Real Walking in Place: HEX-CORE-PROTOTYPE Omnidirectional Treadmill

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Abstract

Locomotion is one of the most important problems in virtual reality. Real walking experience is the key to immersively explore the virtual world. Several strategies have been proposed to solve the problem, but most are not suitable to solve the locomotion problem in Room-Scale VR. The omnidirectional treadmill is an effective way to provide a natural walking experience within the Room-Scale VR. This paper proposes a novel omnidirectional treadmill named HEX-CORE-PROTOTYPE (HCP). The principle of synthesis and decomposition of velocity is applied to form an omnidirectional velocity field. Our system could provide a full degree of freedom and real walking experience in place. Compared to the current best system, the height of HCP is only 40% of it. The application shows the effectiveness of our system to solve the locomotion problem in Room-Scale VR.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Computing methodologies—Computer graphics—Graphics systems and interfaces—Virtual reality

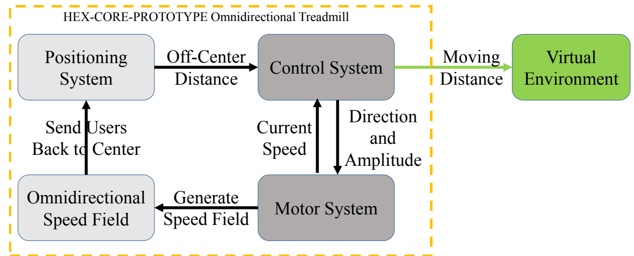

Figure 1: The flow chart of HCP system. First the positioning system will calculate the off-center distance of the users. Then, the control system will control the motor to generate a velocity field with a certain direction and amplitude. Users in the velocity field will be sent back to the center. The output information of HCP is the users' moving distance. It could be calculated by the control system based on the off-center distance and current speed.

1 Introduction

With the rapid development of virtual reality (VR), a lot of commercial VR products could provide an immersive experience for users. The head-mounted displays (HMDs) provide a real visual experience. The controllers provide a preliminary experience of interacting with the natural environment. However, only the visual, auditory and interactive experiences are not enough. No matter in the virtual or real world, the greatest pleasure is the exploration of the world. Natural locomotion is one of the most important problems for interacting with the environment and immersive experience in VR [31]. Several solutions have been proposed, such as walking in large space, controller-based, walk in place, redirected walking and omnidirectional treadmill. However, most of the solutions are not suitable to solve the locomotion problem in Room-Scale VR. In contrast, omnidirectional treadmill is an effective way to provide a natural walking experience within the Room-Scale VR or even $3m^2$.

Walking in large space [32] is the most intuitive solution. It can provide a 1 to 1 locomotion experience between the real and virtual world. But the apparent shortage is that the real world space limits the virtual world space. When we close to the wall in the real world, we could not take one more step in the virtual world.

To exceed the space limit, using the handheld controller to control the direction and speed of the locomotion is the most simple method. But it can lead to a serious 3D motion sickness [16–18]. Teleportation is another way based on the handheld controller [17]. Due to the lack of cognition on the intermediate path, this method will affect people's positioning of the current location and results in the loss of way. A common commercial solution combines the walking in large space and the handheld controller method together. When walking close to the real world boundary, users can use the controller to teleport to another place in the virtual world. However, this will disrupt the continuity of the users' experience and result in immersion reduction.

Walk-in-place (WiP) could provide a better experience than the handheld controller [9, 30, 34]. This method replaces the natural walking by some specified actions, such as jogging [9, 15, 21, 23], arm swinging [24,34], etc. However, these proxy actions are contrary to the usual habits, i.e. walking with your leg and touching with your hand. Actions used to replace the locomotion are limited and often cause misuse. Such as if we apply the arm swinging strategy, we could not swing the arm when we want to beat something using two hands. In addition, this strategy can only provide locomotion functions with low degrees of freedom. Users can only move in limited orientations corresponding to the specific proxy actions. Such as the forward, backward and lateral movements (right and left) [33] need 4 proxy actions. It is impossible to take different actions synchronously. So if we need the diagonal movements, some other specific proxy actions should be designed.

Redirected walking (RDW) is an effective strategy to compress the large space. It utilizes the human body's insensitivity to slight rotation and translation and leverages visual dominance to subtly manipulate the user's physical path [3, 4, 19, 23, 26]. RDW fine tune the physical path to guide users to walk in the limitless virtual world within the limited real world space. This strategy could provide more immersive and unlimited experiences. The minimum demand for space is about $7m$ in radius or $200m^2$ [4]. When applying this strategy, users can not move too fast, otherwise, users will notice the changes in the physical path and will result in motion sickness. Omnidirectional treadmill (ODT) could provide users with realistic walking experiences while keeping the user stationary in place [1]. The walking experience in ODT is similar to the traditional treadmill but can move in any direction. The only downside of ODT compared to other methods is the need for dedicated mechanical device. Cur-

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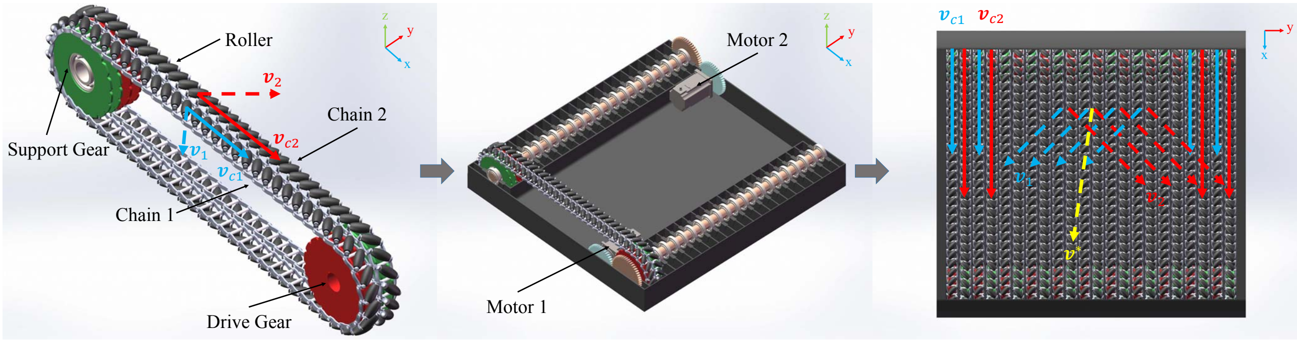

Figure 2: The mechanical design of the omnidirectional velocity field. The left image demonstrates the core components of our scheme, i.e. the two mirror-symmetrical chains. Each chain contains a support gear, a drive gear and a number of rollers that are inclined at 45°. The mid image shows that these two kind of chains are driven by two identical servo motors respectively. The right figure shows the system surface structure after arranging the two kinds of chains alternately.

rent design schemes can preliminarily realize the omnidirectional function. There are still some defects need to be improved, such as laborious to use, dead zone, low freedom degree, and bulkiness. This paper focuses on these problems and proposes a novel omnidirectional treadmill system named HEX-CORE-PROTOTYPE (HCP), which could provide a full degree of freedom and real walking experience in place. There is no dead zone in HCP and the height is only 40% of the current best system.

2 Related Work

ODT contains several design schemes. The low-friction surface is a simple scheme [2, 6, 10]. The users stand on a low-friction surface, such as the ball-bearing surface, the polytetrafluoroethylene (PTFE) surface, and their waist are tied to the machine. More precisely, users are sliding on the surface. Many commercial products are based on this principle, such as the Kat Walk, Virtuix Omni, Cyberith Virtualizer, etc. It is easy for users to overcome the friction of forward movement, however, it is very hard for the other directions. Users can only move forward laboriously, and can not move backward or sideways in a normal way [6]. Another problem is that the distance measurement are inaccurate. The Kat Walk [1] and Virtuix Omni [2] are based on the inertial measurement unit (IMU) to realize omnidirectional locomotion. This is a common method in WiP system [9, 30, 34] to count the steps but not the distance.

CirculaFloor [13] and String Walker [14] are two interesting schemes designed by H Iwata, etc. CirculaFloor uses 4 footpads to bring the user back and Hiroo use several strings to pull the shoes back to the center. The dynamic performance and safety need to be improved.

CyberCarpet [8, 28] lays a layer of steel balls on a traditional treadmill. Rotating the treadmill does not affect the user who stands on the platform. Therefore, it can provide users with an omnidirectional movement. Since the treadmill underlying the steel balls layer could only be rotated slowly, users can not quickly change the direction of movement. StriderVR is a commercial product which is similar to CyberCarpet in principle. The difference is that StriderVR rotates the layer of steel balls but not the treadmill. However, it has the same problem as the former.

Omnideck [5] uses a number of rollers to construct a platform. Each roller rotates towards the platform center, thus creating a velocity field that contracts inward. Users will be sent to the center when standing on the platform. The disadvantage is that the different positions are not parallel to each other during the transfer. And the central area is a dead zone that can be clearly felt when the user moves close to the center. This will ruin the immersion of the experience.

The belt-based omnidirectional treadmill [7] consists of two sets of vertical belts that, by the combination of two vertical motions, create a fast-responding velocity field on the platform surface. There are several researches based on this principle, such as Torus [12], Cyberwalk [27, 29], F-ODT [20, 25], Infinadeck [22]. This scheme could provide the real walking in place experience with full degrees of freedom. Due to the vertical belt structure, it is hard to further reduce the volume. Currently, Infinadeck is the smallest one and the height is about 40*cm*. Besides, the motor systems of the two sets of vertical belts are totally different, which will cause certain difficulties for the control system.

Our system HCP could create a fast-responding velocity field on the platform surface based on the principle of synthesis and decomposition of velocity, which is similar to the principle of the Mecanum wheel [11]. HCP has two identical motor systems and could provide the real walking in place experience with a full degree of freedom. Most importantly, our system structure requires only a small volume, which can be reflected in the height that our system only has 16*cm* height which is 40% of the Infinadeck.

3 HEX-CORE-PROTOTYPE Omnidirectional Treadmill

As shown in Figure 1, the HCP system consists of four functional modules. The positioning system will calculate the off-center distance of users. Based the off-center distance signal, the control system will control the motor system to generate a velocity field to send users back to the center. Users can walk continuously on the platform in a natural way. The control system could record the corresponding moving distance based on the off-center distance and the current speed. The moving distance is the output information of HCP system, which could be used to control the movement in the virtual environment.

We apply a traditional control strategy, i.e. PID (proportional integral derivative) controllers, in the control system. The motor system contains two identical servo motors. The main contribution of the HCP system are the omnidirectional velocity field scheme and the positioning system. This section will demonstrate these two parts in detail from the mechanical mechanism to the calculation method.

[1] https://www.manualslib.com/manual/1474138/Kat-Vr-Walk.html

[2] https://www.roadtovr.com/virtuix-omni-preview-production-model-video/

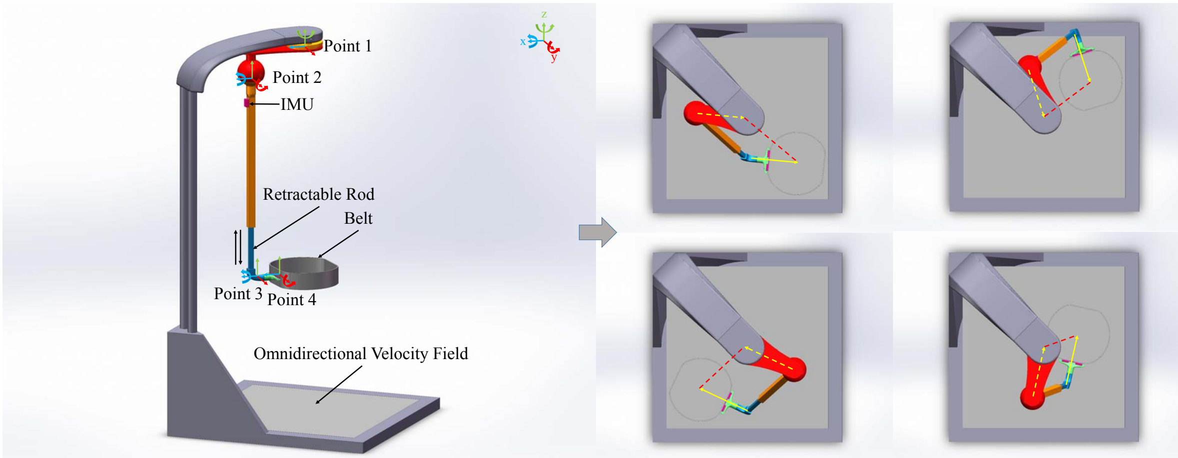

Figure 3: The inertial measurement unit (IMU) based positioning system. As shown in the left part image, the user stands on the omnidirectional velocity field and is tied by the belt. There are four rotation points. Each rotation point has specific rotation axes. Point1 can rotate along the z-axis. Point2 can rotate along the x-axis and the y-axis. Point3 rotates along the x-axis. Point4 rotates along the y-axis. The length of the retractable rod can change. The four rotation points and the retractable rod jointly provide six degrees of freedom (6-DoF) for the user. As the right part shows, no matter where the user standing on and which direction facing for, the line from the center of the user's body to Point1, i.e. the red dash line, is always parallel to the retractable rod. Therefore,the position of the user can be calculated by measuring the spatial attitude of the retractable rod using the IMU.

3.1 Omnidirectional Velocity Field Scheme

Figure 2 shows the mechanical design of the omnidirectional velocity field scheme in HCP system. The core components are the two mirror-symmetrical chains shown in the left image of Figure 2. Each chain contains a support gear, a drive gear and a set of rollers which is inclined at 45°. These two kinds of chains could be driven by two identical servo motor as shown in the mid image. After arranging the two kinds of chains alternately, the system surface structure is shown in the right of the image.

When the system is running, Motor1 and Motor2 will provide the power of the omnidirectional velocity field. Chain1 and Chain2 could be driven by Motor1 and Motor2 respectively through the drive gear. As shown in Figure 2, Motor1 drives the Chain1 at the velocity of v_{c1}, i.e. the blue solid line, and Motor2 drives the Chain2 at the velocity of v_{c2}, i.e. the red solid line. Due to the rotation of the rollers, the velocity along the roller's rotation direction is offset, and the velocity along the roller's axle direction is preserved, i.e. the blue and red dash line. Based on this structure, the originally two parallel velocities are decomposed into two vertical velocities, which could be calculated by

$$\begin{aligned} |v_1| &= \frac{\sqrt{2}}{2}\,|v_{c1}|\,, \theta_{v_1} = \theta_{v_{c1}} - \frac{\pi}{4}; \\ |v_2| &= \frac{\sqrt{2}}{2}\,|v_{c2}|\,, \theta_{v_2} = \theta_{v_{c2}} + \frac{\pi}{4}; \\ \theta_{v_{c1}v_{c2}} &= 0 \; or \; \pm\pi, \theta_{v_1 v_2} = \pm\frac{\pi}{2}. \end{aligned} \tag{1}$$

After arranging the two kinds of chains alternately, v_1 and v_2 are alternately distributed on the surface, as the right part of Figure 2 shows. The velocity of the omnidirectional velocity field, i.e. the synthesis velocity v_* could be computed by

$$\begin{aligned} &|v^*| = \sqrt{|v_1|^2 + |v_2|^2}, \\ &\theta_{v^*} = \mathrm{atan2}\left(|v_1|\sin\theta_{v_1} + |v_2|\sin\theta_{v_2}, |v_1|\cos\theta_{v_1} + |v_2|\cos\theta_{v_2}\right). \end{aligned} \tag{2}$$

Here $\theta_{v^*} \in (-\pi, \pi]$, which means the velocity v_* is omnidirectional.

When we want to have a synthesis velocity v_* which has the amplitude $|v^*|$ and direction θ_{v^*} on the omnidirectional velocity field, substituting Equation 1 into Equation 2, the servo motor velocities v_{c1}, v_{c2} could be computed by

$$\begin{aligned} &|v_{c1}| = |v^*|\,|\cos\theta_{v^*} - \sin\theta_{v^*}|\,, \theta_{v_{c1}} = \begin{cases} 0 \;\; for \;\; \cos\theta_{v^*} - \sin\theta_{v^*} \ge 0 \\ \pi \;\; for \;\; \cos\theta_{v^*} - \sin\theta_{v^*} < 0 \end{cases}, \\ &|v_{c2}| = |v^*|\,|\cos\theta_{v^*} + \sin\theta_{v^*}|\,, \theta_{v_{c2}} = \begin{cases} 0 \;\; for \;\; \cos\theta_{v^*} + \sin\theta_{v^*} \ge 0 \\ \pi \;\; for \;\; \cos\theta_{v^*} + \sin\theta_{v^*} < 0 \end{cases}. \end{aligned} \tag{3}$$

Based on the Equation 3, we can control the servo motors to construct a fast-responding omnidirectional velocity field.

3.2 Positioning Scheme

The scheme in the above subsection provides an omnidirectional velocity field that can send users back to the center. However, the final control effect also depends on the feedback of the user's current position information. A low-delay, precise positioning system is of great importance. To our best knowledge, the Bluetooth, Zigbee, Wifi, UWB (Ultra Wide Band), RFID. etc. wireless positioning strategies could provide the location precise at most down to 5cm, and at least 3 base stations are needed. This kind of strategy is costly and cannot meet the accuracy requirements. The camera-based strategy typically has a high time delay because it needs a lot of time to capture and process the images. In addition, it is not stable enough and is susceptible to illumination. In HCP system, we have comprehensively considered the low-delay, accuracy, and safety, then propose an inertial module based positioning strategy.

Figure 3 demonstrates the positioning system in HCP. The user stands on the omnidirectional velocity field and is tied by the belt. The four rotation points and the retractable rod in common provide six degrees of freedom (6-DoF) for the user. Point1 provide the heading angle for the user. Point2, Point3 and Point4 jointly provide the x-axis and y-axis movement. The retractable rod provides the z-axis movement. Point3 and Point4 provide the pitch angle and the roll angle respectively. Based on the structure, the right part of Figure 3 further demonstrates the line from the center of the

Table 1: Comparison with different omnidirectional treadmills.

Device	Motor		Active Area	Height	Weight	Maximum Speed	Maximum Acceleration
CyberWalk	X-axis Y-axis	40kW 37.7kW	6.5*6.5m	1.45m	12000kg	2m/s	0.75m/s^2
F-ODT	X-axis Y-axis	8.8kW 3.6kW	2.5*2.5m	0.64m	576kg	2.5m/s	3m/s^2
Infinadeck	X-axis Y-axis	- -	1.2*1.5m	0.4m	225kg	>2m/s	-
HCP	X-axis Y-axis	0.5kW 0.5kW	1*1.2m	0.16m	150kg	1.6m/s	1.3m/s^2

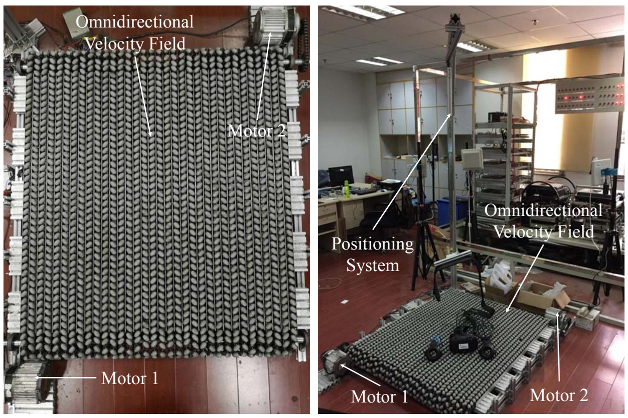

Figure 4: The shootings of HCP System. The omnidirectional velocity field is consists of 34 chains which are driven by the two identical $0.5kW$ servo motors. The size is about $1.2m \times 1.5m \times 0.16m$, and Weighs approximately $150kg$. The right part shows the overall view of the HCP system.

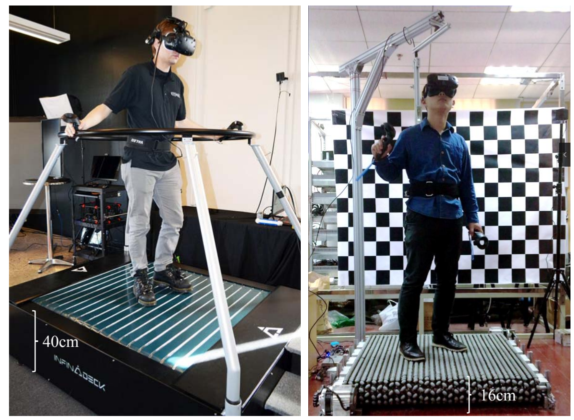

Figure 5: The comparison of HCP with Infinadeck. It is intuitive that HCP is much thinner and smaller. HCP has only $16cm$ height which is 40% of the Infinadeck. That means the corresponding volume will reduce at least 60%.

user's body to Point1, i.e. the red dash line, is always parallel to the retractable rod. We could calculate the position of the user by measuring the spatial attitude of the retractable rod using the IMU.

When the user standing on the center of the velocity field, record the length of the retractable rod by L. Take the Point1 as the coordinate origin. The user's current position coordinates could be denoted by $\mathbf{p}_0 = (0,0,-L)$. We suppose the height of the user does not change when moving around, i.e. the coordinate of z-axis does not change.

Based on the IMU, when the user walks to $\mathbf{p}_t = \left(x_t^p, y_t^p, -L\right)$, the spatial attitude of the retractable rod could be denoted by the quaternion $\mathbf{q}_t = (w_t^q, x_t^q, y_t^q, z_t^q)$. The unit vector in this spatial attitude is denoted by $\mathbf{n}_t = (x_t^n, y_t^n, z_t^n)$, which could computed by the quaternion operation that

$$(0, x_t^n, y_t^n, z_t^n) = \mathbf{q}_t^{-1}(0,0,0,-1)\,\mathbf{q}_t. \quad (4)$$

Table 2: The detail parameters of HCP system.

Motor Model		Positioning System	
Rated Power	0.5kW	Accuracy	3mm
Rated Speed	3000rpm	Time Delay	2ms
Gear Ratio	6:1	Update Rate	500hz
Device Parameter			
Total Power	1kW	Maximum Speed	1.6m/s
Total Area	1.2m*1.5m	Active Area	1m*1.2m
Height	0.16m	Weight	150kg

Since $\mathbf{n}_t$ and $\mathbf{p}_t$ are collinear and in the same direction, the $\mathbf{p}_t$ could be computed by

$$\mathbf{p}_t = -\frac{L}{z_t^n}\mathbf{n}_t. \quad (5)$$

$\left(x_t^p, y_t^p\right)$ are the position of the user in the velocity field. When this value is off center, i.e. $\left(x_t^p, y_t^p\right) \neq (0,0)$, the control system will control the servo motors to send the user back to the center.

4 Comparison

Based on the principle in Section 3, we build the HCP system as shown in Figure 4. The omnidirectional velocity field is driven by two identical $0.5kW$ servo motors, and consists of 34 chains. Detailed parameters are shown in Tabel 2.

Since the belt-based omnidirectional treadmill could provide a full degree of freedom experience, we conduct a comparison with several belt-based omnidirectional treadmills. The comparison result is shown in Table 1. The other three belt-based ODT have the same problem that the motor in X-axis and Y-axis are different. Different motors always have different electrical characteristics, such as the rated speed, the torque etc. All of this will bring difficulty to the control system. In contrast, HCP system apply the mirror-symmetrical structure, therefor the two identical motors could be applied in our system. Another advantage of the chain structure is its ease of reducing the height. Figure 5 demonstrate this advantage of our system. Compared with commercial product Infinadeck, our prototype only have the 40% height of it. The volume have already reduced about 60%. When taken more optimization, it is easy to reduce the height under $10cm$.

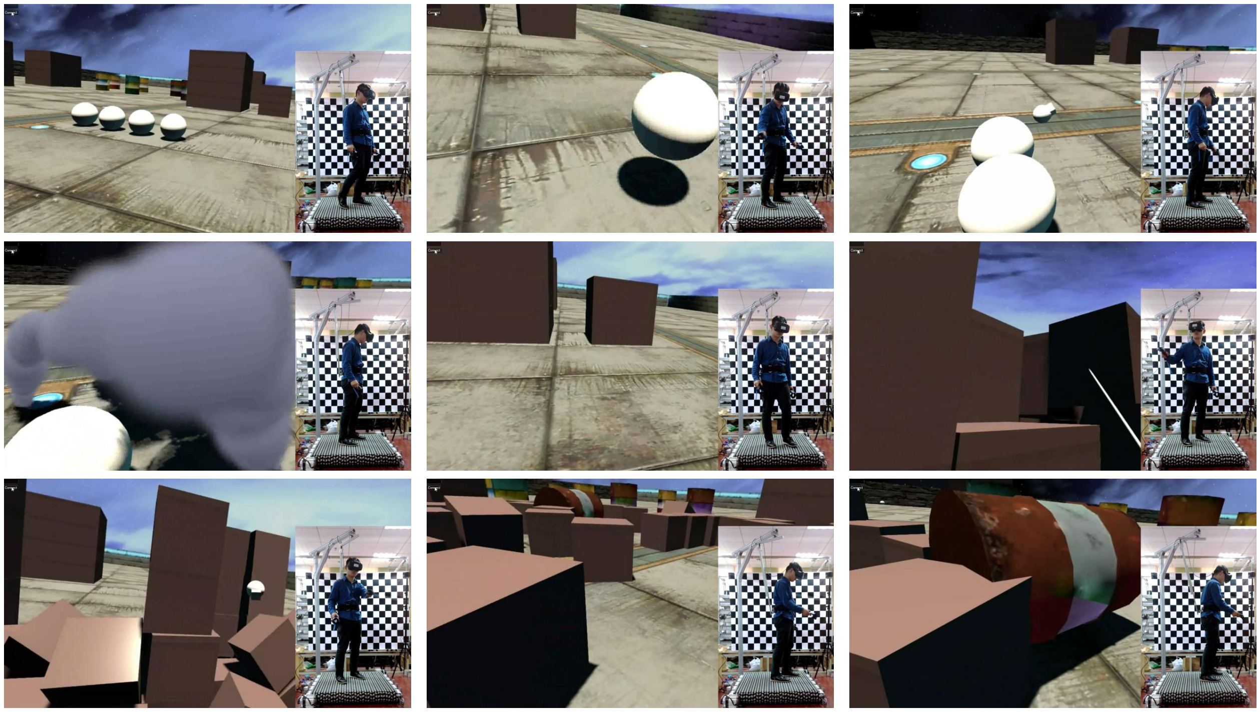

Figure 6: The demo video screenshots. The user stands on the HCP system and tied by the belt. In the virtual environment, the user is exploring a big area. Screenshots are arranged in order from left to right and top to bottom. Firstly, the user walks towards the four white balls. After close to them, the user uses a stick to toggle these balls. Then the user threw a grenade to the balls. The ball was blown up. Then the user turns around and walks to a pile of red cubes. Using the stick and grenade to destroy the cubes. Finally, the user walks towards a new oil barrel and continues exploring the virtual world.

5 Application

We further develop a virtual environment to demonstrate the effectiveness of our HCP system. The virtual environment was developed based on UNITY3D, and take the HTC-VIVE as the HMD. The demo video screenshot is shown in Figure 6.

The user in the demo is standing within $2m^2$ and can walk omnidirectionally in a natural way. It shows our system has effectiveness to solve the locomotion problem. The complete demo video is attached in the supplementary material.

6 Conclusion

This paper proposes a novel omnidirectional treadmill system named HEX-CORE-PROTOTYPE. The main part of HCP system are the design of the omnidirectional velocity field and the positioning system. The application result shows that HCP is an effective scheme to solve the locomotion problem in VR. Compared to current omnidirectional treadmills which could provide the real and full degree of freedom walking experience, HCP has a mirror-symmetrical structure. The two identical motor system makes it is easier for the controller to control the system. The chain structure make HCP is much more compact. With a fixed active area, a smaller height enables the system to have a smaller volume. This is very important for users to use in the home.

Currently, there are still some drawbacks. The comparison results show the maximum speed of HCP has a lot of room for improvement. The height can be further reduced and the control system can introduce some more advanced control strategies to get a more immersive experience.

Acknowledgments

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