B WALK-THROUGH EXAMPLE

In this section, we describe a beyond-real locomotion technique from the literature and walk through how the *beyond being real* framework can be used to describe this interaction. In the paper, we presented a high-level description of the Go-Go interaction technique for selection and manipulation. Here, we focus on a more in-depth description that also includes details about the implementation of a different interaction technique: Seven-League Boots.

B.1 Seven-League Boots

Translational gain is a simple beyond-real interaction that increases users' perceived walking speed in VR by amplifying their movements along a horizontal plane [B8]. Seven-League Boots is a variation of this technique that only amplifies movements along the user's walking path without amplifying side-to-side head sways that naturally occur when walking [B6]. This method aims to create the illusion that every step is longer in VR. We describe one implementation of the Seven-League Boots locomotion technique, similar to [B1], using our descriptive framework.

B.2 The Beyond-Being Real Framework

Our framework (see Figure 1) provides a scaffolding for describing beyond-real interactions in three stages, by describing (1) the data that captures the state and movements in the real world and is utilized in the implementation of the beyond-real interaction, (2) the set of transformations that have been applied to this real-world input for creating remappings in VR, and (3) the VR renderings that provide signifiers and feedback to users as they experience the beyond-real interaction. In the following subsections, we go through these three stages and answer sets of questions to describe the Seven-League Boots locomotion technique. For more details about the framework, please refer to Section 3 in the paper.

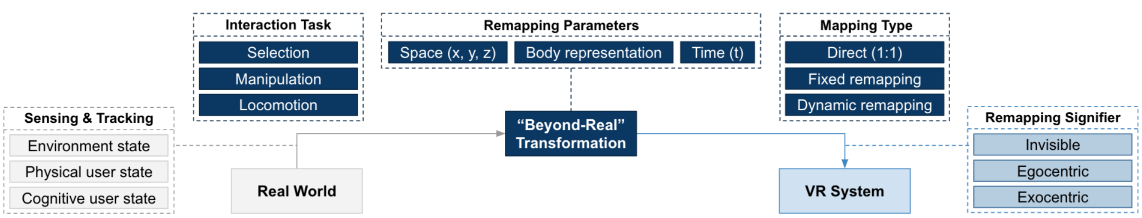

Fig. 1. The VR system receives input from the real world, applies beyond-real transformations, and renders the remapping.

B.3 Real-World Sensing and Tracking

(1) **What sensing and tracking devices are available?** The HTC Vive headset is used to track users' movements in space as they walk around. The headset is also equipped with the Tobii eye-tracking technology. For tracking users' feet, two HTC Vive trackers are secured on top of each shoe.

(2) **What limitations do they have (e.g., range, rate, precision, accuracy)?** A single 6 DoF position is sensed for the headset (precision error: $0.1 - 0.3mm$) and for each foot tracker (precision error: $0.3 - 0.5mm$) [B2], using 2 SteamVR base stations (update rate: 250-1000 Hz)[1].

[1] https://partner.steamgames.com/vrlicensing

(3) **What aspects of the real-world environment are captured?** The SteamVR base stations are mounted in the opposite corners on the ceiling to provide room-scale tracking. The calibration process is used to align the ground with the horizontal plane in a left-handed Y-up coordinate system: $\pi_{xz} = \{(x, 0, z)|x, z \in \mathbb{R}\}$. The size of the room is also known: $2.8m$ x $4m$ x $2.8m$.

(4) **What aspects of the user's physical and cognitive state are captured?** After putting on the HTC Vive headset, users' eye height is known. The position of the headset at every frame ($\overrightarrow{r_h}$) can be used to capture the displacement of the user's head: $\Delta\overrightarrow{r_h}$. The position of the trackers at every frame can be used to determine the displacement of the right foot ($\Delta\overrightarrow{r_{rf}}$) and the displacement of the left foot ($\Delta\overrightarrow{r_{lf}}$), and to capture more information about the users' gait. The eye tracking technology provides information about users' pupil size and gaze patterns.

B.4 Beyond-Real Transformations

(1) **What is the goal of the beyond-real interaction (i.e., interaction task)?** The Seven-League Boots technique enables rapid locomotion in large virtual environments, while creating an illusion that every step is longer in VR.

(2) **What remapping parameter does the interaction modify (space, body, time)?** To achieve this goal, the Seven-League Boots locomotion technique remaps users' movements in space.

(3) **What real-world data is needed and utilized for the implementation of this interaction?** The displacement of the headset at every frame $\Delta\overrightarrow{r_h}$ is needed. The movements of the user's feet at every frame are used to determine whether the user is stationary by evaluating if the displacements of the left and right foot are negligible: $\left\|\Delta\overrightarrow{r_{lf}}\right\| < \epsilon$ and $\left\|\Delta\overrightarrow{r_{rf}}\right\| < \epsilon$, where $\epsilon = 0.5mm$. When walking, the displacement of the moving foot is used to estimate the user's walking direction: $\hat{d}$, as a unit vector projected onto the horizontal plane π_{xz}.

(4) **What transformation is applied?** In the Seven-League Boots, users' movements are amplified by a predefined gain ($g > 1$) along their walking path. This is implemented by taking the headset's displacement at every frame, projecting it onto the user's walking direction, multiplying that projection by the gain, and translating the camera rig (i.e., the headset position) by that additional amount, to obtain a new headset position:

$$\overrightarrow{r_h}' = \overrightarrow{r_h} + (g-1)Proj_{\hat{d}}\Delta\overrightarrow{r_h} \tag{1}$$

(5) **What is the mapping type (direct, fixed, dynamic)?** The illusion of longer steps breaks when users are stationary, but move their head and that movement is amplified. To mitigate this effect, the Seven-League Boots is deactivated when the displacement of both foot trackers is negligible. So while walking, the mapping is fixed (i.e., the translation is constant regardless of the users' walking speed or step size), but when users are not walking, the mapping becomes direct (i.e., no translation is applied to the user's head movements).

B.5 VR Renderings and Remapping Signifiers

(1) **What aspects of the renderings are independent of the real-world movements?** There are no VR renderings that communicate the remapping to users independent of their actions. Therefore, users can only discover the remapping after they start walking and take a step forward.

(2) **What are the remapping signifiers (invisible, egocentric, exocentric)?** As a result, there are no visible signifiers. In contrast, becoming a giant (another beyond-real interaction that can achieve similar speed gains in VR) provides an egocentric signifier that makes the remapping clear to users before they begin to walk [B1].

B.6 Discussion Around Sensory Integration

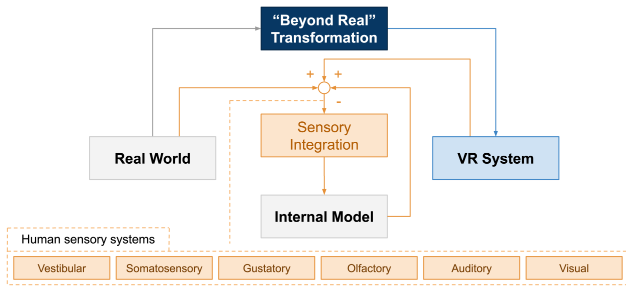

Fig. 2. Users receive sensory information from both the real world and the VR system which are then integrated. Understanding sensory integration and how the user's internal model is updated accordingly is integral for exploring open research questions around beyond-real VR interactions.

(1) **What sensory feedback are users receiving from the real world?** Users continue to receive multimodal sensory feedback from the real-world. In particular, the vestibular system provides information about the perception of self-motion, including linear acceleration ($\overrightarrow{a_{ves}}$), corresponding to users walking in the real world.

(2) **What sensory feedback are users receiving from the virtual system?** Users mainly receive visual information from VR. While walking, the Seven-League Boots maintains the user's head rotation and side-to-side head sways, but amplifies the movements along their walking path in VR. The applied translation results in users visually perceiving a higher linear acceleration: $\overrightarrow{a_{vis}}$.

(3) **Do users perceive a sensory conflict?**
As a result, the user receives incongruent sensory feedback from the visual and vestibular systems:

$$\overrightarrow{a_{vis}} - \overrightarrow{a_{ves}} = (g-1)\frac{d^2\overrightarrow{r_h}}{dt^2} \quad (2)$$

(4) **What are the implications of this sensory conflict?** This mismatch of perceived translation is known as the "stretch factor" which will likely result in motion sickness [B5]. This motion sickness is also likely to increase with increasing gain (g) [B7]. Existing theories and models for vestibular motion sickness that can be leveraged to further study these implications [B3].

B.7 Open Research Questions

While our descriptive framework allows HCI researchers and practitioners to communicate their beyond-real interaction designs with others and to make preliminary inferences about the consequences of the resulting sensory conflict, it does not offer any predictive power. As researchers we need to fill in many gaps in our understanding by (1) conducting more research around multisensory processing and integration that generalizes across a range of interaction tasks and timelines, as well as (2) further studying existing research findings (e.g., from neuroscience literature) in more applied contexts to obtain practical insights for VR interaction design. Some of these open research questions include:

- Where does the mismatch lie in the streams of sensory prediction and sensory feedback?
- How is the discrepant sensory information integrated?
- What information is known about the user and their individual responses and sensitivities?

- What prior knowledge and experiences do users have? How might this influence multisensory processing?
- What are users attending to? How might the unexpected mapping shift users' attention and what are the effects on sensory integration?
- How might users' actions be disturbed by the beyond-real transformations?
- What learning strategies does the remapping require?
- Are users expected to discover actions that lead to successful outcomes through trial and error (model-free learning) or to learn new control policies (model-based learning) [B4]?
- Are users required to learn multiple novel dynamics and is there a risk of interference? How might performance improve over time?

We believe by answering such open research questions our framework can be extended, pointing us towards a future where we can perform model-based analyses of beyond-real interactions. Systematic analyses can allow us to evaluate alternatives from a large design space of possible beyond-real transformations in order to design usable interactions beyond what is possible in the real world.

APPENDIX B REFERENCES

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