavement follow a particular pattern. Consequently, they represent a structured type of road surfaces. The marble pavement has a smooth surface which makes it unique in comparison to the other three rough surfaces.

III. Modeling

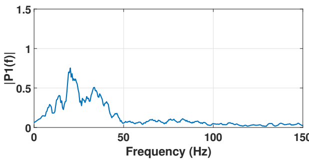
Data-driven input-output based haptic texture modeling algorithm [6] was adapted for generating road surface texture models. The velocity and tire pressure of the bicycle are defined as an input for the algorithm and output is described by acceleration patterns propagated from the road surface to the handlebar of the bicycle. We followed three steps for modeling: data analysis and processing, data segmentation, and model building. The acceleration signal was high pass filtered with cut-off frequency 7 Hz to remove gravity effect and noise induced by macro road pit, bumps and others. To illustrate the power spectral frequencies of the recorded signals, we converted the signals into a frequency domain and utilized Savitzky-Golay filter with a span value of 0.01 for smoothing (See Fig. 3). It can be noticed that the dominant frequencies are below 50 Hz for all data. Meanwhile, the plotted graphs show that each sample differs from the other in terms of its dominant frequency and power spectrum.



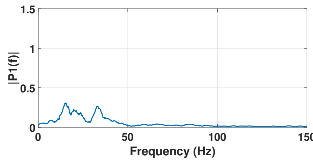
(a) Power spectrum of Asphalt



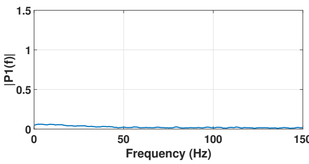
(b) Power spectrum of Tile



(c) Power spectrum of Brick



(d) Power spectrum of Marble



(e) Power spectrum of Rendering Bicycle chain mechanics.

Fig. 3. Recorded 3 seconds data of the road surfaces at 15km/h speed and 6.5 bar tire pressure (a-d). The vibrations measured while cycling on the Rendering Bicycle with magnetic resistance system (e).

IV. Rendering

For rendering, we used a second bicycle which is identical to data collection bicycle. This fact allowed us to preserve vibration transmission at the same level as our first bicycle. The most of the bicycle trainers generate unacceptable noise and vibrations during exercising. Therefore, we built a magnetic resistance unit that produces pedaling resistance based on Eddy Current phenomenon. This does not require any mechanical coupling that may generate undesired vibration. The resistance unit was made of aluminum and 3D printed components that incorporated 20 pieces of prism 35 Neodymium magnets with $20 \times 20 \times 10$ mm dimensions. We utilized the frame of the conventional bicycle trainers to mount the resistance unit and Rendering Bicycle (See Fig. 4). The level of noise induced by the chain mechanism is provided in form of frequency response plot in 3(e).

The rendering system is composed of a smartphone (Galaxy S7; Samsung Electronics Co. Ltd., Suwon, Korea), six vibrotactile actuators (BMXC series), hall sensor (Reed Switch Sensor Magnetron) with magnets, amplifier (XH-M190), single-board computer (Raspberry Pi 3 Model B) and power supply (12V 4Ah Battery) shown in Fig. 4. The rendering algorithm was implemented in Java programming language and integrated into an android application that was developed for rendering system evaluation. This software has simple user interface that allowed us to change the data-driven road surface models and tire pressure values during the experiment. The output vibration signals were displayed on sound card of the phone and analog amplifier that stimulated the vibrotactile actuators. The speed of the augmented bicycle was tracked using magnets and hall sensor, the same technique described in

Fig. 4. Rendering System: 1) Power Supply; 2) Six Haptuators; 3) Magnetic Resistance Unit; 4) Hall sensor and Magnets; 5) Raspberry Pi; 6) Amplifier; 7) Samsung Galaxy S7

Section II. The cycling velocity input values were transferred to the smartphone via wireless communication.

We found first mentioned vibrotactile motor (Haptuator BMXC series) shown in Fig. 4 as the most feasible haptic display for our application, because of its mechanical simplicity and affordability. Two haptuators were attached under the seat and on the frame of the rendering bicycle. Remaining four haptuators were equally distributed and rigidly attached to the handlebar from both left and right side to deliver localized vibrotactile responses as shown in Fig.4. The proposed technique allows integrating our rendering system with any other bicycle training simulators.

V. Evaluation

We conducted a psychophysical experiment to evaluate the identification, discriminability, and realism of the simulated virtual road surfaces.

Participants. In total, nine participants (8 male and one female) were involved in the experiment. Their average age was 27 (24-35 years old). They were selected while keeping in mind their cycling experiences and weight. For example, four subjects have five years experience of regularly riding a bicycle. However, two of them had three years experience but they do not cycle frequently, and the other two had not ridden a bike for the last two years. Moreover, the subjects were divided into three groups according to their weights such as: below 55 kg, 55-85 kg and above 85 kg. There were three subjects in each group. In fact, all the participants have experienced exercising on indoor bicycle training system or/and stationary bike installed on a trainer. Additionally, two subjects had experienced using general haptic displays before our evaluation, whereas the others were naive. After the experiment, all subjects were compensated for their time and effort.

Fig. 5. Psychophysical experiment: the subject explores a virtual road surface.

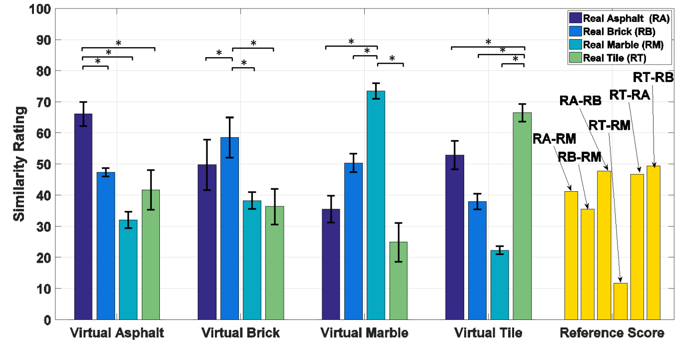


Fig. 6. The similarity rating between each road surface and all virtual road surfaces. Asterisks indicates statistically significantly difference that satisfies conditions ($p < 0.005$).

Procedure. Two sessions were performed in the psychophysical experiment. In the first session, in order to build a perceptual scale, the subjects freely explored four virtual and four real road surfaces in VR and real bicycle respectively. In the main (second) session, the participants were asked to compare the vibrotactile responses perceived from the real and virtual environments. After the trial, the subject gave similarity scores for a real surface against each of the virtual road surfaces in the range of 0 to 100, where 0 meant utterly different, and 100 represented definite similarity. The presentation order of the virtual textures were randomized during the session. Each participant explored a particular real road surface three times, thus 48 comparisons were performed ($4 \times 4 \times 3 = 48$) in total. We played rainstorm white noise through headphones to mask auditory cues, and blocked their vision with blindfold while exploring virtual road surfaces. We performed an additional experiment where the subjects pairwise compared four real road surfaces. Similarity ratings from the additional experiment (reference score) were considered to be a ground truth for the main experiment (see Fig. 6).

VI. Results and Discussion

The goal of our evaluation was to assess the realism of the synthesized vibrotactile responses. The realism was measured using similarity ratings and summarized in the Fig. 6. It is clearly seen that the participants rated the real-virtual pair of Marble and Tile significantly higher than the other combinations of matching real-virtual surfaces. The similarity ratings for none matching real-virtual surfaces resembles to the similarity scores that were rated in pair-wise comparison of two real surfaces (see Fig. 6). In order to compare the corresponding real-virtual road surface similarity ratings, we performed a two way ANOVA on the experimental data. The dependent variable was considered as similarity rating, while the subjects and real-virtual road surfaces were defined as independent variables. ANOVA test results are shown in the Fig. 6, where the asterisks indicates statistically significant differences. Even though the realism scores for real-virtual pairs of Asphalt and Brick are slightly higher than scores for non-matching pairs, the ANOVA test shows statistically significant difference across all virtual surfaces. Overall, the participants were successfully able to discriminate and identify all the corresponding real-virtual road surface pairs, and the corresponding road surface pairs received a realism score in the range of 65∼75 percent.

In post experimental interview, the participants reported several important comments. First, the lack of the feedback from macro features from the road surfaces had a negative impact on the realism. Since it is impossible to render macro features using vibrotactile actuators, it is required to use actuators that are able to move the whole bicycle frame. Thus in our future work we are planning to incorporate the rendering of macro features by using a perturbation platform as in [4]. Second, several participants reported that it is quite hard to focus on the feedback response during pedaling. They might presume that for low velocities the vibrations came from the chain mechanism, even though the level of vibration from the chain mechanism is negligible (see Fig. 3(e)).

VII. Conclusion

We developed VR bicycle with Data-Driven vibrotactile responses that can provide realistic haptic feedback of the real bicycle-road surface interaction. The data collection bicycle was designed to capture vibrations in the handlebar while cycling on different road surfaces. The recorded data was utilized to build the models of the road surfaces. The rendering system was developed and integrated with the augmented stationary bicycle. The resultant virtual model surfaces were simulated using the proposed rendering system and were evaluated by nine participants. The overall results show that participants were successfully able to discriminate and identify virtual road surfaces.

In the future, we will develop a pedaling resistance system that will allow us to reproduce a slop effect by providing a non-linear resistance. Additionally, we will incorporate visual and auditory cues as well as data-driven rendering of macro features from road surfaces to enhance the realism of our VR bicycle simulator.

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