Motion Sickness Reduction for 6-DoF-Navigation in a Virtual Solar System

- overview of CSVR
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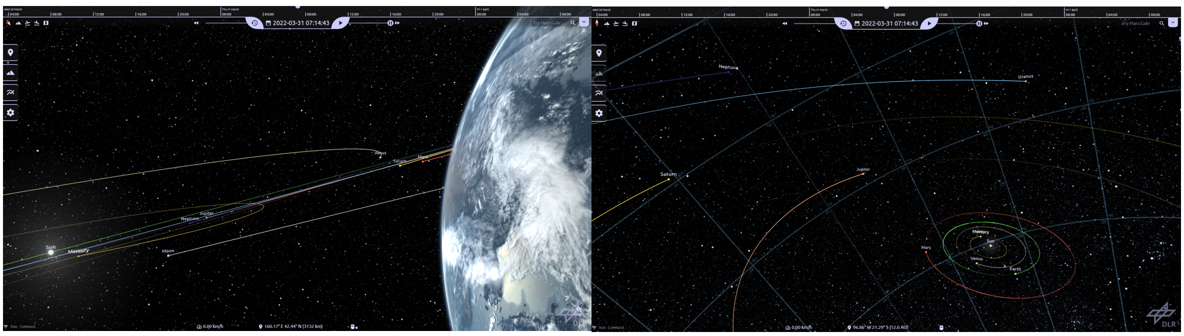
- overview of cybersickness sources and mitigation
.
- scope of the thesis
.
- floor grid
.
- FoV vignette
.
- automatic movement overhaul
.
- user study

What is CosmoScout VR?

- Modular, scientific, 3D visualisation of the Solar System
- High resolution elevation models and satellite imagery
- Interactive and immersive exploration of large datasets at diverse scales



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(1) Modular, scientific, 3D visualisation of the Solar System

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(2) High resolution elevation models and satellite imagery

- international community has produced vast amounts of data
- Interactive and immersive exploration of large datasets at diverse scales
- allows exploration from surface up to solar system scale

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- high-flexibility for different user cases through plug-ins

What Causes Cybersickness?

Sensory Conflict Theory

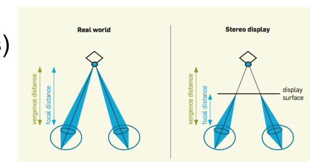
- Sensory mismatch between sensory systems of the body (visual ↔ somatosensory / vestibular system) [1]
- Conflicts due to vection (illusion of self movement while stationary) [2]

Postural Instability Theory

- Uncontrolled movements and changes to the center of gravity → inability to maintain postural stability [3]
- Postural instability i.e., lateral-medial body sway often precedes experiences of motion sickness [4]

Vergence-Accommodation Conflict Theory

- Vergence (lateral eye movement adjusting to objects at different distances) and Accomodation (adjusting eye's focal length to focus on the objects) occur at different distances [5]



Vergence-Accommodation Conflict in Stereoscopic Displays [6]

1: Barrett, G. V. and C. L. Thornton: *Relationship between perceptual style and simulator sickness*.
2: Keshavarz, B., et al.: *The effect of visual motion stimulus characteristics on vection and visually induced motion sickness*.
3: Riccio, G. E. and T. A. Stoffregen: *An ecological theory of motion sickness and postural instability.*
4: Stoffregen, T. A. and L. J. Smart: *Postural instability precedes motion sickness.*
5: Kim, J., et al.: *The rate of change of vergence–accommodation conflict affects visual discomfort.*
6: Kroeker K. L.: *Looking beyond stereoscopic 3D's revival.*

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(1) Sensory Conflict Theory
- Information from senses does not match each other or expectation
- somatosensory => self-movement & body position
- vection => illusion of self movement

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(2) Postural Instability Theory
- uncontrolled small movements like natural body sway
- usually happens before motion sickness
- naturally unstable people may be at a higher risk to show symptoms
- Rest Frame Theory → instability from confusing reference frames not coinciding with gravity gradient

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(3) Vergence-Accommodation Conflict Theory
- vergence => lateral eye movement adjusting to objects moving towards and away from the observer
- accommodation => adjusting the eye's focal length to focus on the object
- happens at different distances in stereoscopic displays → causes eye strain resulting in cybersickness
- highly active content with different stimulus distances worsen the problem
- Hardware problem difficult to fix/prevent on a software basis

How to Prevent Cybersickness?

Best Practices

- Limit exposure times and allow adaptation to the virtual environment [1]
- Avoid high rates of linear or rotational acceleration, or extraordinary maneuvers [1]

Field of View Limitations

- Vection comes from peripheral visual field and is therefore strongly tied to FoV size [2]
- Reducing the FoV results in less vection and reduced presence, leading to less cybersickness symptoms [3]

Stable Reference Frames

- Provide stable frames of reference to reduce sensory conflicts and improve postural stability [4]

1: McCauley, M. E. and T. J. Sharkey: *Cybersickness: Perception of self-motion in virtual environments*.
2: Duh, H. B. L., et al.: *Effects of field of view on balance in an immersive environment*.
3: Lin, J. J. W., et al.: *Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment*.
4: Chang, E., et al.: *Effects of rest frames on cybersickness and oscillatory brain activity*.

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(1) Best Practices
- limit exposure times & provide adaptation phase
- avoid high linear or rotational acceleration & extraordinary/unrealistic (abrupt) maneuvers
.
(2) Field of View Limitations
- vection strongly tied to peripheral visual flow → decrease FoV to decrease vection
.
(3) Stable Reference Frames
- stable reference frame to reduce sensory conflicts and improve postural stability
- display grids over the scene / pseudo-AR mode to provide stability at the cost of presence/immersion

What is Part of the Thesis?

I. 6-DoF-Navigation control scheme with VR remote lead to complex rotations in free movement
   - Reduce cybersickness in interplanetary space and close to, or on body surfaces

II. Automatic navigation uses simultaneous translation and rotation during travel path
   - Overhaul automatic navigation system to provide general, more predictable movements

III. Design user study to measure user satisfaction and cybersickness symptoms

(1) 6-DoF-movement
- free interplanetary movement
- free surface movement
- different features due to different sources for cybersickness

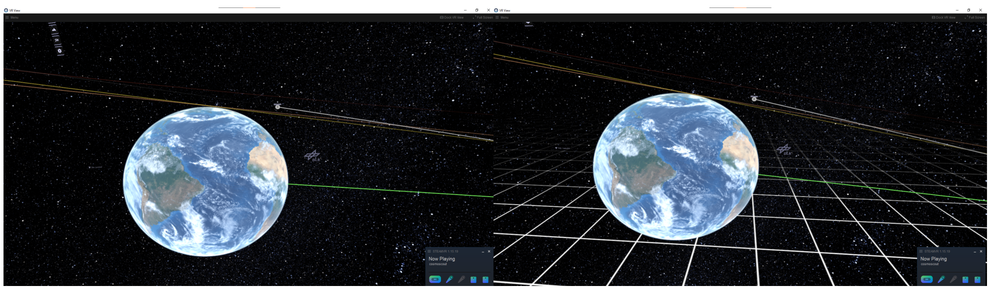
.

(2) Automatic Navigation System
- old navigation uses simultaneous translation and rotation
- overhaul to provide general, predictable movements & separate rotation and translation

(3) User Study Design
- prepare study to measure user satisfaction & cybersickness for the developed features

How To Mitigate The Problems? - Floor Grid

- Provides a stable simulated frame of reference during interplanetary free and automatic navigation
  - Assist with postural stability and sensory conflicts
- Change interaction context from egocentric to exocentric
  - Mitigates sensory conflict problems because VR orientation mirrors real-world situation



(1) Images Floor Grid On/Off

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(2) provide stable frame of reference for interplanetary movements

- help maintain postural stability during complex movements(rotation) → postural instability theory

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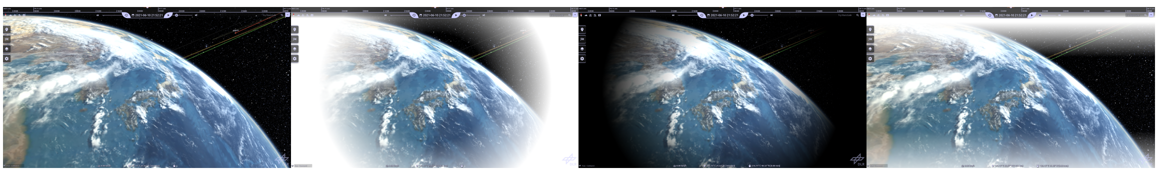
(3) change interaction context to fixed user w/ simulation moving around them (exocentric)

- stationary user → reduced sensory conflict
- may require additional changes to control scheme (not part of the project)

How To Mitigate The Problems? - FoV Vignette

- Popular method of cybersickness reduction
  - Applications with high detail and/or movement in peripheral areas of vision
- User tends to react to high peripheral detail / movement by moving their eyes instead of their head
  - Employ vignette to limit users FoV, focusing on the center of HMD lenses



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(1) FoV Vignette images (Off/Circular white/Circular black/Vertical white)

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(2) popular & proven method of sickness mitigation

- especially for application with high detail/movement (in peripheral vision)

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(3) focus user on center of HMD lenses (sharper image)

- moving eyes instead of head leads to unfocused images straining the eyes and increasing risk of sickness

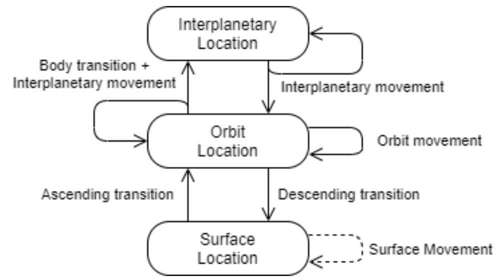
.

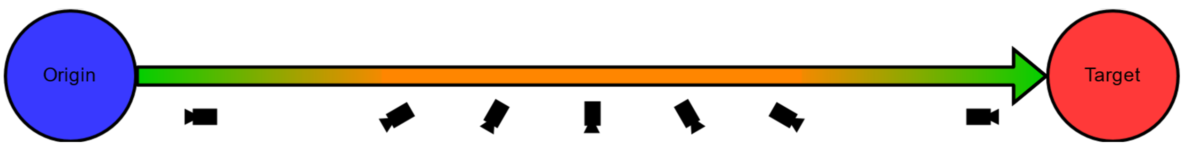
- vignette drawn as post-processing shader w/ fixed or dynamic radius
- dynamic → based on observer velocity
- fixed → animation to closed vignette when above threshold
- vertical, asymmetrical vignetting due to studies suggesting a more natural limitation of the FoV

How To Mitigate The Problems? - Automatic Navigation Overhaul

- Separate origin and target location into general cases
  - Interplanetary locations
  - Orbital locations
  - Surface locations

- Movements and transitions between layers
  - Surface, orbit, and interplanetary movements
  - Ascending, descending, and body transitions





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- old nav for reference
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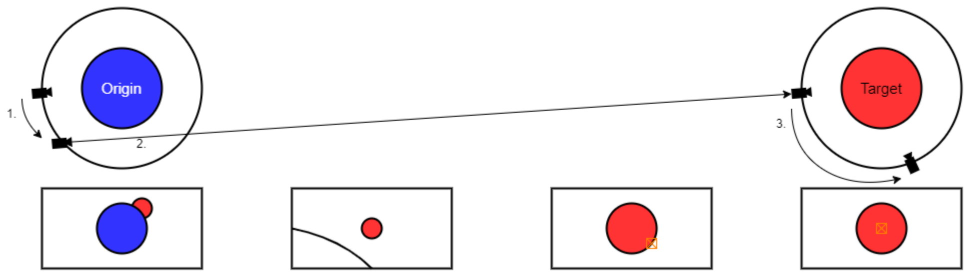
(1) separate possible locations into general categories
- interplanetary → outside a body's sphere of influence (location tracked in root frame J2000)
- orbital → inside a body's sphere of influence (location tracked relative to body's frame & center)
- surface → close to, or on body's surface (- " -)
.
(2) movements and transitions between these locations/layers
- movements on each layer (surface, orbit, interplanetary)
- transitions between layers (ascension/descension → surface ↔ orbit; body → orbit ↔ interplanetary)
- transition: movement from position from one layer to valid position in next layer layer
- interplanetary movement always ends in interp. location or valid orbital location

How To Mitigate The Problems? - Automatic Navigation Overhaul



(0) origin and target overview (w/ locations)
.
(1) old navigation
- linear, translation and rotation simultaneous
.
(2) body transition
- find position where origin & target are in unobstructed view based on angular constraints
.
(3) interplanetary movement
- linear movement to target orbit
- results in valid orbital position → no interp. → orbital transition
.
(4) orbit movement
- orbital movement to target location in orbit
.
(5) overview
- ascension/descension transition if necessary before/after this movement

How To Mitigate The Problems? - Automatic Navigation Overhaul
Orbital Movement Comparison

Video available at https://youtu.be/BOdHpa2pD1I

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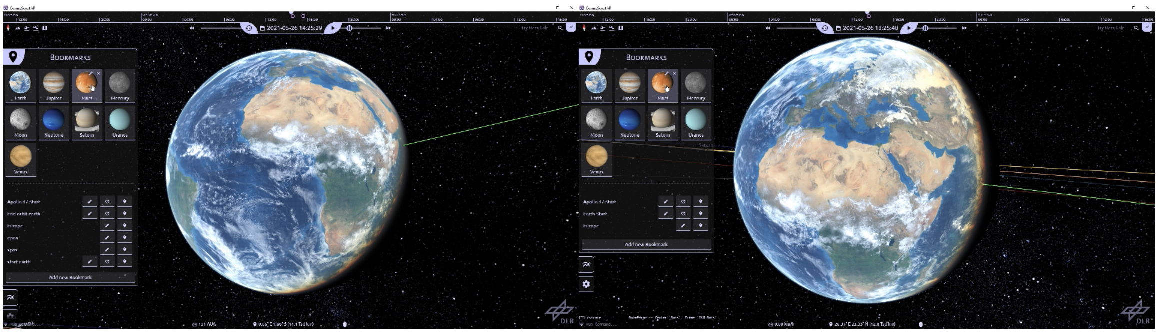
(0) show comparison Orbital movement

How To Mitigate The Problems? - Automatic Navigation Overhaul Interplanetary Movement Comparison



Video available at https://youtu.be/oHTQS1gfXe0

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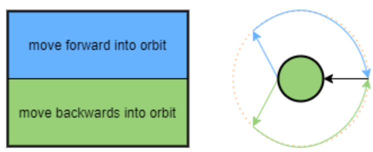
(0) show comparison Interplanetary movement

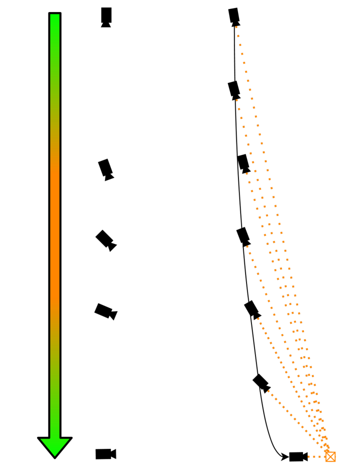
How To Mitigate The Problems? - Automatic Navigation Overhaul

- Travel paths moving the user forwards
  - Move in orbit over and rotate towards target
  - Lock view direction onto target and move along parabola curve down to target

- Simple, predictable movements to mitigate sensory conflicts
- Parabola movement instead of linear to "move into" target orientation

- Surface movement via orbital movement
  - Transition to orbit
  - Move to target
  - Transition back to surface





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(0) old descension tansition
- only one method → linear & simultaneous

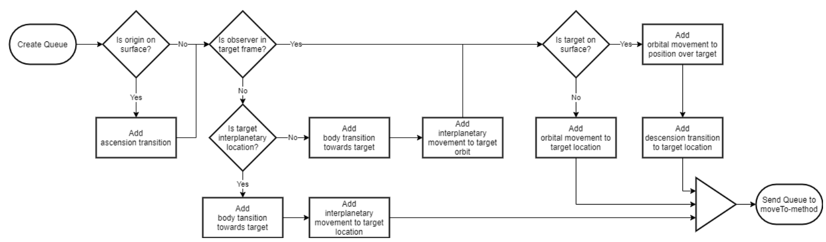
.
(1) new transition
- move observer forward along curve
- view locked onto point in direction of final view

.
(2) simple & predictable movements
- curve to move forward instead of sideways movement
- similar to Google earth’s descension

.
(3) surface movement vial orbital
- offer general solution independent of distance or local topography: (ascend, orbit, descend)
- extendable in future for short distances etc. (complex topic of itself)

How To Mitigate The Problems? - Automatic Navigation Overhaul

- Parameter for elementary movements in information packages
- Bundle basic movements in a queue to create complex movements
- Movement queues can be constructed anywhere and passed as a bundle to the navigation system to execute



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(1) package parameters into Packages for elementary movements
- all basic movements into move packets
.
(2) movement queue to allow chaining of multiple basic movements
- to create more complex movement orders
.
(3) queues can be constructed anywhere
- constructed and passed instantaneous as a bundle of basic movements

How To Measure the Effectiveness?

- Within subjects user study to measure effectiveness of developed features
  - Features tested independently

- Mixture of subjective and objective measurements
  - CoG measurements to record postural stability
  - Fast Motion Sickness Scale (FMS) measurements to record cybersickness incidence and severity
  - Questionnaires to record user feedback and satisfaction

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(1) within subject study → every subject is tested on every scenario
- measure effectiveness of developed features
- features developed to fix independent aspects (grid→ interp. free nav; vignette→ surface free nav; etc.)
- measure user satisfaction/preference for each feature
- cybersickness severity & incidence, intuitiveness of controls (floor grid / control scheme rework),
  obstruction of view (vignette), predictability/easiness (auto nav)

.

(2) measurements for these goals both objective and subjective measurements

.

(3) Center of Gravity to measure postural stability changes between scenarios
- measure using a balance board or inertial measurement unit (IMU) of VR HMD

.

(4) Fast Motion Sickness Scale for cybersickness incidence and severity
- polling subject ~every minute inside the scenario to rate cybersickness on a 20 point scale
→ generating sampled datapoints over the exposure time of each scenario

.

(5) Questionnaires to recorded user feedback
- satisfaction and factors above (intuitiveness of controls, obstruction of view, easiness of movement)

How To Measure the Effectiveness? - Execution Plan

Start time	Task	Duration
0 min	Introduction and gathering basic information	5 min
5 min	VR acclimation, and training phase	5 min
10 min	First feature scenario, variant A	10 min
20 min	VR break	5 min
25 min	First feature scenario, variant B	10 min
35 min	VR break, and checkpoint scenario questionnaire	5 min
40 min	Second feature scenario, variant A	10 min
50 min	VR break	5 min
55 min	Second feature scenario, variant B	10 min
1 h 5 min	VR break, and checkpoint scenario questionnaire	5 min
1 h 10 min	Automatic navigation scenario, variant A	5 min
1 h 15 min	VR break, and automatic navigation questionnaire	5 min
1 h 20 min	Automatic navigation scenario, variant B	5 min
1 h 25 min	VR break, and automatic navigation questionnaire	5 min

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(1) Introduction Phase
- basic info about subject & 5 min training to acclimate subject
.
(2) First feature phase (counterbalanced → different for each subject)
- variant A/B either with or without feature (counterbalanced)
- 5 min breaks in between scenarios to reset to some baseline (→ best practices & sickness goes up with exposure time)
- after both scenarios questionnaire during break (preference, obscuring view, ease of use, ease of control)
.
(3) Second feature phase (counterbalanced)
- other feature tested like first feature, A/B, breaks & questionnaire
.
(4) Auto Nav Scenarios (counterbalanced)
- questionnaire during each break (satisfaction, predictability)
.
- overall ~1.5h

How To Measure the Effectiveness? - Hypotheses

1. Significant results that each new feature produces less cybersickness compared to the initial situation
2. Significant results that subject's acceptance or satisfaction is higher for each feature compared to the initial situation
3. Automatic navigation overhaul will show the most improvement
4. Floor grid will show the least improvement
5. Vignette will show less improvement than the navigation overhaul

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(1) significant difference between old and new situation
.
(2) significant results that new features are better than initial situation
.
(3) auto nav will perform best
- worst symptoms in initial situation, very noticeable improvements by separation of rotation & translation
.
(4) floor grid will perform worst
- initial cybersickness in interplanetary space relatively low
- control scheme may hinder satisfaction
.
(5) vignette will perform in the middle
- vignette is quite subject specific and default settings may be insufficient for some subject's
- default settings should be approximated in a pre-study

Summary & Outlook

✔ Designed and implemented floor grid to mitigate cybersickness in interplanetary space
✔ Designed and implemented FoV vignette to mitigate cybersickness on, or close to a body's surface

✔ Designed flexible and robust automatic movement system
  ✔ Implemented linear movements (for interplanetary movements)
  ✔ Implemented circular movements around a frame center (for orbital movements)
  ✔ Implemented movement queue system
  ✗ Not implemented body transition
  ✗ Not implemented ascending/descending transition (covered currently by implemented linear movement)
  ✗ Not implemented surface movement

○ Designed user study, but not conducted due to COVID-19 restrictions

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Overview what was done, and what wasn't done:
.
(1) design & implementation of customisable floor grid
.
(2) design & implementation of customisable vignette
.
(3) designed the automatic movement system & implemented basic functions:
.
(4) linear movements (old movement method & interplanetary movements)
.
(5) circular arc movements (around center of frame → orbital movements)
.
(6) movement queue system for future improvements and flexible system
.
(7) not implemented body transition
- calculation of the point within the constraints → queuing orbital movement to calculated point
- (not enough time)
.
(8) not implemented asc/desc transition
- currently covered by implemented movements (orbital, but linear) resulting in linear movement with separated rotation
- focus was on orbital & interp. movement since missing mapserver & topology → hard to test, not enough time
.
(9) not implemented surface movement
- movement via orbit (no mapserver & topology, focus on orbital/interp. Movement) → not enough time
.
(10) designed userstudy, no execution, due to covid-19 & time constraints