LOW FATIGUE WALKING-IN-PLACE LOCOMOTION TECHNIQUE FOR MOBILE VR USING SMARTPHONE'S INERTIA SENSORS

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By

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LOW FATIGUE WALKING-IN-PLACE LOCOMOTION TECHNIQUE FOR MOBILE VR USING SMARTPHONE'S INERTIA SENSORS

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June 2020

Chair : Puteri Suhaiza Binti Sulaiman, PhD
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Mobile Virtual Reality (VR) headset that utilizes mobile smartphone for processing is a cheaper solution in experiencing VR immersion. However, locomotion in mobile VR is still a challenge because of the limitation to interact with the smartphone, as the smartphone is attached to VR headset. A common solution is walking-in-place (WIP), which is a hands-free input method to control locomotion inside the mobile VR environment. WIP uses inertia sensors in a smartphone such as accelerometer and gyroscope to capture the inertia data generated by the WIP gesture.

This thesis introduces Swing-In-Place (SIP) implementation that addresses three VR locomotion research problems, which are: reducing the fatigue level of WIP locomotion, enable viewing to different direction while moving forward, and reducing the fatigue caused by speed controlling during WIP locomotion.

First, in order to achieve a low fatigue level WIP technique, this thesis proposes a gesture, SIP which is less tired than the common jogging gesture used by WIP implementation in mobile VR environment. The SIP gesture generates acceleration by raising one foot and leaning the body to opposite site to create horizontal impulsive force. Bilateral Horizontal Impulse (BHI) detection algorithm is introduced to detect the positive and negative impulsive force captured from y-axis of accelerometer. Experiment results show that there is a significant difference between the fatigue level of SIP and jogging gesture-based WIP implementation with a significance level of 0.001 using paired t-test, where SIP is reported to have lower fatigue level.

Secondly, the steering direction of WIP techniques in mobile VR environment is commonly controlled based on the user's gaze direction because the available sensors in a smartphone are limited. However, in reality we may walk and look to different directions at the same time. Thus, this thesis presents a walking-in-place method with the “Side View” feature, Side Viewing-enabled-Swing-In-Place (SV-SIP), which can detect the following situations: (1) user performs SIP gesture while looking to the front direction and (2) user performs SIP gesture while looking to the left or right directions. A Cross-Axis Cross-Sensors (CACS) algorithm is introduced to capture different situations using different axes input from accelerometer and gyroscope. Experiment results show that significant differences were found between the SV-SIP and a gaze-directed WIP implementation for the time taken to complete the side view task and the fatigue level using paired t-test, with a significant level of 0.02 and 0.01, respectively. The results show that the SV-SIP implementation can increase efficiency of side view task as compared to gaze-directed WIP implementation, and the fatigue level of SV-SIP is lower than the gaze-directed WIP implementation.

Finally, WIP techniques for mobile VR typically use step frequency to control the locomotion speed, which will cause the user getting fatigued easily. This thesis proposes the Pace Switching-Swing-In-Place (PS-SIP) method to reduce the fatigue level of speed control during WIP locomotion. The PS-SIP method uses amplitude of body movement to switch the locomotion speed. The Amplitude Pace Switching (APS) detection algorithm is introduced to detect the amplitude of the user’s body movement for pace switching. The fatigue level of PS-SIP method is reported to be lower than step frequency speed control method. Significant difference was found between the fatigue level of the two methods using paired t-test with a significance level of 0.002 for quantitative measurement and significance level of 0.01 for qualitative measurement.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

TEKNIK GERAK ALIH UNTUK BERJALAN SETEMPAT DENGAN KELESUAN YANG RENDAH BAGI REALITI MAYA MUDAH ALIH MENGGUNAKAN SENSOR INERSIA TELEFON PINTAR

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Set kepala Realiti Maya (VR) mudah alih yang menggunakan telefon pintar mudah alih untuk pemprosesan adalah satu kaedah yang murah dalam mengalami rendaman VR. Walau bagaimanapun, lokomosi bagi VR mudah alih masih satu cabaran disebabkan oleh keterbatasan untuk berinteraksi dengan telefon pintar, kerana telefon pintar diletakkan di set kepala VR. Satu penyelesaian yang umum adalah berjalan setempat (WIP), iaitu satu kaedah input bebas tangan untuk mengawal lokomosi dalam persekitaran VR mudah alih. WIP menggunakan sensor inersia di dalam telefon pintar seperti *accelerometer* dan *gyroscope* untuk menangkap data inersia yang dijana oleh gerakan WIP.

Tesis ini memperkenalkan pelaksanaan gerakan berayun-setempat (SIP) yang menangani tiga masalah penyelidikan lokomosi VR, iaitu: mengurangkan tahap keletihan lokomosi WIP, membolehkan memandang ke arah yang berbeza sambil bergerak ke hadapan, dan mengurangkan keletihan yang disebabkan oleh kawalan kelajuan semasa lokomosi WIP.

Pertama, untuk mencapai satu teknik WIP tahap keletihan rendah, tesis ini mencadangkan satu gerakan, SIP yang kurang penat daripada gerakan joging biasa yang digunakan oleh pelaksanaan WIP dalam persekitaran VR mudah alih. Gerakan SIP menjana pecutan dengan mengangkat satu kaki dan menyandar badan ke arah bertentangan untuk mencipta daya impulsif mendatar. Algoritma pengesanan *Bilateral Horizontal Impulse* (BHI) diperkenalkan untuk mengesan daya impulsif positif dan negatif yang ditangkap dari paksi-y *accelerometer*. Hasil eksperimen menunjukkan terdapat perbezaan yang signifikan antara tahap keletihan SIP dan pelaksanan WIP berasaskan gerakan joging dengan tahap

signifikan 0.001 menggunakan *paired t-test*, di mana SIP dilaporkan mempunyai tahap keletihan yang lebih rendah.

Kedua, arah kemudi teknik WIP dalam persekitaran VR mudah alih secara umumnya dikawal berasaskan arah pandangan pengguna kerana sensor sedia ada dalam telefon pintar adalah terhad. Walau bagaimanapun, dalam realiti kita mungkin berjalan dan memandang ke arah yang berlainan pada masa yang sama. Oleh itu, tesis ini membentangkan satu kaedah WIP dengan ciri "Pandangan Sisi", *Side Viewing-enabled-Swing-In-Place* (SV-SIP), yang boleh mengesan keadaan berikut: (1) pengguna melakukan gerakan SIP sambil memandang ke arah hadapan dan (2) pengguna melakukan gerakan SIP sambil memandang ke arah kiri atau kanan. Algoritma *Cross-Axis Cross-Sensors* (CACS) diperkenalkan untuk menangkap keadaan yang berbeza menggunakan input paksi yang berbeza daripada *accelerometer* dan *gyroscope*. Hasil eksperimen menunjukkan perbezaan yang signifikan telah dijumpai antara SV-SIP dan satu pelaksanaan WIP pandangan terarah bagi masa yang diambil untuk menyelesaikan tugas pandangan sisi dan tahap keletihan menggunakan *paired t-test*, dengan tahap signifikan 0.02 and 0.01, masing-masing. Hasil ini menunjukkan pelaksanaan SV-SIP boleh meningkatkan kecekapan tugas pandangan sisi berbanding dengan pelaksanaan WIP pandangan terarah, dan tahap keletihan SV-SIP adalah lebih rendah daripada pelaksanaan WIP pandangan terarah.

Akhirnya, teknik WIP bagi VR mudah alih biasanya menggunakan kekerapan langkah untuk mengawal kelajuan lokomosi, yang akan menyebabkan pengguna berasa letih dengan mudah. Tesis ini mencadangkan kaedah *Pace Switching-Swing-In-Place* (PS-SIP) untuk mengurangkan tahap keletihan kawalan kelajuan semasa lokomosi WIP. Kaedah PS-SIP menggunakan amplitud pergerakan badan untuk mengalih kelajuan lokomosi. Algoritma pengesanan *Amplitude Pace Switching* (APS) diperkenalkan untuk mengesan amplitud pengerakan badan pengguna bagi peralihan langkah. Tahap keletihan kaedah PS-SIP dilaporkan lebih rendah daripada kaedah kawalan kelajuan kekerapan langkah. Perbezaan yang signifikan telah dijumpai antara tahap keletihan kedua kaedah tersebut menggunakan *paired t-test* dengan tahap signifikan 0.002 bagi pengukuran kuantitatif dan tahap signifikan 0.01 bagi pengukuran kualitatif.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

Abbr.	
APS	Amplitude Pace Switching
BHI	Bilateral Horizontal Impulse
CACS	Cross-Axis Cross-Sensors
IMU	Inertia Measurement Unit
PS-SIP	Pace Switchable Swing-in-Place
SIP	Swing-in-Place
SV-SIP	Side Viewing-enabled Swing-in-Place
VR	Virtual Reality
WIP	Walking-in-Place

CHAPTER 1

INTRODUCTION

1.1 Background

Virtual Reality (VR) technology is undergoing a revival (Boletsis, 2017) and gradually into our daily lives along with the rapid development of mobile smartphone and the introduction of VR headset, which is a ski-masked shaped goggle device designed specifically for VR (Desai et al., 2014). In recent years, many VR headsets which are portable and essentially rely on smartphone as the main unit for display and data processing have been released in the market. For example, Samsung Gear VR, Google Daydream, Pansonite VR, and etc. This kind of mobile smartphone-dedicated VR products is commonly named as "Mobile VR" by the researchers of the field of virtual reality such as Hanson et al. (2019), Wallgrün et al. (2019), Shi et al. (2019), and Lee et al. (2019).

Mobile VR is acting as an important part of the VR industry, because it has the advantages of what a mobile application has, which are: anywhere, and anytime. Moreover, mobile VR can be realized with relatively low cost because the necessities for implementation are only a smartphone and a mobile VR headset. Since smartphone has already become one of our daily necessities, whereas the VR headset usually can be bought with a reasonable low price, range from $8 to $130 USD depending on the brand and specifications (Noble, 2019), hence the cost to get started with a mobile VR is low. These kind of low cost smartphone VR headsets were actually can achieve similar immersive experience as those expensive head-mounted displays such as Oculus Rift (Papachristos et al, 2017).

1.2 Motivation

Locomotion, which is the ability to move from one point to another point, is an important aspect for a VR application because locomotion is a fundamental human activity, and it provides a basic way for the users to explore the virtual environment. However, facilitating locomotion in virtual reality is still a challenge (Al Zayer, et al., 2018), especially the locomotion in mobile VR since there are limited ways to interact with the smartphone (Anthes et al., 2016) because the smartphone is being placed inside the VR headset when the user is exploring the mobile VR environment. Some of the common locomotion methods used in mobile VR including: using a controller, teleportation, auto navigation and walking-in-place.

Using a controller for locomotion is reliable and easy to use, but it is less immersive than walking-in-place (Boletsis & Cedergren, 2019). In fact, you will be pulling back to the reality every time you realize you have to press the button in order to move ahead. On the other hand, teleportation required users to point to a location to move on, and users will “jump” to the location immediately after that. Teleportation usually use a controller or gaze selection as a pointer. The nature of teleportation, which is totally different from normal locomotion, can break the immersion feeling of users (Boletsis & Cedergren, 2019).

Next, auto navigation is a method that follows user’s gaze direction to travel forward automatically, regardless the actual intention of the user. For example, a user might not want to move at that moment. Hence, auto navigation method will lower down the feeling of immersion when compared to walking-in-place. The research by Usoh et al. (1999) has also stated that walking-in-place method can achieves higher sense of presence than auto navigation method. Nevertheless, auto navigation method has the advantage to allow the user under a hands-free condition. A navigation method with hands-free condition provides advantage for a VR application to maximize the ability of user interaction with the virtual environment (LaViola et al., 2001), for instance, user can use their hands to do others operation such as interacting with objects in the virtual environment.

Although real walking can definitely provide the greatest immersive feeling in a virtual environment. However, complicated apparatus setup and preparation of a large area in the real world is required in order to apply real walking in VR. Therefore, real walking is not suitable for mobile VR because of the spatial and apparatus constraints.

In conclusion, walking-in-place is a better solution for locomotion in mobile VR because it can provide better immersive feeling, and at the same time allows a hands-free situation. In addition, locomotion methods which using the user’s own legs to perform a gesture similar to “walking” can reduce motion sickness (Lee et al., 2017).

Nevertheless, one of the critical concerns of walking-in-place method is it will cause physical fatigue when compared to controller-based or teleportation method (Bozgeyikli et al, 2016). Furthermore, due to the limitation of apparatus, some of the realistic movement of human in real world such as walk to a direction and look to a different direction simultaneously is not realizable without adding additional apparatus requirements.

Finally, it can be seen that the challenge of walking-in-place method for mobile VR applications is to reduce the fatigue level caused by the walking-in-place gesture so that walking-in-place method will be more suitable and acceptable by the users of non-sport designed VR application which requires longer usage time because a general consumer just wants to experience VR leisurely. Moreover, it is a good challenge to simulate and realize some real world situation during locomotion to enhance the reality presented by a mobile VR application, but at the same time, without using additional apparatus to avoid adding installation requirements of a mobile VR application.

1.3 Problem Statement

The fatigue resulting from a walking-in-place method is because of the walking-in-place gesture. In a walking-in-place implemented mobile VR application, a user has to perform the walking-in-place gesture to travel in the virtual environment. In this case, if the walking-in-place gesture requires high energy consumption, this will cause the user to feel fatigue easily. Therefore, the use of a new walking-alike gesture which requires less energy consumption is able to reduce the fatigue level caused by walking-in-place method.

Next, the steering methods used in the walking-in-place locomotion technique remain as a challenge because of hardware limitation (Nilsson et al., 2018). One of the common situations during locomotion in the real world is the human walking to a direction and looking to a different direction. This situation happens on our real life naturally when we are walking. Therefore, simulating this situation in virtual locomotion should be able to improve the user experience on virtual locomotion. However, the common walking-in-place method implemented in mobile VR does not support this situation because the available sensors for mobile VR are limited.

Lastly, the common walking-in-place method used in mobile VR usually control the travel speed using the step frequency, which means that, the user has to perform the walking-in-place gesture faster in order to travel in higher speed. However, this action will increase the fatigue level of the whole locomotion process because the user has to perform the gesture many times within a shorter time period.

The problem statement is discussed in detail in the following sub-sections.

1.3.1 Fatigue

The common walking-in-place gesture used in mobile VR application such as the gesture used in VR-STEP (Tregillus & Folmer, 2016) causes physical strain. This is because the VR-STEP implementation relies on the user's head upward acceleration to detect a step. In order to achieve upward head acceleration, a user has to perform big body movement which is similar as "jogging". As the result, the fatigue level of the gesture is high. Hanson et al. (2019) have point out that the marching gesture which is commonly used as the walking-in-place gesture can cause the user to become tired easily.

The tiredness causes by walking-in-place locomotion technique is an important issue that should not be neglected as compare to other locomotion techniques (Bozgeyikli et al., 2016) because fatiguing will affect the user experience when they perform locomotion and limit the user from exploring a larger environment (Cherni et al., 2020). The fatigue issue has been discussed as a limitation in the researches regarding to walking-in-place, such as VR-STEP by Tregillus and Folmer (2016), and the research by Lee et al. (2018). Besides that, the research by Lee et al. (2019) has also considered the tiredness as one of their measurements to evaluate their proposed method.

The fatigue level caused by the walking-in-place method can be reduced by introducing a new walking-alike gesture which is less energy consuming to replace the walking-in-place gesture. However, using a new gesture requires a new algorithm to detect the gesture. Likewise, the new algorithm should not increase the needs of additional apparatus others than the sensors inside a smartphone, so that it is ready to be implemented on a basic mobile VR application. Therefore, further research on a less-fatigue walking-alike gesture and the gesture detection algorithm is needed.

1.3.2 Gaze-directed Steering

The common walking-in-place method implemented in most of the mobile VR applications rely on the inertia sensors inside the smartphone, for example, the method used by VR-STEP (Tregillus & Folmer, 2016). By using the smartphone's built-in sensors, additional apparatus is not needed. However, this walking-in-place implementation can only navigate based on gaze direction.

The difficulty of gaze-directed steering was reported in early years (Bowman et al., 1997), whereas researchers on recent years also highlight the limitations of gaze-directed steering method which gaze-directed steering method will limit the user from looking into different directions while doing locomotion (Al Zayer et al., 2018). Moreover, the ability to travel and look to different direction is reported to be more natural (Ruddle et al., 1999) because it is similar to the real world situation. In addition, Nilsson et al. (2016) have reported that gaze-directed steering method is less natural because it is different from how people walk in the real world.

The VR-STEP method uses gaze-directed steering technique because VR-STEP relies on the upward acceleration signal to detect a step, as the result, the acceleration pattern of a step when a user is looking forward or looking to other direction is similar, thus, it is hard to differentiate the head orientation and body orientation while the user is walking-in-place using only the built-in sensors of a smartphone.

Park et al. (2018) proposed a method to track the sight view direction and body direction separately using an additional waist-worn sensor. However, this method required additional apparatus, which is not desirable for a normal mobile VR user. It is ideally to enable the user to look to the side direction while travelling forward during virtual locomotion without adding additional apparatus requirements.

Therefore, in order to identify the user's situation, which whether the user is looking to the front or looking to the side direction during walking-in-place using only the sensors inside a mobile smartphone, a gesture which is able to generate different acceleration patterns while the user is under different situations can be used. So, a new algorithm to recognize the different acceleration patterns and detect the different situations has to be developed.

1.3.3 Speed Controlling

The traditional way of speed controlling in a walking-in-place implementation using the step frequency requires the user to perform high intense of body movement in a short period of time in order to increase the travelling speed. This will cause the user to feel extremely tired if the user continues to perform the walking-in-place gesture in high frequency. The fatigue issue of walking-in-place method is an important concern when compare to other locomotion methods as discussed by Bozgeyikli et al. (2016) and highlighted by researchers who worked with walking-in-place technique such as Lee et al. (2019). In order to achieve less fatigue experience, Bruno et al. (2013) and Bruno et al. (2017) have introduced the use of step amplitude instead of step frequency for speed controlling. Therefore, an alternative way to control the travel speed of walking-in-place implementation is feasible to reduce the physical strain caused by speed controlling in locomotion. However, the methods proposed by Bruno et al. (2013) and Bruno et al. (2017) use additional sensing camera in front of the user to capture the footstep height of the user, which is not workable in mobile VR. Thus, it is possible to introduce a similar way to control the travelling speed of the walking-in-place locomotion method, which is less tired than using the step frequency. However, a new algorithm for the newly introduced speed control method has to be developed.

1.4 Goal and Objectives

The goal of this research is to develop a low fatigue walking-in-place locomotion method for mobile VR using a walking-alike gesture which requires less intense body movement. The walking-in-place locomotion method should support different travel and view direction, and has a speed control mechanism which uses the step amplitude as the main control unit to reduce the fatigue level of the overall locomotion process without adding additional apparatus requirements. In order to achieve the goal, the following objectives have to be accomplished:

- To propose a gesture detection algorithm for detecting a less intense walking-alike gesture in order to decrease the fatigue level of mobile VR walking-in-place locomotion.
- To propose a side viewing feature which enable a user to walk and look to the side direction during walking-in-place locomotion as an efficient supporting feature for side view task.

- To propose a speed control method based on the amplitude of the walking-alike gesture for reducing the fatigue caused by step frequency speed control method.

1.5 Scope of Research

Mobile VR uses a low cost VR headset with a smartphone to realize a relatively low costing VR experience (Wallgrün et al., 2019). Besides that, the nature of mobile VR that uses only an untethered VR headset and a smartphone has allowed the user to experience VR anywhere and anytime (Shen et al., 2019), and this is an ideal situation for a general user (Li & Gao, 2019). Therefore, the research scope is limited to the implementation on mobile VR application without adding additional apparatus requirements to avoid hindering the inherent advantages of mobile VR, which are low cost, anywhere, and anytime.

For that reason, only the sensors available in a common smartphone are being considered in the research. The use of VR controller is not considered in order to achieve the hands-free condition and avoid adding additional apparatus requirements.

Since the proposed walking-in-place implementation is specifically for the low cost mobile VR application only, thus implementation on others VR gaming devices, such as PlayStation VR and HTC Vive is not under the scope. This is because the VR gaming device is expensive, and the VR headset is tethered with the processing unit, thus it is difficult to be used in anytime and anywhere. Moreover, a comparison between the low cost mobile VR headset and an expensive VR headset, Oculus Rift have been conducted by Papachristos et al. (2017), and their results show that there are no differences in term of immersion levels between these two types of VR hardware. Hence, the uses of low cost mobile VR hardware will not affect the immersive feeling of the user.

1.6 Thesis Organization

The overview of the thesis organization is as follows:

Chapter 1 is an introductory chapter, which describes the research motivation, then clarify the problem statements, goal and objectives, and the scope of the research.

Chapter 2 discusses the related studies, starting with an overview of locomotion techniques used in virtual reality and focus on the walking-in-place techniques. Then, the chapter continues to cover the locomotion techniques in related to fatigue, multi-directional walking-in-place techniques, and alternative speed controlling methods, which are the important issues which constitute to the thesis.

Chapter 3 reports the overall research framework, and the following chapters elaborate the separate study in related to each research objective.

Chapter 4 explains the details of the SIP gesture detection, including the SIP gesture and the Bilateral Horizontal Impulse (BHI) detection algorithm, followed by the experiment, results and discussion.

Chapter 5 explains the details of side viewing detection, including the Side View Side Viewing-enabled-Swing-in-Place (SV-SIP) method and the Cross-Axis Cross-Sensors (CACS) algorithm, followed by the experiment, results and discussion.

Chapter 6 explains the details of pace switching method, including the Pace Switchable-Swing-In-Place (PS-SIP) and the Amplitude Pace Switching (APS) detection algorithm, followed by the experiment, results and discussion.

Chapter 7 provides the conclusions of each of the research chapters related to the research objectives, followed by the clarification of research contributions of this thesis. Finally, the recommendations for future works are given at the end of the chapter.

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