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Locomotion vault

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DOI:
10.1145/3411764.3445319

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Document Version
Peer reviewed version

Citation for published version (Harvard):
Di Luca, M, Seifi, H, Egan, S & Gonzalez-Franco, M 2021, Locomotion vault: the extra mile in analyzing VR locomotion techniques. in *CHI '21: Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems.*, 128, CHI: Conference on Human Factors in Computing Systems, Association for Computing Machinery (ACM), CHI '21: CHI Conference on Human Factors in Computing Systems, Virtual, Online, Japan, 8/05/21. https://doi.org/10.1145/3411764.3445319

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Download date: 29. Mar. 2024

Locomotion Vault: the Extra Mile in Analyzing VR Locomotion Techniques

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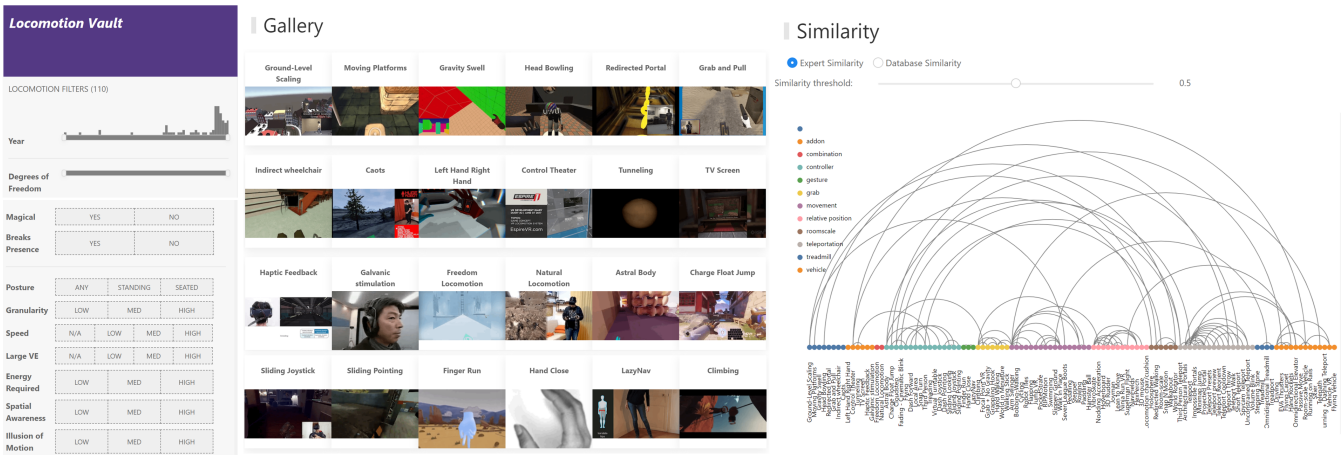


Figure 1: Features of the Locomotion Vault interactive database and visualization include: filtering by attributes (left image), an animated gallery with individual technique descriptions for over 100 locomotion techniques (middle), and two similarity graphs that are expert-created or calculated from the attributes (right).

ABSTRACT

Numerous techniques have been proposed for locomotion in virtual reality (VR). Several taxonomies consider a large number of attributes (e.g., hardware, accessibility) to characterize these techniques. However, finding the appropriate locomotion technique (LT) and identifying gaps for future designs in the high-dimensional space of attributes can be quite challenging. To aid analysis and innovation, we devised Locomotion Vault (https://locomotionvault.github.io/), a database and visualization of over 100 LTs from academia and industry. We propose similarity between LTs as a metric to aid navigation and visualization. We show that similarity based on attribute values correlates with expert similarity assessments (a method that does not scale). Our analysis also highlights an inherent trade-off between simulation sickness and accessibility across LTs. As such, Locomotion Vault shows to be a tool that unifies information on LTs and enables their standardization and large-scale comparison to help understand the space of possibilities in VR locomotion.

CCS CONCEPTS

• **Human-centered computing → User interface management systems**; *Information visualization.*

KEYWORDS

VR, locomotion technique, locomotion method, movement, traveling, navigation, database, visualization

ACM Reference Format:
Massimiliano Di Luca, Hasti Seifi, Simon Egan, and Mar Gonzalez-Franco. 2021. Locomotion Vault: the Extra Mile in Analyzing VR Locomotion Techniques. In *CHI Conference on Human Factors in Computing Systems (CHI*

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CHI '21, May 8–13, 2021, Yokohama, Japan
© 2021 Copyright held by the owner/author(s). Publication rights licensed to ACM.
ACM ISBN 978-1-4503-8096-6/21/05…$15.00
https://doi.org/10.1145/3411764.3445319

'21), May 8–13, 2021, Yokohama, Japan. ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3411764.3445319

1 INTRODUCTION

Locomotion – the ability to move in space – is an essential component of experiences in Virtual Reality (VR). It is one of the most frequently performed tasks, as it allows the user to reach spatially separate locations for exploration, search, and maneuvering [16, 26]. Despite its ubiquity, locomotion in VR presents a unique set of challenges that are yet not adequately addressed, and it is not clear whether there should be a unique "best" way in all scenarios and tasks. Several tactics, methods, or (using the term we will employ here) locomotion techniques (LTs) have been attempted with different degrees of success in terms of scientific review, user satisfaction, and finally adoption.

In the real world, physical constraints and energy consumption are limiting factors which determine the best LT for each situation, but VR introduces a different set of affordances that are less limiting [11], and they allow for a broader range of LTs. Indeed, different LTs have been proposed to fulfill user preferences, system capabilities, and task demands [16]. However, the search for new and better LTs is far from over as no LT meets all requirements. Perhaps, this exploration will never end, as different LTs might be more tailored to specific tasks, so no single LT will ever fully satisfy all constraints.

For most LTs there are discrepancies between the situation in the real world and the one in VR. If such discrepancies did not exist, VR would be only capable of replicating reality (at best). Rather, creators have purposefully introduced or taken advantage of these discrepancies in order to bend the laws of physics (e.g., the user can avoid inertia and gravity), decrease energy consumption (e.g., small user movement are mapped to fast speeds and high accelerations [1]), and increase user comfort and accessibility [17] (e.g., the user can stay seated while their avatar is standing, or use alternatives forms of interaction). However, sometimes new LTs involve low vestibular stimulation that causes simulator sickness in users [12, 24], an outstanding problem for the general adoption of VR.

As the search for LTs progresses, several attempts have been made to understand the space of possibilities for VR locomotion and inform the search for practical and tailored solutions. New LTs are often compared against popular or well-established ones to evaluate their properties and justify their design. More systematic attempts, instead, focus on analyzing the features of the LTs by decomposing, grouping, or scoring them against a set of criteria. Our review of the literature suggests that LTs are analysed in terms of metaphors, dichotomous typologies and taxonomies, underlying low level components, criteria to fulfill, or advantages and disadvantages. Many different schemes have been proposed, each capturing one or more aspects of LTs. However, in most schemes, the opportunity of combining several analyses for a deeper understanding of the space is not pursued. Moreover, most attempts propose a scheme, but do not apply it systematically to evaluate each LT.

In this paper, we present Locomotion Vault, a visualization tool and a database of over 100 techniques that were proposed by researchers and practitioners in the academia and industry. Our work is inspired by recent interactive databases that facilitate browsing and searching of inventions through a multifaceted visualized taxonomy of a large number of attributes [14, 22]. Similarly, our database contains a selection of 19 attributes derived from the analysis of the literature and 2 new attributes that are proposed by ourselves to code existing LTs. We report our observations of the space of existing LTs and their similarities and discuss how such a large interactive database can enable future analysis and design. The main contributions of our work are the following:

(1) A comprehensive review of existing locomotion taxonomies and attributes.
(2) A large open-source database and interactive visualization of locomotion techniques, populated with 109 records of LTs from academia and industry coded with 21 existing and newly-proposed attributes (Figure 1).
(3) The proposal to employ the attribute values to define similarity of LTs and the validation of this metric through the comparison with experts' similarity assessment.
(4) An analysis of the LT records, their relationships, and their attributes via summary statistics, correlations, and symbolic regression.

2 RELATED WORK

We reviewed past research on taxonomies, attributes, and evaluation criteria for VR locomotion. As we intend to capture the largest amount of LTs, we do not include analyses that are specific to only a subset of the existing techniques (such as redirection [19, 25] and walking-based LTs [18]).

2.1 Taxonomies and Attributes of LTs

To characterize the space of VR locomotion possibilities, researchers have proposed a wide range of categorization schemes. These categorizations use different terms such as metaphors, taxonomies, attributions, and typologies. We treat all of these terms the same in the rest of this paper.

One of the first analysis of locomotion was in terms of the metaphor that the LT employs [27]. Metaphors refer to what the user understands the interface to be "like". They are the internal model with which the user summarises the interface characteristics and makes predictions of the system behaviour. Metaphors promote desirable behaviours by constraining the range of transformations allowed and changing the interpretation of the user behaviour. The authors proposed three interaction metaphors: (i) Eyeball in hand where the user moves a device that determines the viewpoint of the scene; (ii) Scene in hand where the user moves the scene by attaching it to a device via a button and moving the device around; and (iii) Flying vehicle control where the viewpoint moves according to the displacement of the device relative to an initial position. Their results showed that metaphors can influence behaviour as users already have an internal model of what the interface should do [27]. An important aspect is the degree to which a metaphor can be extended to new tasks, environments, and requirements. In a more recent review, McMahan et al. [16] described the above metaphors to be exocentric and divided the remaining egocentric LTs to: automated if they do not provide real-time control (i.e., allow users to designate a target or movement path before movement

begins), and steering plus motion if the LT allows users to control the orientation and velocity in real-time. Boletsis [4] divided LTs of 36 manuscripts into four categories: motion-based techniques require physical movement to generate a change in position, room-scale-based LTs map user location to VR location, controller-based LTs require a device, and teleportation-based LTs in which the viewpoint changes in steps. Recently, Boletsis and Cedergren [5] suggested to drop the room-scale category for a more focused analysis. In a similar way, LaViola Jr et al. [15] proposed metaphors that describe the mode of traveling in the virtual environment: walking, steering, selection-based travel, and manipulation-based travel. Last year, Al Zayer et al. [2] surveyed over 200 manuscripts and grouped them according to the same four categories. Finally, Zhang et al. [29] noted that these techniques apply mostly to the motion on the ground plane and proposed to also categorize LTs depending on whether the user can move beyond the ground (i.e., flying in the air) or not.

	Boletsis [4]	Boletsis and Cedergren [5]	LaViola Jr et al. [15]	Al Zayer et al. [2]
Walking			X	
Motion	X	X		X
Room	X			
Controller	X	X		
Teleport	X	X		
Steering			X	X
Selection			X	X
Manipulation			X	X

Table 1: Summary of top-level metaphors and categories proposed in the literature.

Other categorizations suggest attributes that researchers believed were the most important for understanding the techniques. Slater and Usoh [23] proposed a distinction between magical and mundane VR interactions. A mundane interaction attempts to faithfully reproduce a corresponding interaction in everyday reality (e.g., driving an automobile). Magical interactions involve actions that are not possible in everyday reality (e.g., superman flying, walking through walls, teleportation). Bowman et al. [6] subdivided LTs into active and passive depending on whether the viewpoint is controlled by the user or by the system. They also included a mixed category called route planning which is both active and passive where users actively plan their path through the environment and then the system executes this path. Wendt [28] proposed a taxonomy based on whether the user is active or passive, which part of the body is moving, and how the VR movement is controlled. Nilsson et al. [20] employed the two previously-proposed LT distinctions to create a taxonomy based on three orthogonal dimensions: (i) whether the user is stationary or performs physical movement (user mobility, as proposed by [6, 28]), (ii) whether the technique involves a virtual vehicles or not (source of virtual motion), and (iii) whether the techniques qualify as mundane or magical (metaphor plausibility, as proposed by [23]). Cherni et al. [10] proposed a taxonomy to distinguish three main categories of LTs according to whether they were centered on the user body, external peripheral device, or both. The body-centered techniques were further divided into leaning vs. stepping LTs, while the peripheral LTs were subdivided into semi-natural vs. non-natural techniques. The main distinction of body vs. peripheral control is similar to the exogenous and endogenous categories in [16]. The naturalness categorization is similar to [23]. Finally, Bowman et al. [8] suggested a taxonomy that, although not complete, can describe most LTs and their functioning by considering three low-level attributes: direction-target selection, velocity/acceleration selection, and conditions of input. The authors showed that these attributes can help identify performance problems of the LTs. The above-mentioned taxonomies and attributes describe and analyze LTs in unique ways, yet the growing list of attributes demands a unification scheme. Inspired by the recent interactive taxonomies in other domains [14, 22], we summarized and included these attributes into the multifaceted database of Locomotion Vault (see Table 2) and visualized the database for efficient access.

Existing review papers mainly rely on academic publications in their analysis and rarely consider the rapidly growing number of techniques that are proposed by the industry practitioners. As an example, Cherni et al. [10] observed that the majority of the techniques utilized the leaning-based subdivision of the user body-centered category in their taxonomy. The high frequency of leaning-based LTs is likely due to the choice of focusing on scientific literature, which does not necessarily reflect user preference and mass adoption. Therefore, we extended the search for LTs to both industry and academia and included them all in the database of Locomotion Vault. What resulted was a large spectrum of LTs, currently 109. From the analysis of the literature, we selected 9 implementation attributes (Table 2) and one top-level classification ("category" attribute in Table 5) to characterize how they function and what are their main characteristics.

2.2 Evaluations of LTs

Researchers have also proposed a set of attributes for evaluating the user experience (UX) with an LT. However, because the studies required to try each technique, to date only a small portion of existing techniques have been tested and compared according to the UX attributes.

Bowman et al. [8] introduced a list of attributes for assessing the efficacy of LTs. These attributes include: speed in performing tasks, accuracy, spatial awareness (knowledge of the user position and orientation during and after travel), ease of learning (the ability of a novice user to employ the LT), ease of use (cognitive load during the use of the LT), information gathering (the ability to obtain information about the environment during the travel), sense of presence, and user comfort (motion sickness). Although this evaluation scheme allows for the comparison of LTs, the authors only examined three LTs according to one of the attributes due to time and resource constraints.

Cherni et al. [10] analyzed advantages and drawbacks of 22 scientific papers using a set of nine criteria. Five of these attributes coincided with the ones from [8] (precision, ease of use, spatial orientation, presence, and motion sickness), whereas the other four

were new: tiredness, self-motion sensation (i.e., illusion of controlling the movement), adaptation for large virtual environments, and adaptation for virtual reality interactions. The authors assigned 5-point ratings to each technique ranging from "criterion not fulfilled at all" to "criterion completely fulfilled".

Boletsis and Cedergren [5] asked participants to perform a game-like task with three types of LTs (motion-based, controller, and teleportation) and assessed user experience using three surveys: System Usability Scale, Game Experience Questionnaire, and a semi-structured interview. Results indicated that walking-in-place facilitated the sense of presence but also led to some discomfort due to the physical activity. Controller LTs were easy-to-use and teleportation was fast and effective but could break presence. The authors noted that the following dimensions could describe the locomotion experiences: presence, flow, ease-of-use, mastering, competence, sense of effectiveness, and discomfort.

To overcome the limitations of the previous work, which required testing each of the LTs one at the time, the authors, all of whom are experienced in VR, rated all the 109 LTs according to the UX attributes in the Locomotion Vault (Table 2).

3 LOCOMOTION VAULT

We collated the attribute proposed in the literature (see Table 2) and created an online database and visualization of over 100 LTs in Locomotion Vault.

Locomotion Vault enabled us to analyze the space of VR locomotion possibilities in a data-driven way and examine the efficacy of the proposed attributes in describing this space. In contrast to a review paper, the online database can be kept up to date as new techniques are proposed in the future. Furthermore, the visualization tool can serve as a community resource and help users find appropriate methods for a VR scenario or aid in performing further analysis in the future. The dataset and the visualization tool are open source and are hosted on GitHub. Researchers, practitioners, and the public can report new techniques or suggest a change on the Locomotion Vault interface and GitHub repository.

Below, we detail the three main components of the Locomotion Vault: the database of attributes, the similarity of LTs, and the visualization.

3.1 Database

To create a comprehensive LT database, we searched academic publications, gaming venues, game house websites, social media, and blog posts on VR locomotion. We reviewed technical blog posts on VR locomotion which led to 48 LTs. Then, we examined games with over 20k users (https://steamspy.com/tag/VR+Only) and 350 titles in three app stores (oculus, steam, sidequest) collecting 27 LTs. Finally, 34 LTs originated from academia as they are originally described in a scientific paper. This resulted in 109 unique LT records in the database.

The rule for inclusion in the database was simple, as if no record in the database captured each and all aspects of the newly-discovered LT, we would create a new record with the new information and amend any record that could be ambiguous. This approach was intentionally inclusive, as we wanted to capture LTs even if they were in a preliminary state (i.e., if they had not been fully implemented and evaluated).

Term in the references	Ware and Osborne [27][15]	McMahan et al. [16]	Zhang et al. [29]	Slater and Usoh [23]	Bowman et al. [6]	Bowman et al. [8]	Wendt [28]	Suma et al. [25]	Cherni et al. [10]	Boletsis and Cedergren [5]	Locomotion Vault
Implementation Attributes											
metaphor (see Table 1)	X	X									
exocentric/egocentric		X						X			vection
ground / air			X								beyond ground
magical/mundane				X					X		magical
active/passive		X			X		X		X		energy
direction						X		X			direction
input						X					hardware
body part							X				posture
recentering							X				
subtle/overt							X				
discrete/continuous							X				discrete
velocity/acceleration/control						X	X				degrees of freedom
UX Attributes											
speed						X				X	speed
precision						X			X		granularity
effectiveness										X	
ease of learning						X					intuitive
ease of use						X			X	X	
spatial awareness						X			X		spatial awareness
information gathering						X					
presence						X			X	X	presence
flow										X	
challenge										X	
motion sickness						X			X		nausea
tiredness									X	X	
self-motion sensation									X		embodiment
large environment									X		large VE
interaction									X		multitask

Table 2: Summary of the implementation and UX attributes proposed in the literature and indication of the ones selected for Locomotion Vault. For a complete description of the attribute, see Table 4 and 4.

3.1.1 LT Information and Attributes. For each of the records, we have collected general information (16 database fields, Table 3), two type of attributes (implementation and UX attributes) which include 21 attributes that help describe the techniques and search among them (Table 4), including the "category" attribute (Table 5).

LT information include a unique name and identifier, as well as a description of the completeness and accuracy of the entry (preliminary, partial, needs review, and complete). Metadata ensures that the LT can be identified and includes a short verbal description of what the LT entails, all names used to refer to the LT, the year of the first mention, example applications (e.g., a video-game or a demo that employs it), citation information for any academic publications, a created or linked graphic depiction of the LT, and links to multimedia content if available. A complete list of this information is included in Table 3.

The implementation and UX attributes are collated from the literature review (details of each attribute are described in Table 4). The purpose of the implementation attributes is to describe the function and properties of the LTs, so that they can be discriminated based on how they work. The UX attributes, in contrast, are intended to capture how well the LTs perform according to different criteria. Most of the attributes can be traced directly to the taxonomies in

Name	Description
id	A unique number that is used for the identification of the record. We stared at one and increased the id by one for each new record
state	State of the entry (complete, good, preliminary, revise, rename, check duplication)
short name	A unique phrase of 3 words or less. The most common name is selected if more than one exist. Modifiers after "+" differentiate multiple implementations
names	Other names used to refer to the method
disambiguation	A description of the way(s) this method differs from other similar methods
description	A summary of how the method works and its features
year	Year of first mention, publication of the scientific paper, or earliest example
creator	Name or pseudonym of the person that invented the LT
game dev	Name of the software house that invented the LT
examples	List of example applications (e.g., video-games or demos that employ the LT)
citation	Reference to the scientific studies that proposed or examined the LT
image	A graphical depiction of the LT
video	Animation illustrating the LT
media	Links to the media, websites, and other references that demonstrate or discuss the LT
pros	List of advantages based on the sources we reviewed
cons	List of disadvantages from the sources we reviewed

Table 3: List of the information included in Locomotion Vault related to each LT record, including database fields, metadata, references, examples, and the description of their content

Name	Citation	Type	Description
vection	[10, 16]	O3	How much does the users feel that they are moving? This attribute depends on the exocentric or egocentric point of view.
beyond ground	[29]	B2	Is the motion of the user in VR limited to the ground floor or can extend above it?
magical	[10, 23]	B2	Is the motion magical (abstract) or mundane (natural)?
energy	[8, 16, 25]	O3	How much energy does the user spend to move in VR?
direction	[7]	C11	What determines the direction of movement (e.g., gaze, pointing, controller, walking)?
hardware	[7]	C17	What hardware is required in addition to the headset (e.g., hand tracking, button, treadmill)?
posture	[3]	C3	What posture(s) does the locomotion method support (e.g., standing, seated, any)?
discrete	[28]	B2	Is the navigation in the VR space continuous or in discrete steps?
degrees of freedom	[8, 28]	O7	How many directions and rotations can the user control?
category		C11	Top-level description of the type of LT. Attributes and scores are assigned according to Table tab:categoriesscores
speed	[8]	O4	How fast does the user travel in the VR space?
granularity	[8]	O4	How precise can the control of the location in VR be with this LT?
intuitive	[8]	O3	How easy is it to adopt this LT without any training or learning?
spatial awareness	[7, 10]	O3	Does the LT allow the user to be aware of their surrounding and their location and/or orientation in the VR environment?
presence	[5, 8, 10]	B2	Can the use of the LT break the sense of presence?
nausea	[7, 10]	O3	How much simulation sickness can this LT induce in a novice user?
embodiment	[10]	O3	How much does the LT invoke the sense of having a body in VR?
large VE	[10]	O4	Does the LT allow movement in large VR environments?
multitask	[10]	O4	To what extent can the user perform other tasks at the same time as locomotion?
videogamer		B2	Would a professional gamer adopt this LT?
accessibility		O3	How easy is adopting this LT for users with disabilities?

Table 4: List of implementation and UX attributes. The "type" entries are binary (B), categorical (C), and ordinal (O) followed by the total number of possible values for the corresponding attribute.

the literature as shown in Table 2. For some attributes, however, we made adjustments as indicated in the comparison between the leftmost and rightmost column. This was necessary as the scope of the description in the original taxonomy was intended for a subset of the LTs and needed to be expanded to include all the LTs in our database. In particular, in the literature "recentering" had been used exclusively for walking LTs and we expanded it to define the "type of hardware employed". We extrapolated the concept of "velocity/acceleration control" to "degrees of freedom". Furthermore, we combined the terms "ease of learning", "ease of use", and "challenge" into the attribute "intuitive". We also combined "active/passive" and "tiredness" into "energy required". We did not incorporate "metaphor", "information gathering", "effectiveness", and "flow", as for at least one third of the LTs the authors could not reach a consensus on what value should be assigned. We found that "subtle/over" largely matched "break of presence" and excluded this attribute. Finally, as all of the attributes were obtained from the academic literature, we introduced "videogamer" and "accessibility" attributes to discriminate the potential user bases.

We analyzed each implementation and UX attribute to identify the possible values it can take. The values were chosen by the authors in concert, considering the type of attribute, the range of LTs, and the values that could be associated to them. All the authors assigned the attribute values for the LTs in parallel. To assign the attribute values, the authors had access to the description of the LTs, and they either tested the LTs, watched videos, or performed a web search to determine the details of the LTs. Next, the authors merged the attribute assignments and discussed the values if two or more authors disagreed. For some attributes, it was not possible to assign a value for some of the LTs, so the value "n/a" was entered and this instance was excluded from our later exploratory analysis. If such occurrences were more than one third of the LTs, the attribute was excluded from Locomotion Vault ("metaphor", "information gathering", "effectiveness", and "flow").

Finally, the "category" attribute was defined at the end of the process based on other metaphors and categories in the literature (i.e., Table 1) and on an analysis of the records. Although we expect that in the future we will be able to define a procedure for the automatic assignment of the "category" attribute, in this work the labels were assigned by hand and scores are pre-computed and shown in Table 5. This category is an important dimension to understand LTs (Figure 7) and here we seek a relation of its values

with the implementation and UX attributes to understand the space of possibilities in VR locomotion (see section 3.3).

3.2 Similarity Metric and Validation

We propose that similarity between LTs could be an intuitive way to explore and search the large space of VR LTs. Similarity enables the users to start from one LT and find other ones that have comparable attribute patterns across the database. To obtain an automatic and scalable measure for LT similarity, we compared expert judgements of similarity to the database-obtained similarity. Specifically, we considered the expert similarity assessments as the gold standard, and we tested whether computing similarity from the attributes is consistent with it. In this approach, if the two similarities correlate, expert judgments are not essential in the future updates to the database. For this, we visualized both these two types of similarities in the current implementation of Locomotion Vault and compared the results in this paper.

For the database similarity, we calculated the distance between the LTs by assigning numerical values to the labels of the implementation and UX attributes in the database (20 attributes). Specifically, we assigned equally-spaced scores to the rated attributes (e.g., 1 and 2 to the binary attributes and 1, 2, and 3 to low, medium, and high labels of the ordinal attributes). For categorical attributes such as "direction", "hardware", and "posture", we assigned scores that retained their configuration similarity. For example, we obtained the scores for the "category" attribute by performing a multidimensional scaling (MDS) on a matrix of pair-wise similarity scores that the first author assigned to the categories (results are shown in Table 5). We then scaled the scores to be between 0 and 1 for each attribute. If each LT is represented as a point in a multidimensional coordinate system made of every attribute score, the similarity between the LTs can be simply expressed as a function of the distance between dots.

Attribute label	Score
Movement	0.4381
Gesture	0.0558
Roomscale (plus treadmill)	0.1885
Grab	0.4539
Relative Position	-0.0407
Teleportation	-0.2390
Vehicle	-0.4105
Controller	-0.4461
Addon	n/a
Combination	n/a

Table 5: Labels and scores of the "category" attribute. The attribute scores are used for the analysis to calculate the similarity and symbolic regression. The Add-On and Combination categories were not included in the analysis, and were not assigned a score.

For the expert similarity, experts were asked to hand-pick up to 10 other LTs that were similar in the database. Since this task required a deep understanding of all the LTs, it was done by all the authors who through the process became experts on all the LTs in the database. Independently-produced lists of up to 10 similar techniques per LT were produced by reviewing the information available in Table 3. Specifically, the authors had access to the general information fields. We defined the distance between the LTs to be inversely proportional to the square root of the number of the authors that reported similarity between a given pair.

As we envision the database to be ever-changing and increasing in size, we aim to find a scalable way to determine similarity between the LTs. Therefore, we calculated the degree of correspondence between the database and the expert similarity scores (section 4.2).

3.3 Symbolic Regression

By employing symbolic regression, we intend to shed further light on the relationship between the records in the database. The purpose of this analysis is to examine whether there is a link between the "category" attribute (Table 5) and the other attribute scores. In this way, we will be able to avoid expert intervention and automatically select a "category" for a new technique from its other attributes.

Statistical analyses like MDS are based, among other things, on the assumption of linearity in the parameters which is likely to be violated in a complex high-dimensional space such as the one created by the attributes in our database. Symbolic regression, instead, does not rely on such linearity, and therefore, it can discover complex relationships between variables using genetic programming [13]. For example, this methods has been shown to be able to discover complex laws of physics from empirical data [21]. Here, we use the Eureqa by Nutonian tool to do a genetic exploration of our dataset.

We used the following operators in the symbolic regression: constant, +, -, ×, /, power, logical values (if-then-else, equal-to, less-than, less-than-or-equal, greater-than-or-equal, and, or, xor, not), and basic statistical functions (min, max, mod, floor, ceiling, round, abs). The population size (number of formulae per generation) was chosen by Eureqa as $1.9 * 10^7$. For each analysis the program ran on a 20-core cluster and left running for more than 24 hours, until the solutions stabilized and converged to 100%. Half of the database was used for training and half for testing the goodness of the fit. .

3.4 Visualization

We created an online visualization to enable efficient browsing and analysis of the techniques in our database (Figure 1). The visualization is hosted as a public repository on GitHub: https://locomotionvault.github.io/. The interface consists of the following six components:

a. Similarity view: An arc diagram visualizes all the LTs and their similarities. The LTs are presented with small circles and are colored according to their "category" attribute. The arcs connect LTs with a similarity value above a user-adjustable threshold. The default value for the similarity threshold is set to 0.5 on a 0.1 (slightly similar) to 1 (highly similar) scale. Users can switch between the expert and database similarities as needed. Hovering over and clicking on a node highlights its connections and lets the user explore similar LTs. The mouse hover and click actions also present a preview of the LT's GIF image on the top right corner of the view. The user can click on the "See details" button to open the Details pop-up view for the technique.

b. Gallery view: Located at the bottom of the page, the Gallery view lists the names and gif images for all the LTs. Clicking on the box for each technique opens its Details pop-up view.

c. Details pop-up view: This view presents all the information about one technique, including the gif image, general information, and the list of implementation and UX attributes for the technique.

d. Filter panel: The users can select a subset of the filters on the right sidebar to narrow down the list of the LTs according to their needs and criteria.

e. Data entry form: The users can enter data for new LTs on a Google form. Our team reviews and verifies the data before adding them to the database and visualization.

f. Change request: The users can report mistakes or suggest a change by posting an issue on the GitHub repository for the project which is accessible from the top right corner of the visualization interface.

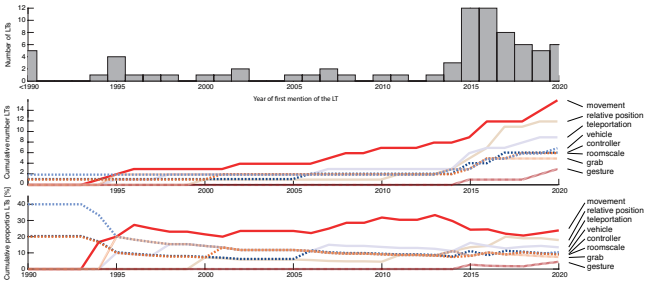


Figure 2: Evolution of the appearance of LTs over time. Top: Number of LTs separated by the year of their first mention. Middle: Cumulative number of LTs per year, separated by their "category" attribute. Bottom: Relative cumulative number of LTs per year separated by their "category" attribute.

4 RESULTS

Below, we present our observations and summary statistics on the dataset, compare the space of VR locomotion similarities obtained from our two similarity metrics, and examine the most predictive attributes with a symbolic regression analysis.

4.1 Observational Analysis

Locomotion in VR is certainly not a new field. The earliest attempts to devise useful LTs are as old as the first VR setups. But as VR has grown in popularity in recent years, due to the availability of low-cost hardware and a large selection of content, we notice that the number of records in the database is more concentrated in the last 5 years (Figure 2, top). The exploration of new techniques and modification of previous ones peaked around 2015, with a slight decline afterwards, possibly because new LTs take time to be refined and publicized.

Nowadays, the majority of records describe LTs categorised in the Movement, Relative Position, and Teleportation categories. A historical analysis of the LT records can help picture how these numbers came to be what they are. Figure 2, middle shows the cumulative number of the LTs separated by their categories. The presence of horizontal traces in the graph indicates that the earliest-invented LTs, i.e. Roomscale (which in this analysis includes LTs with treadmill-like hardware), Controller, and Vehicle, have not notably grown in popularity over the years. On the other hand, inventors have been modifying movement-based LT over the course of 20 years, suggesting that there has been an attempt at optimising such techniques as head and hand tracking has developed and reached the market. Teleportation and Relative Position have seen a resurgence after 2015 due to the availability of hand tracking, which gave these techniques a larger range of possibilities. Grab techniques have seen a slight increase in absolute numbers recently. However, if we look at the relative proportion graph in Figure 2, bottom, we see a constant decline in invention in the Grab techniques, even in recent years. Vehicle techniques follow the same path, despite a slight increase in recent years probably due to availability of room-scale and hand tracking technologies. Gesture LTs have only been recently discovered, thanks to the availability of hand tracking to the public, so it is not surprising that they have only seen a small increment in their number.

One note of caution should be made about Figure 2. The data shows the number of novel LTs, that is, how many novel ways of moving around in VR have been invented. These values should not be interpreted as a representation of the frequency of use or as an evaluation of the LT. Rather, techniques that have not shown innovation might have reached the maximum development possible until a new device or a new experience requiring a different way of locomotion is invented.

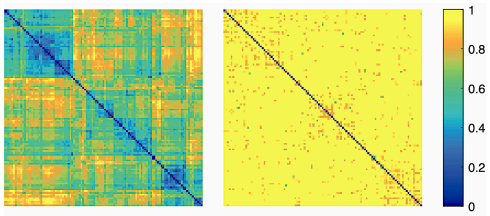


Figure 3: Distance matrices. Left: euclidean distance between pairs of LTs in normalized attribute score space for all the implementation and UX attributes. The LTs have been ordered based on a clustering analysis and a minimization of the inner squared distance. Right: distance between the LTs based on similarity judgments by the four authors. The order of the LTs is the same in both matrices.

4.2 Similarity Space of VR Locomotion

We compared the low-dimensional representation of the LT similarities obtained with our two similarity methods (database and experts) in order to validate the automatic method and assess its efficacy in presenting the design space of LTs. Figure 3 visualizes the distance matrices for the two types of methods. The left matrix presents the normalized euclidean distance between the LTs according to their attribute scores, while the right matrix presents the distances measured based on the expert similarity. The sparse matrix obtained from the experts is due to the limited number of reports (i.e., the highest number of similar techniques that were

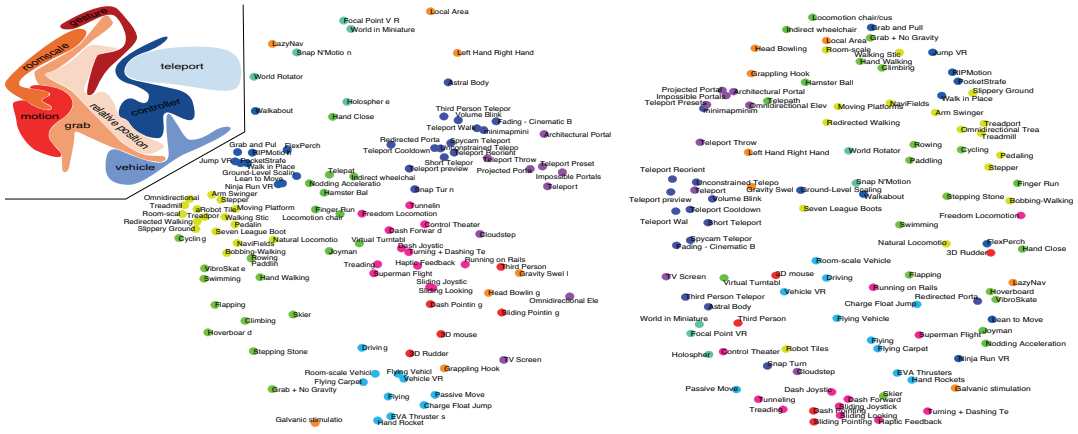


Figure 4: MDS analysis visualises the LTs in low-dimensional spaces and highlights commonalities: Left: from database similarity data. Right: from expert similarities. The dots represent the 109 LTs and have been colored based on a clustering analysis with 10 clusters. We employed the same clustering analysis to order the rows and columns of the matrices in figure 3. The insert shows the location of the "categories" in the MDS space using the same color code as Figure 7.

reported for an LT was 10 and the average number was 1.9 similar techniques).

Importantly, the two methods lead to a different meaning of the distances and thus it is expected to find congruence in the configuration of the results but several low-level differences. To derive a space that could visualize the similarity and grouping of LTs in these spaces, we performed an MDS analysis on the values of the two distance matrices in Figure 3. The distances obtained from 21 attribute scores (left) and the expert similarity reports (right) were reduced to two dimensions (Figure 4). In this space, LTs that appear near each other have similar scores (left) or have been reported to be similar (right). Shephard plots showed that the embedding quality increased with more dimensions, but the standard threshold for the stress score did not lead to a stable solution. With two dimensions, which allow a better visualization, we obtained stress scores of 0.20 and 0.28 for the two methods which indicate a fair fit of the data with the database similarity. The lower fit for the expert similarity is most likely due to the sparseness of the distance matrix.

Again we find differences in the configurations of the LTs obtained from the MDS, but clusters of LTs from the high level pattern of reported similarities are largely preserved as evidenced by the colour groupings in Figure 4. Such configuration is congruent with the similarity of the two matrices in Figure 3 which have a small but highly significant correlation ($r(5884)=0.27$, $p<0.001$). Even when considering only the sparse answers of the experts and excluding the missing values in the right graph, such correlation is still present and highly significant ($r(445)=0.16$, $p<0.001$). As such, the MDS analysis on the database scores captures the same underlying representation as the one based on the expert judgments.

4.3 Symbolic Regression

We employed symbolic regression as a data reduction tool to find the link between the attribute scores and the "category" attribute. The tool produces a series of formulas that relate the attributes and the "categories" by a measure of the correlation between predictions and actual values across LTs. After converging (Figure 5), the tool reported 188 equations. Each equation has an associated size parameter that represents the complexity of the equation (ranging from 1, least, to 53, most complex), a fitness value, the square of the correlation coefficient between the response variable and the fitted values from the equation, and the Akaike Information Criterion (AIC). The AIC is an information theoretic measure of the relative goodness of fit of a model to the data. Smaller AIC values represent better goodness of fit, taking also into account the complexity of the model. The AIC is often used in model selection procedures, as discussed extensively in [9]. It is generally not recommended to use an equation with a very high fit as a solution, because it could be over-fitting the data. On the other hand, an equation with a low correlation coefficient may not describe the data adequately.

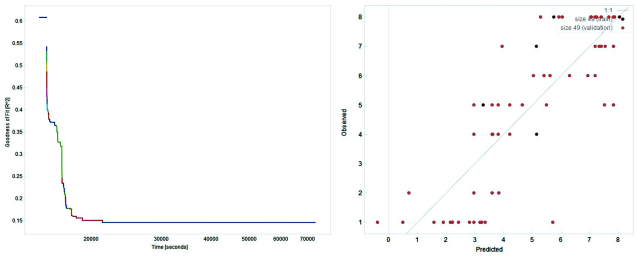


Figure 5: Symbolic regression analysis procedure. Left: Progress over 24 hours in the genetic analysis of the relation between attributes and the "category" values. Results converged into a subset of equations that provided high correlation between the training and the testing datasets. Right: Example of the correlation between observed and predicted values for one example solution.

In our case, we have 100 equations with a correlation coefficient of over 80% and 18 equations with a correlation of over 80% and a

fit score below 80% (Figure 6,top), so instead of proposing a single formula we decided to analyze the commonalities between these solutions in terms of the attributes that are present across all the equations to capture what factors can best describe the LTs (Figure 6, bottom) . This analysis suggests that "accessibility", "direction" and "nausea" are the most reliable predictors of the "category" attribute in the 188 equations, followed by, "presence", and "hardware". Across all these equations, the LT category can be defined using a generic formula: $category = f(accessibility, direction, nausea, ...)$ where the parameters for such an equation are treated in different ways according to the specific model. Interestingly, there are also commonalities in the attributes that are not present in the first 18 solutions: "vection", "beyond ground", "magical", "energy", "degrees of freedom", "speed", "granularity", "spatial awareness", "large VE" and "embodiment".

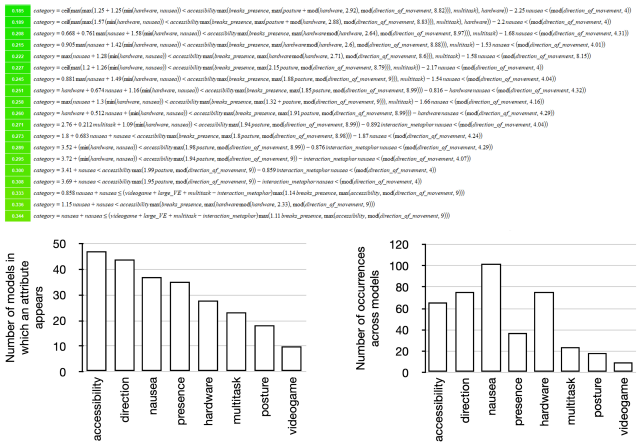


Figure 6: Results of symbolic regression analysis. Top: Solutions that had a fit score below 80% and a correlation coefficient over 80%. Bottom: Summary of the attributes that were frequently used as predictors of the "category" attribute in the 188 solutions.

5 DISCUSSION AND CONCLUSION

In this paper, we propose a data-driven approach to understand the space of LTs. Specifically, we reviewed prior taxonomies and created a database and visualization tool that allows the community to examine past (and future) techniques according to these taxonomies. We realize that any review will become obsolete in a rapidly-changing area such as VR locomotion. Therefore, we have built Locomotion Vault to be a community-sourced tool that can stand the test of time in the following ways:

(1) The database is meant to grow to include new LTs and attributes.
(2) Our analysis suggests that a similarity metric can be extracted from the attribute scores, and we propose an algorithm that can be an adequate substitute for the similarities defined by the experts, which cannot be sustained as new LT records are added to the database. We also propose a method to categorize new LTs based on their attributes, but we expect to further refine this method to fully automate the definition of the categories.
(3) We publicly share the dataset and visualization code on GitHub so that others can contribute to and extend its scope. In fact, since we posted the website link on Twitter five days ago, several researchers have contributed to the GitHub repository, and one has forked it to create another VR-focused database. In addition, we are organizing a workshop in IEEE VR 2021 to incite discussions and momentum on community-sourced databases for VR research. We hope that this public database encourages others to further analyze the LTs with statistical and machine learning techniques and present new insights or an up-to-date view of the field in the future.

Out of the 21 attributes that we included in the symbolic regression analysis based on years of taxonomic research, we find a clear convergence on the attributes that LTs have historically tried to solve in the first place:

- Accessibility is defined as the extent of motor ability that the LT requires and goes beyond the simple amount of effort or the posture that the LT supports. Our results suggest that the more abstract categories can be more accessible for users with limited mobility, while the closer a category is to real-world movement, the less accessible it is.
- Direction of motion is at the core of locomotion. The more the laws of physics that apply to locomotion, the less abstract the technique can be, and hence the direction of movement is more constrained.
- Nausea or simulator sickness is a critical issue in VR development. Separation between virtual world and reality in some LTs can create noticeable visual-vestibular discrepancies that result in user discomfort.

Not only are these attributes critical to locomotion, they validate our analysis of similarity as shown in Figure 7, by which categories on this multidimensional space seem to be linearly ranked according to accessibility, direction of movement, and nausea.

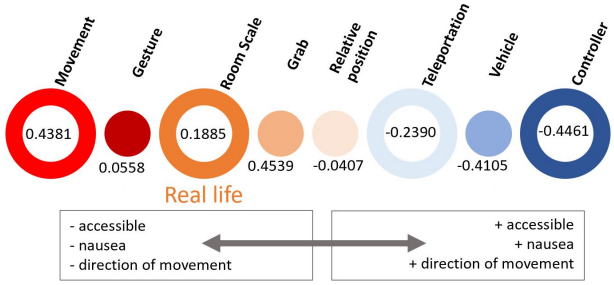


Figure 7: The similarity scores on the "category" attribute can reduce the multidimensionality into a linear mapping that goes from Movements beyond the real life to locomotion using the Controller techniques. We associate this linear mapping with the three main describing attributes from the symbolic regression analysis.

The solutions of the symbolic regression results can be informative about the non-relevant attributes for the categorization. This suggests that LTs in the same "category" might have a wide range

of scores for such attributes thus making them irrelevant for the purpose of predicting the "category". For example, although there are Teleportation techniques that score very low on "spatial awareness", there are some that provide a good solution to the problem by slightly modifying the technique (e.g., providing a preview before teleporation). As this type of example can be found in most categories, including "spatial awareness" attribute would not increase the ability to infer the category of the LT.

Over the last few decades, there has been a continuous evolution in the way LTs were invented. While the early attempts, dating back to 1950's, tried to reproduce real-world locomotion through custom-built devices, the advances in tracking technologies have widened the range of VR locomotion possibilities. For example, the development of room-scale and hand tracking enabled novel metaphors and analogies in the control of locomotion that allow efficient and intuitive movement while reducing motion sickness.

One particular emphasis of our work has been to explore beyond LTs proposed by academic research and capture the growing list of LTs from practitioners in the the VR and gaming industry. Since the arrival of consumer VR, many game designers have produced novel LTs (sometimes even with the goal to show how bad an LT can be). The academic research has been slow to document, study, and learn from this proliferation of techniques. With Locomotion Vault we have tried to bridge that gap and link back all these new methods to the research arena. We hope that with input from both the academic and industry communities, Locomotion Vault can remain an active link between these distinct communities of practice.

While up until now researchers have proposed several useful taxonomies for VR, we advocate a more data-driven approach with Locomotion Vault. We believe this approach is complementary to the review papers and to empirical experimentation. In the hands of researchers and practitioners, the tool can further grow the field of locomotion, support the discovery and creation of new locomotion methods, and help researchers cope with the large set of attributes and techniques in an area in constant innovation, and eventually create new techniques that address the grand challenges in VR locomotion in the years to come.

ACKNOWLEDGMENTS

We would like to thank Justin Clark for sharing his insights and knowledge in developing the database. We also thank NSERC Canada for funding Hasti Seifi. The Locomotion Vault database and visualization code is informed by Haptipedia [22].

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