# Bimanual Haptic Interaction with Virtual Environments

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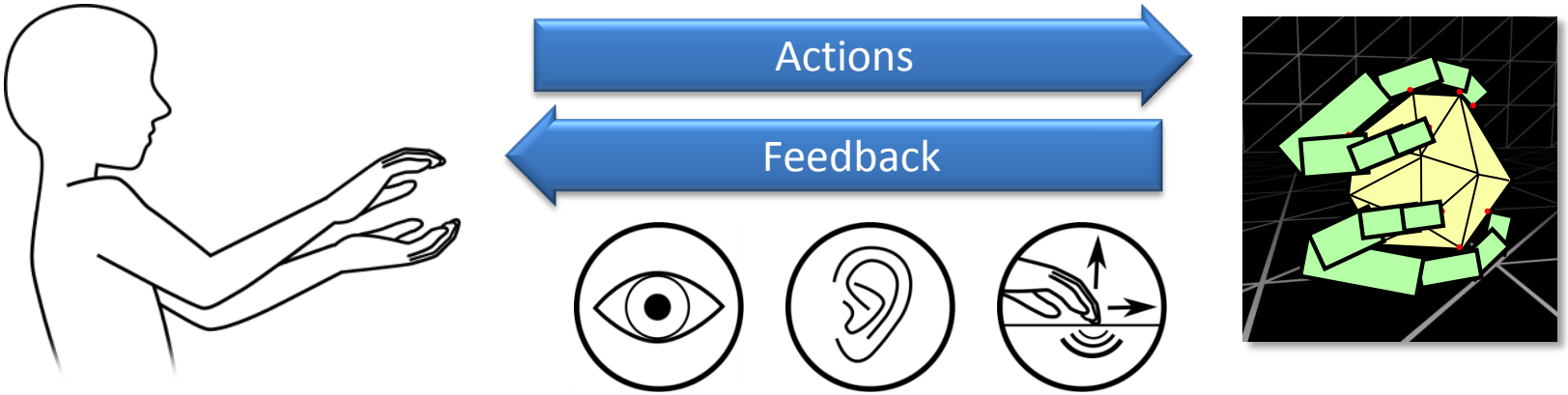
# Virtual Reality and Haptics

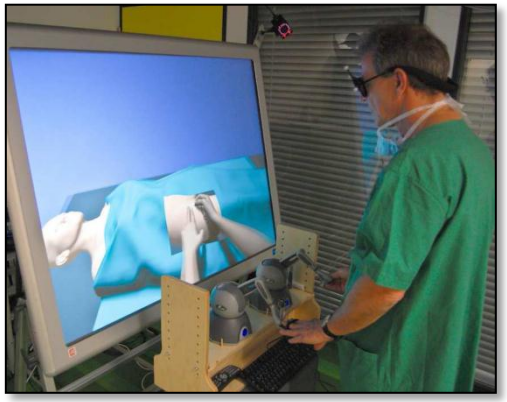
- **Virtual Reality** (VR) : Immersion of a user in a Virtual Environment (VE)
- **Haptic sense**: Kinesthetic and tactile perceptions
- **Haptic devices**: Enhancing immersion in VR through tactile/force feedback

(Geomagic)



# Bimanual Haptics

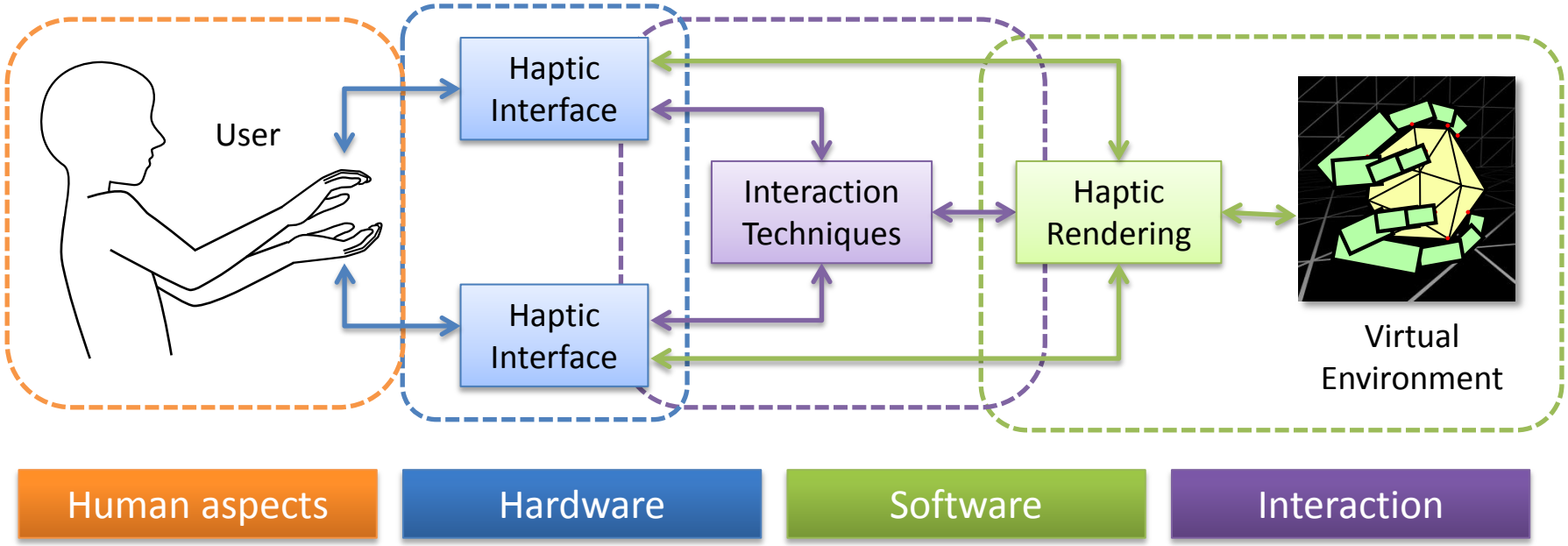
- Haptic applications often one-handed
- Common use of two hands in daily life
- **Bimanual haptics:** Haptic interaction with VEs through both hands



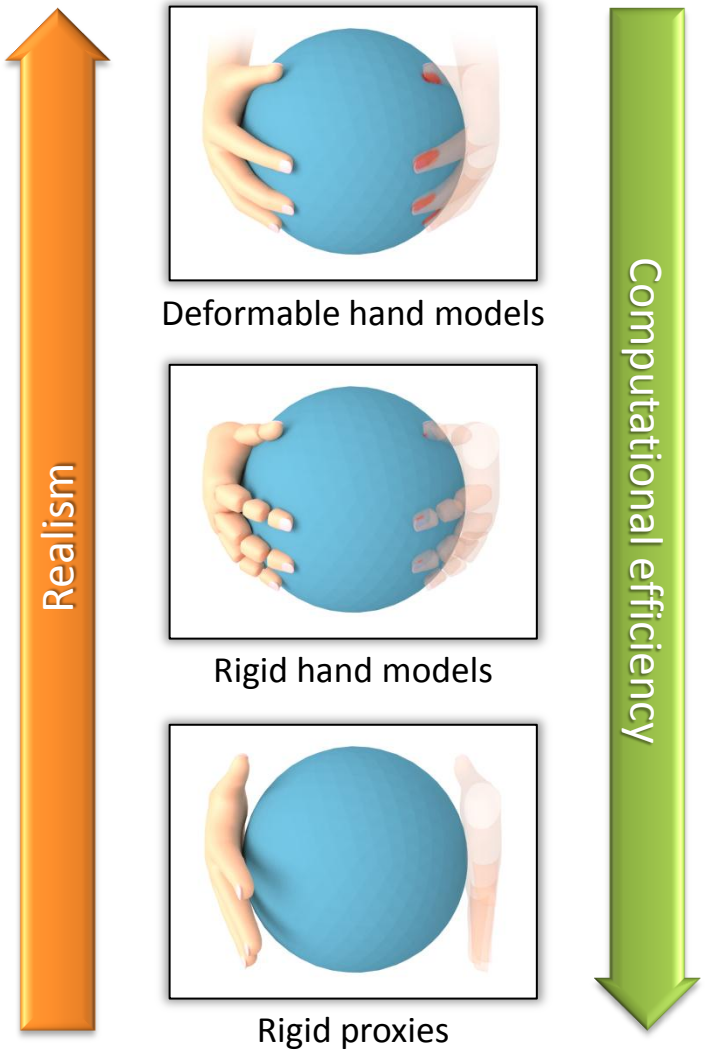
[Ullrich and Kuhlen, 2012]

[Faeth et al, 2008]

# Challenges of Bimanual Haptics



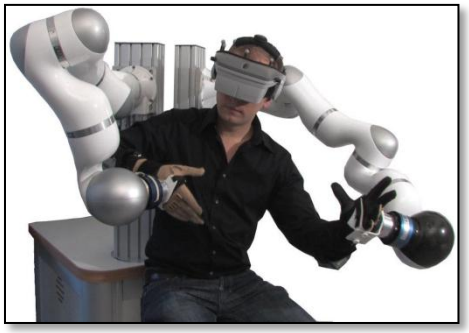
# Objective



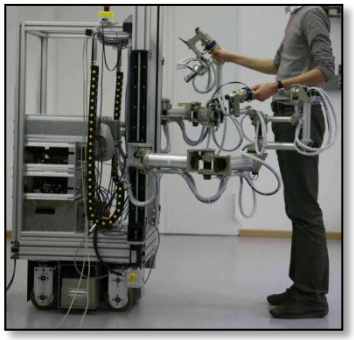

- <u>Objective:</u>
  Improving bimanual haptic interaction by enhancing:
  - Realism of interactions
  - Computational efficiency
- Three main axes:
  - Efficiency of soft hand models
  - Grasping with rigid models
  - Bimanual haptic interaction in VEs with rigid proxies

# Related Work – Hardware

- Bimanual haptic devices
  - Single-point grounded
  - Single-point mobile
  - Multi-finger body-based
  - Multi-finger grounded
- Summary:
  - Mostly symmetrical devices
  - Limited workspaces (+ interface collision)
  - Wide range of degrees of freedom (DOF)

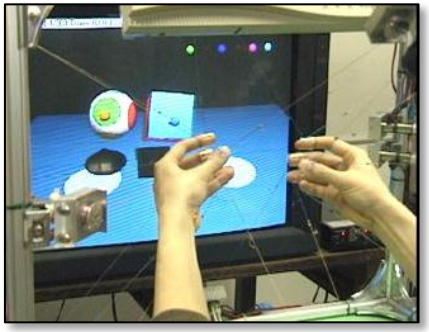


[Hulin *et al.*, 2008]



[Peer and Buss, 2008]

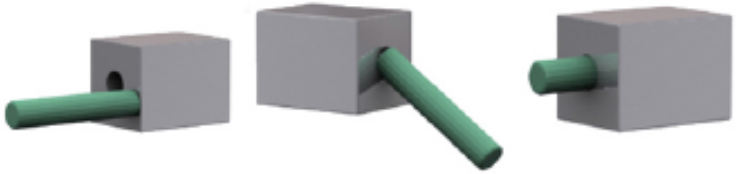
[Formaglio *et al.*, 2006]



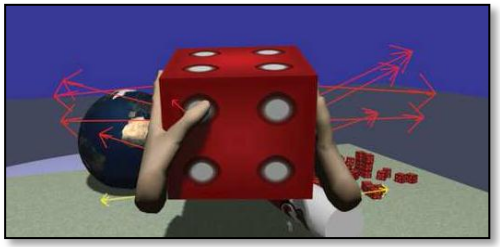
[Walairacht *et al.*, 2001]

# Related Work – Physical Models

- Several hand representations:
  - Point or rigid proxies
    [Zilles and Salisbury, 1995,
    Ruspini et al., 1997, Ortega et al., 2007]
  - Rigid hand models
    [Borst and Indugula, 2005, Kry and Pai, 2006,
    Ott et al., 2007, Jacobs et al., 2012]
  - Deformable hand models
    [Garre et al., 2011, Jacobs and Froehlich, 2011]

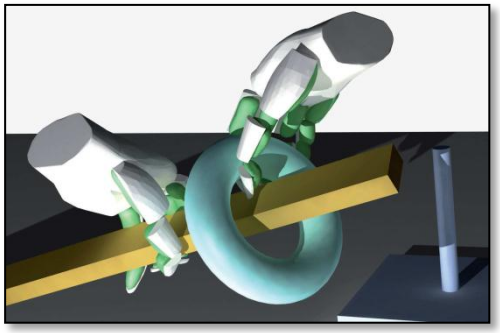


[Ortega *et al.*, 2007]



[Ott *et al.*, 2009]

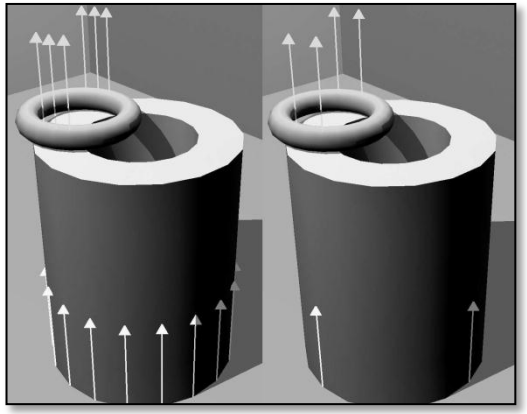
- Summary:
  - Rigid models: Efficient, **unrealistic contact, mostly unused for bimanual grasping**
  - Deformable models: More realistic contact, **very high cost with two hands**



[Jacobs and Froehlich, 2011]

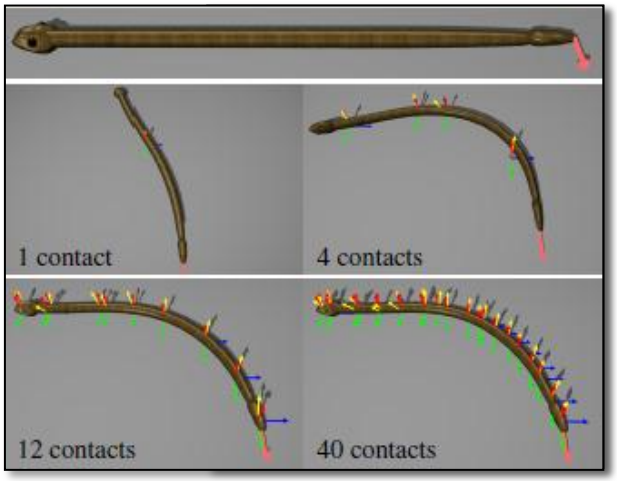
# Related Work – Contact Simulation

- Handling complex contact scenarios
  - Contact reduction methods
    [Moravanszky and Terdiman, 2004, Kim et al., 2003]
  - Separation of constraint sets
    [Miguel and Otaduy, 2011]
  - Volume-based contact constraints
    [Allard et al., 2010]



[Moravanszky and Terdiman, 2004]

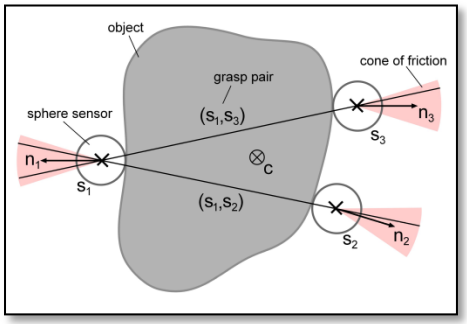
- Summary:
  - Rigid interaction: contact reduction well adapted
  - Soft interaction: still many constraints to solve (e.g. friction)



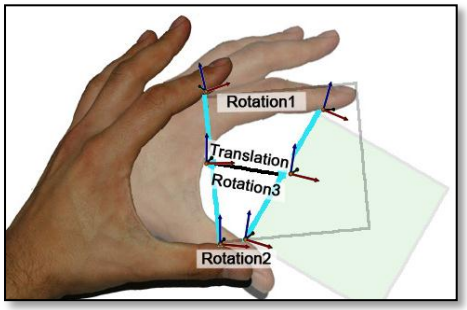

[Allard et al., 2010]

# Related Work – Grasping

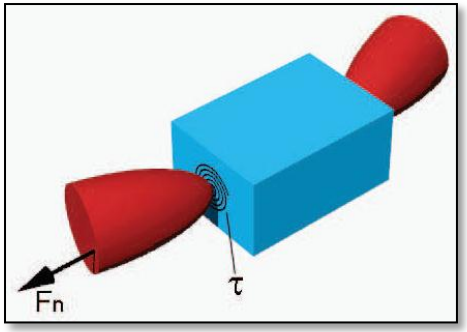
- Grasping detection methods
  - Distribution of contacts between phalanges
    [Zachmann and Rettig, 2001, Moehring and Froehlich, 2005]
  - Relative position of contacts
    [Holz et al., 2008, Moehring and Froehlich, 2010]
- Grasping techniques
  - Controlling object motions with hand motions
    [Holz et al., 2008, Moehring and Froehlich, 2005, 2010]
  - "Soft finger" models for torsional friction
    [Barbagli et al., 2004, Ciocarlie et al., 2007]
- Summary:
  - Physically approximate methods
  - No techniques for bimanual grasping




[Holz et al., 2008]

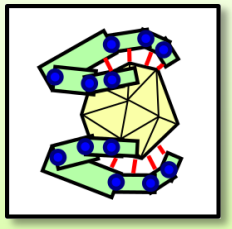



[Moehring and Froehlich, 2010]




[Barbagli *et al.*, 2004]

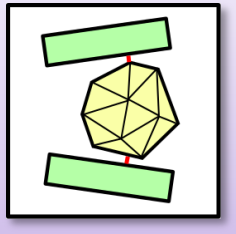
# Approach and Contributions



- Realistic contact
- Efficient simulation

- Many contacts to solve with deformable hand models

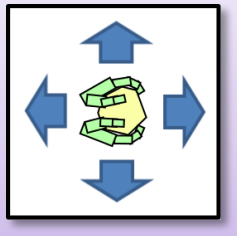
➢ **Novel contact constraints for grasping**



- Adapted hand models
- Stable grasping

- Rigid models have unrealistic contact

➢ **Rendering of contact surfaces with rigid models**



- Exploration while grasping
- Navigation in large VEs

- Challenging exploration of VEs while grasping

➢ **Interaction techniques for bimanual haptics**

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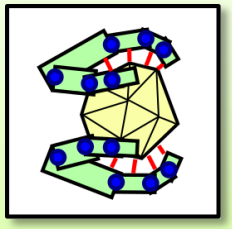

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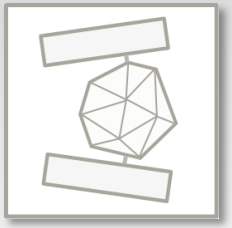

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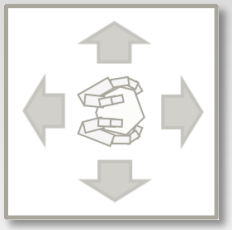

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- Exploration while grasping

- Challenging exploration of VEs while grasping

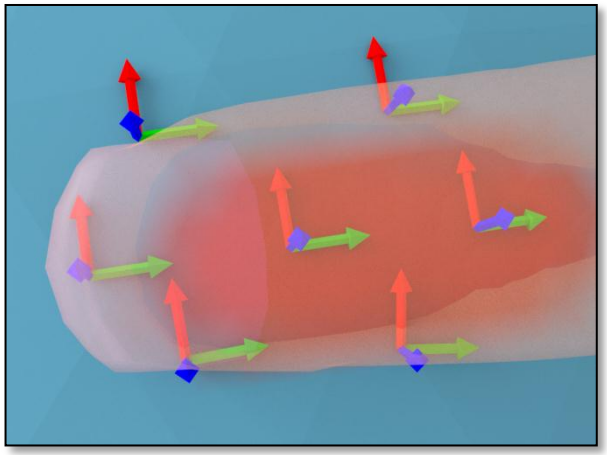
➢ **Interaction techniques for bimanual haptics**

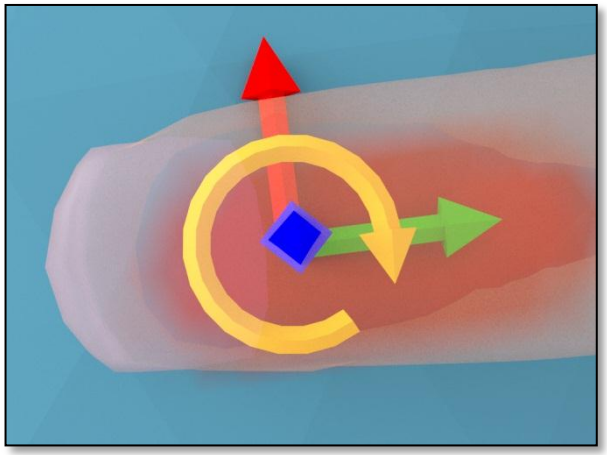
# Objectives

- <u>Objective:</u>
  Improving contact resolution with deformable hand models

- <u>Approach:</u>
  Reducing the number of contact constraints to be solved

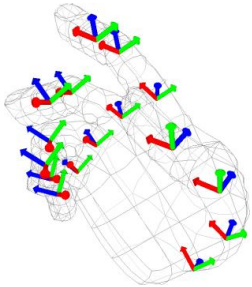
- <u>Requirements:</u>
  Retaining the benefits of a fine contact sampling:
  - Pressure distribution
  - Torsional friction



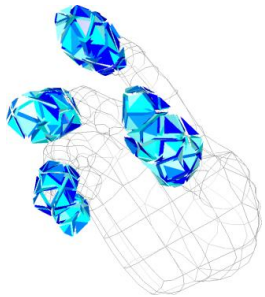


# Deformable Hand Model

Data glove (or scripted animations)



Articulated rigid body hand



FEM-based soft phalanges

Unilateral spring

Unilateral mapping

Bilateral spring

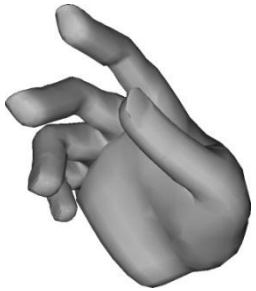
Bilateral mapping

| Joint | Angle |
|---|---|
| thumb1X | 0.1 |
| thumb1Z | 0.22 |
| thumb2 | 0.34 |
| thumb3 | 0.15 |
| index1X | 0.4 |
| index1Z | 0 |
| … | … |

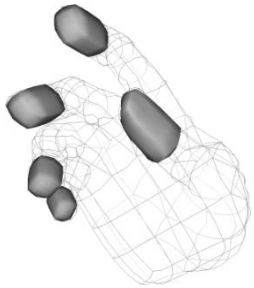
Tracked data

| Joint | Angle |
|---|---|
| thumb1X | 0.12 |
| thumb1Z | 0.25 |
| thumb2 | 0.34 |
| thumb3 | 0.14 |
| index1X | 0.35 |
| index1Z | 0 |
| … | … |

Reduced coordinates model



Visual model



Collision model

# System for Bodies in Contact

- Dynamics of a discretized body in the simulation:

$$\boldsymbol{M}\dot{\boldsymbol{v}} = \boldsymbol{f}(\boldsymbol{q}, \boldsymbol{v}) + \boldsymbol{f}_{\boldsymbol{ex}}$$

Mass matrix  Velocities  Internal forces  External forces

- Implicit Euler integration:

$$\left(\boldsymbol{M} - h\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{v}} - h^2\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{q}}\right) d\boldsymbol{v} = h\boldsymbol{f}(\boldsymbol{q_0}, \boldsymbol{v_0}) + h^2\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{q}}\boldsymbol{v_0} + h\boldsymbol{f}_{\boldsymbol{ex}}$$

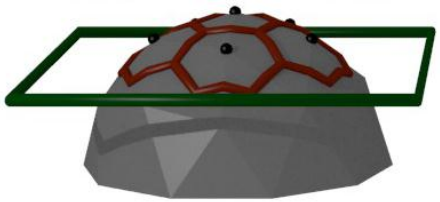
- Two bodies in contact:

$$\boldsymbol{A_1} d\boldsymbol{v_1} = \boldsymbol{b_1} + h\mathbb{H}_1^T\boldsymbol{\lambda}$$
$$\boldsymbol{A_2} d\boldsymbol{v_2} = \boldsymbol{b_2} + h\mathbb{H}_2^T\boldsymbol{\lambda}$$

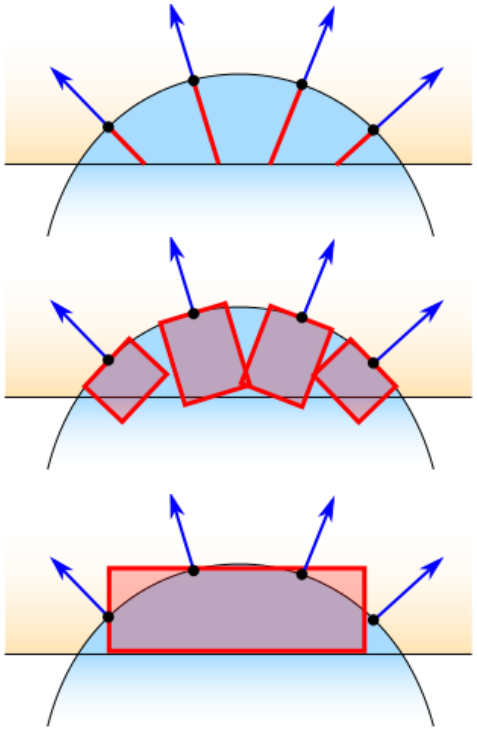
Matrix of constraint directions  Vector of constraint forces

# Volume-based Separation Constraints

- <u>Objective:</u>
  Building a single separation constraint



- <u>Principle:</u>
  Volume contact constraint per phalanx
  [Allard et al., 2010]



- <u>Implementation:</u>
  - Evaluation of areas $S_i$ from the geometry
  - Penetrations $\delta_{n,i}^{free}$ ➔ Volumes $V_i = S_i \delta_{n,i}^{free}$
  - Contact normals $\boldsymbol{n_i^T}$ ➔ Gradients $\boldsymbol{J_{V_i}} = S_i \boldsymbol{n_i^T}$
  - Volumes aggregated into a single constraint

# Volume-based Separation Constraints

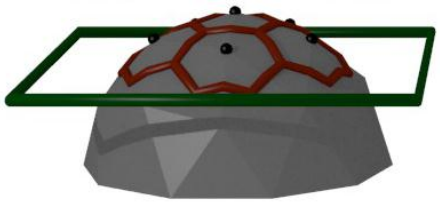
- For each contact point, contribution to the constraint matrix:

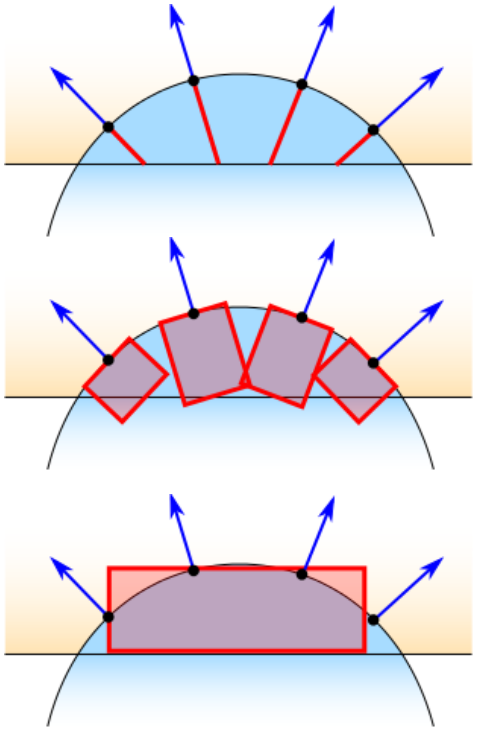
$$\mathbb{H}_{n,i} = S_i \boldsymbol{n_i^T}$$

- Formulation of non-penetration law:

$$\underbrace{\lambda_n \geq 0}_{\text{Constraint force repulsive or null}} \perp \underbrace{\sum \boldsymbol{J_{V_i}} (\dot{\boldsymbol{q}}_{\boldsymbol{0}} + \boldsymbol{\Delta}\dot{\boldsymbol{q}}) \leq 0}_{\text{Penetration volume must not increase}}$$

- In position, removal of the penetration





# Non-uniform Pressure Distribution

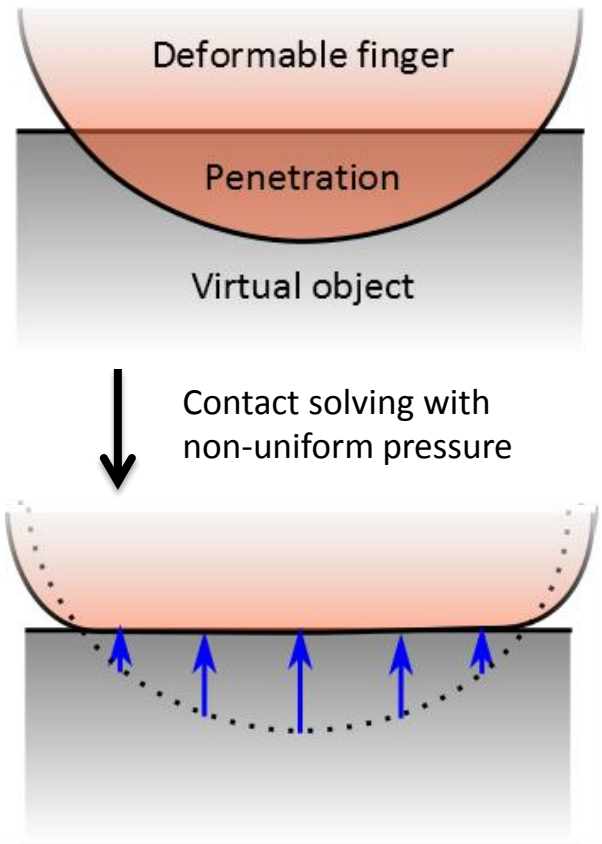
- <u>Objective:</u>
  Ensuring higher constraint forces for higher penetrations

- <u>Principle:</u>
  Weighting each contact contribution in the constraint matrix

$$\mathbb{H}_{n,i} = w_i S_i \boldsymbol{n_i^T}$$

- <u>Implementation:</u>
  Weights proportional to penetration

$$w_i = \delta_{n,j}^{free} \Big/ \left( \sum \delta_{n,j}^{free} / n_j \right)$$



# Aggregate Friction Constraints

- <u>Objective:</u>
  One set of constraints for friction

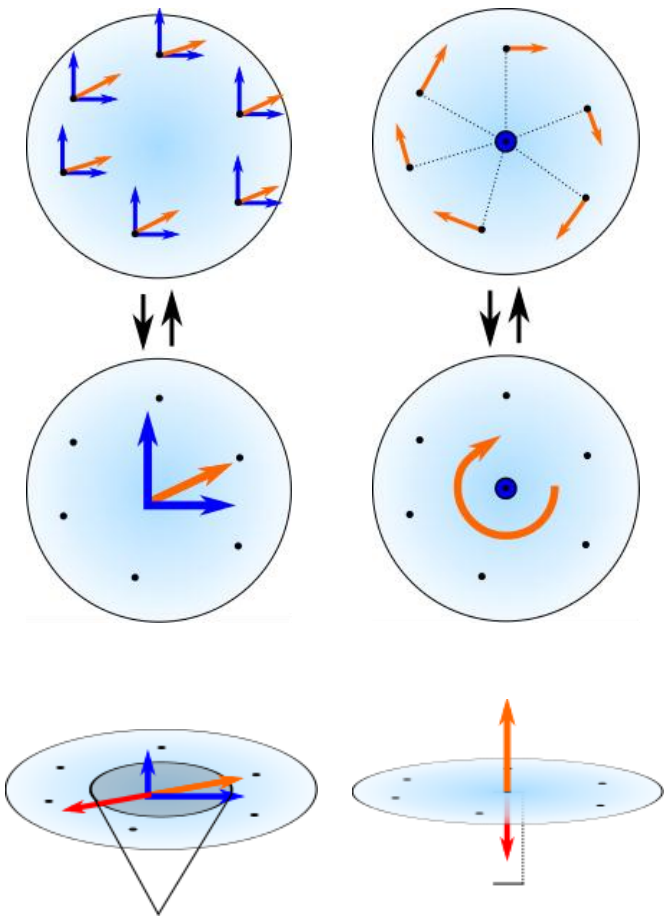
- <u>Principle:</u>
  2 tangential, 1 torsional [Contensou, 1963]

- <u>Implementation:</u>
  - Admissible values computed from $\Phi$
    [Leine and Glocker, 2003]

$$\Phi = \sum_i \frac{S_i}{S} \mu \lambda_n \|v_s\|$$

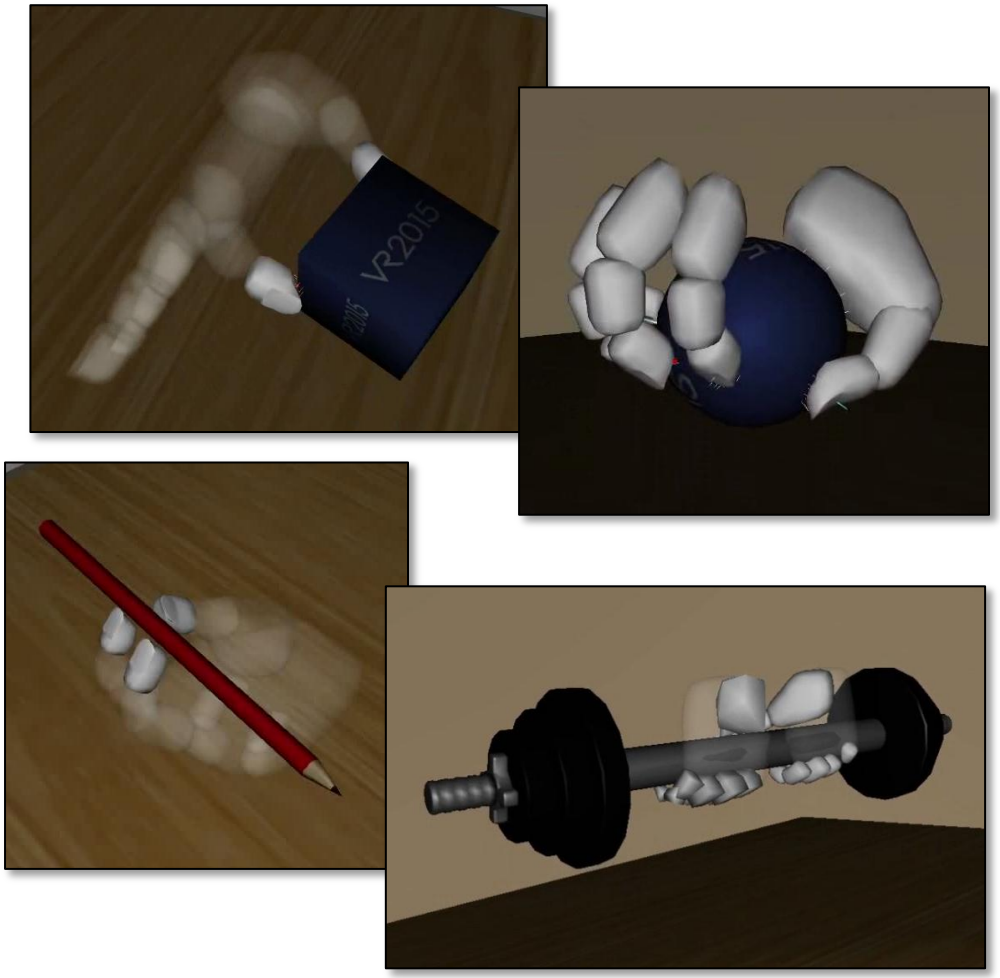
with $v_s$ sliding velocity at contact points $i$

  - Tangential/torsional sticking when friction forces/torques within values



# Results - Use cases

- Grasping a cube from the edges
- Full grasp of a rigid ball
- Spinning a pencil
- Real time interaction with a soft ball using a data glove
- Bimanual dumbbell lifting



# Results - Performance

- Implementation: SOFA framework [Faure et al., 2012]
- With 176 contacts:
  - Constraints / 10
  - Constraint solving time / 4
  - Simulation time - 60%
- In bimanual scenario:
  - Constraint solving time / 2
  - Simulation time - 26%

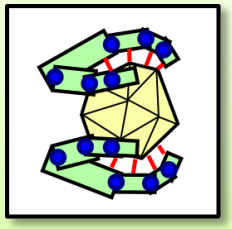
| Scenario | Phalanges | Contacts | Constraints | |
|---|---|---|---|---|
| | | | Point | Aggr. |
| Rigid ball | 15 | 27 | 81 | 23 |
| | | **176** | **528** | **51** |
| Dumbbell | 30 | **86** | **251** | **96** |
| Pen spinning | 3 | 13 | 37 | 12 |
| Edge grasping | 2 | 12 | 37 | 8 |
| | | 21 | 65 | 8 |

| Scenario | Constraint solving (ms) | | Total time (ms) | |
|---|---|---|---|---|
| | Point | Aggr. | Point | Aggr. |
| Rigid ball | 24,73 | 9,44 | 59,98 | 45,81 |
| | **223,69** | **54,75** | **262,13** | **93,63** |
| Dumbbell | **130,45** | **68,45** | **201,86** | **147,03** |
| Pen spinning | 4,2 | 2,32 | 13,88 | 12,19 |
| Edge grasping | 9,64 | 2,23 | 17,64 | 10,22 |
| | 23,01 | 3,45 | 31,17 | 11,8 |

# Conclusion

- Novel constraint formulation for soft finger contact **minimizes the number of constraints** per phalanx
- Weighting method to **retain pressure distribution** over the surface
- Coulomb-Contensou friction law to maintain **torsional friction without additional constraints**
- **Real time grasping of objects** with deformable hand models

# Approach and Contributions



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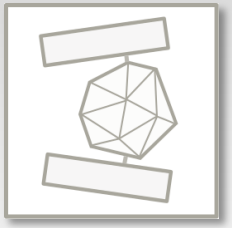
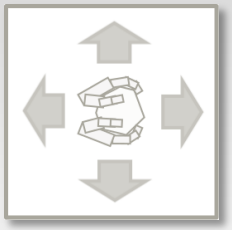


- Adapted hand models
- Stable grasping

- Rigid models have unrealistic contact

➢ **Rendering of contact surfaces with rigid models**



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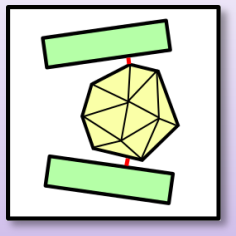

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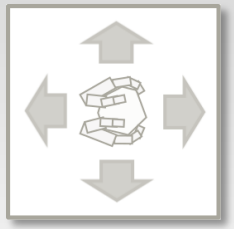


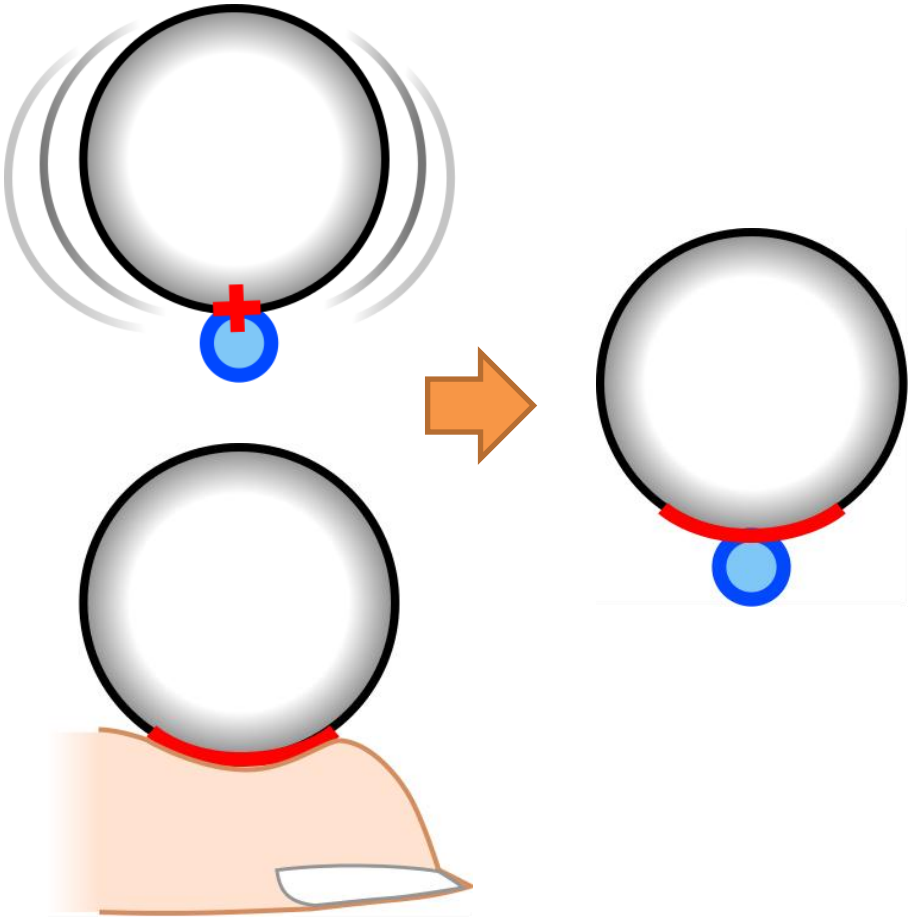
- Navigation in large VEs
- Exploration while grasping

- Challenging exploration of VEs while grasping

➢ **Interaction techniques for bimanual haptics**

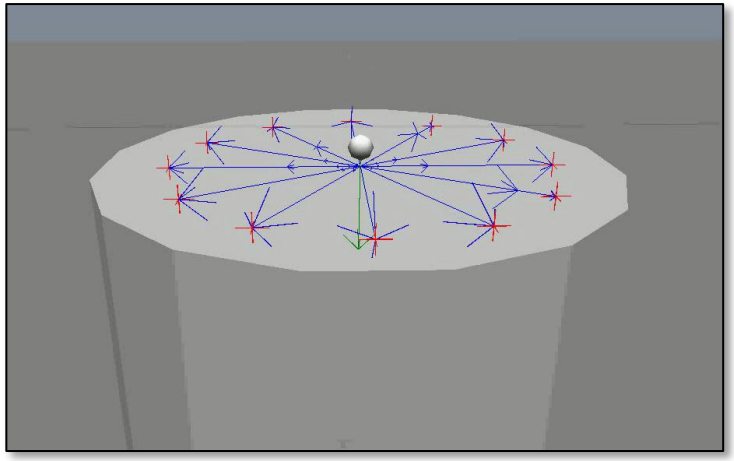
# Objectives

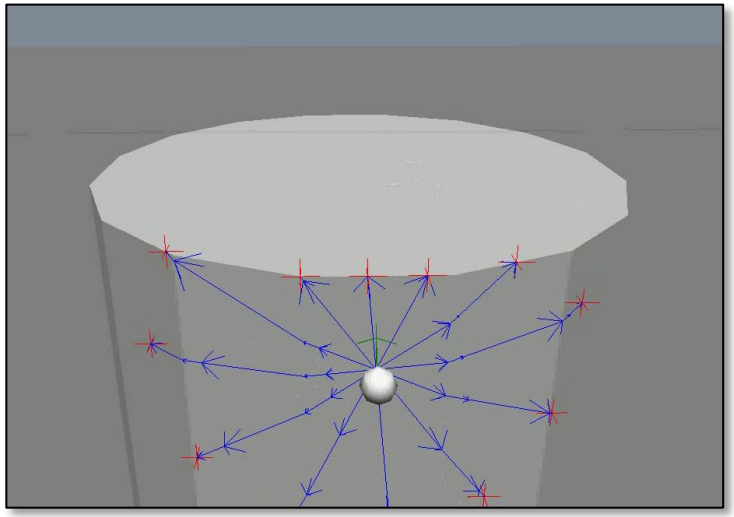
- <u>Objective:</u>
  More efficient contact compared to:
  - Rigid interaction:
    - \+ Fast computation
    - \- No surface
  - Soft body interaction:
    - \+ Finger deformation
    - \- Slow soft body computation
- <u>Approach:</u>
  Heuristic method to render contact surfaces



# God-finger Method

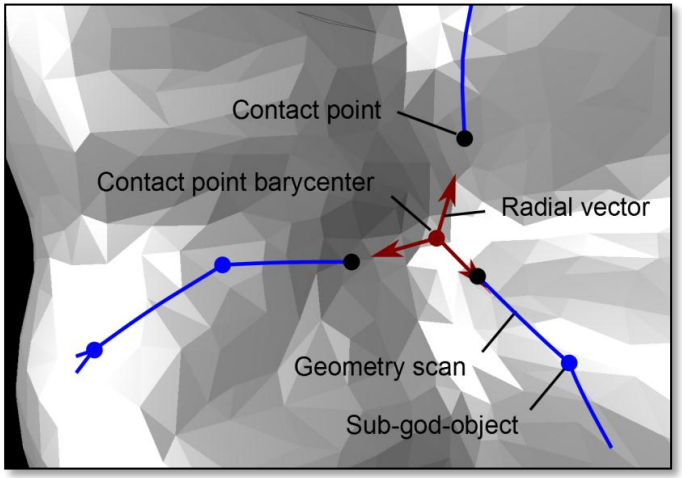
- Propagation of a contact surface from an initial contact point
- Two main steps:
  - Generation of a fingerprint
  - Fitting of the surface on the object geometry
- Contact surface described by *sub-god-objects*

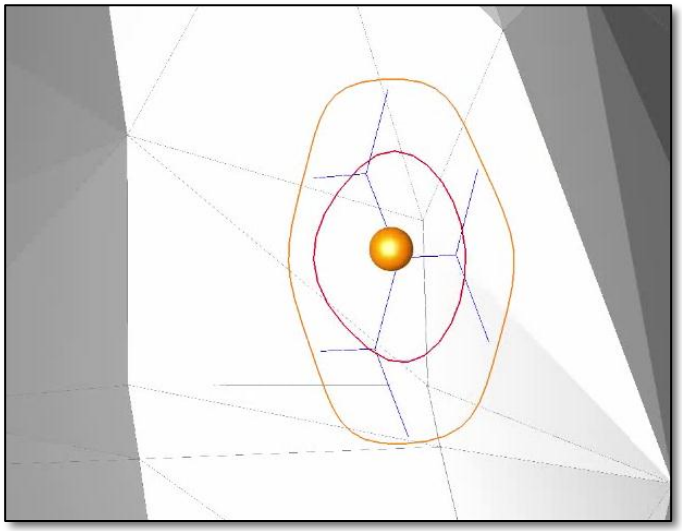




# Fingerprint Generation

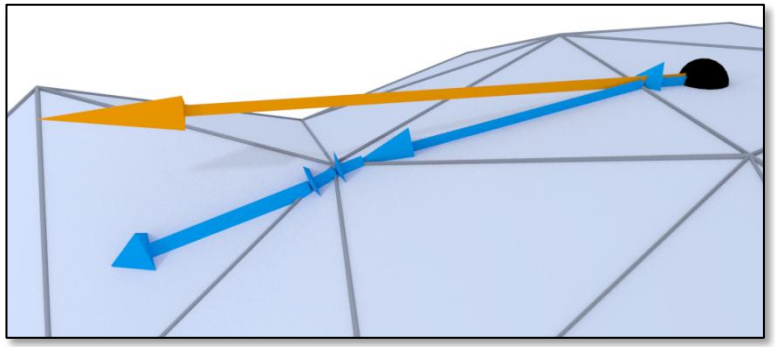
- <u>Objective:</u>
  Guide for the propagation
- <u>Principle:</u>
  Generation of *radial vectors* from the initial contact
- <u>Implementation:</u>
  - With multiple contacts, generation from the centroid
  - Radial tree for uniform distribution
  - Elliptic surface for 6DOF interfaces

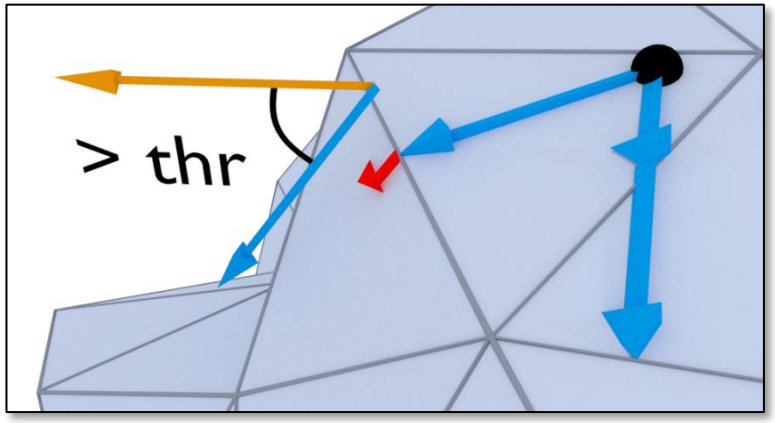


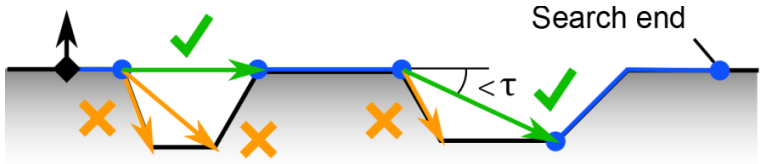



# Local Geometry Scan

- <u>Objective:</u>
  Propagating on the surface
- <u>Principle:</u>
  Scan of the local geometry following the *radial vectors*
- <u>Implementation:</u>
  - The scan stops with:
    - Length of the radial vector
    - Sharp edges
    - Normals exceeding friction cone
  - For rough surfaces, keep scanning after sharp edges

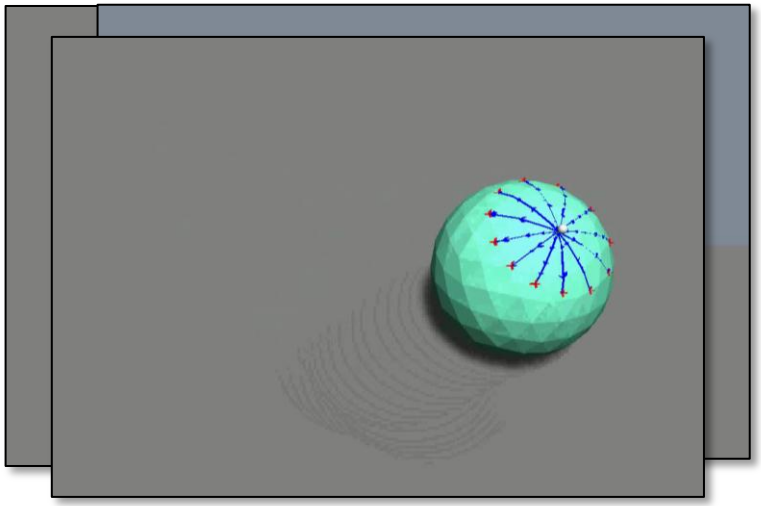


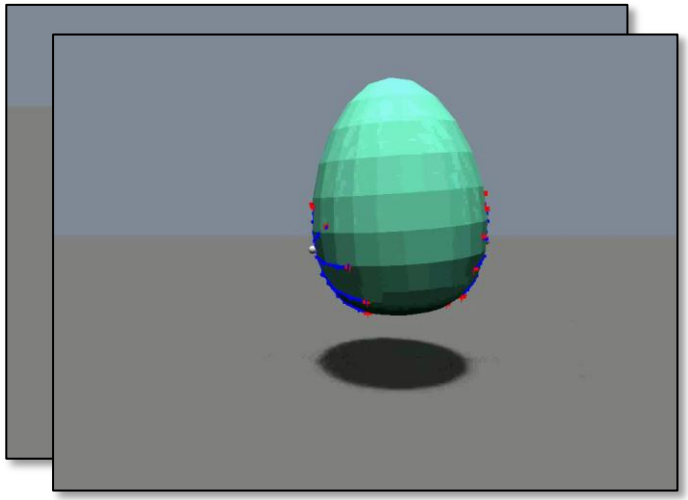


# Results

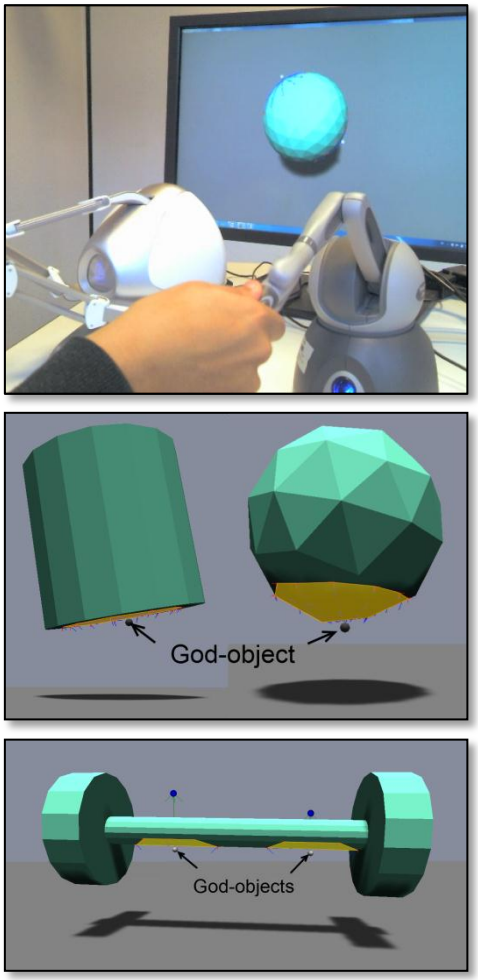
- Implementation:
  Havok Physics
- Simulation rate: 1000 Hz
- Unimanual manipulation
  - Better control of rolling
  - Possibility of lifting objects
- Bimanual manipulation
  - Better control around the grasping axis





# Conclusion

- *God-finger* method: **rendering of finger pad-like contact surfaces** from point or rigid contacts
- **Stabilization of contact and bimanual grasps** with better constraining of the rotation of virtual objects
- **Low cost** allowing for haptic rates

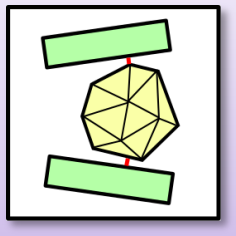


# Approach and Contributions

- Realistic contact
- Efficient simulation

- Many contacts to solve with deformable hand models

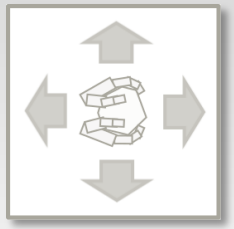
➢ **Novel contact constraints for grasping**



- Adapted hand models
- Stable grasping

- Rigid models have unrealistic contact

➢ **Rendering of contact surfaces with rigid models**



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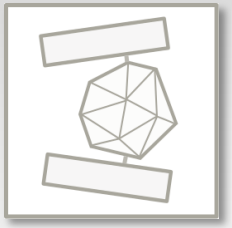

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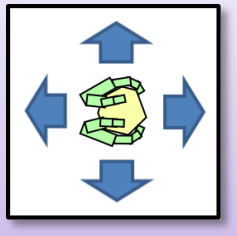
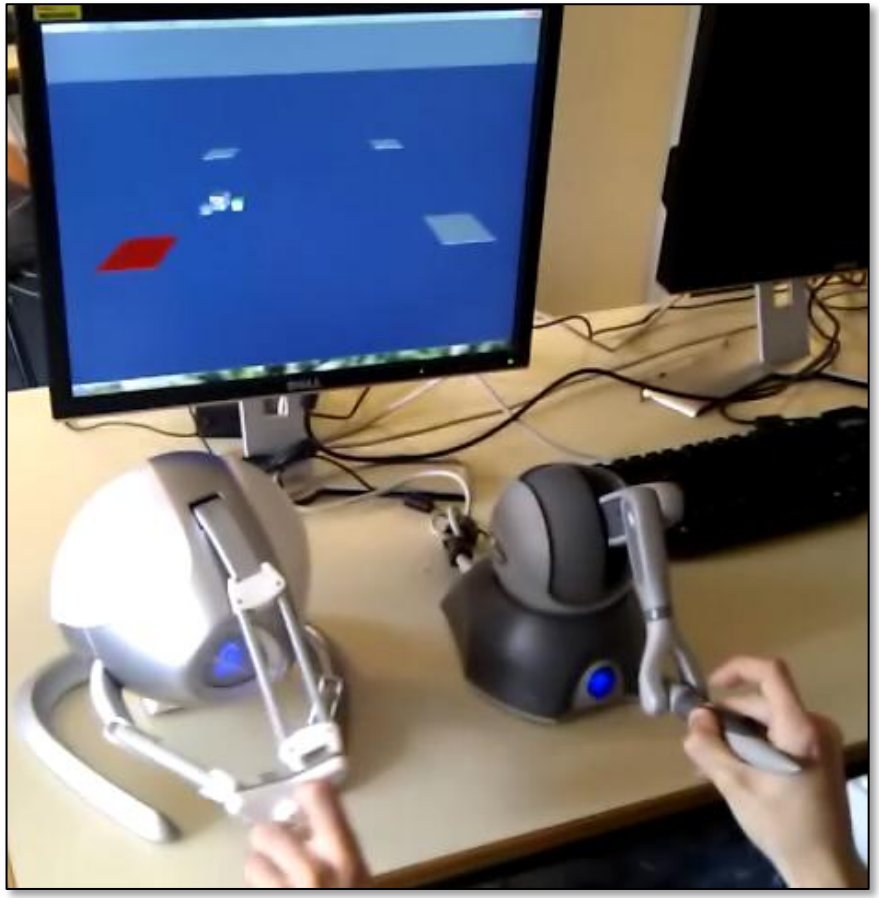


- Navigation in large VEs
- Exploration while grasping

- Challenging exploration of VEs while grasping
- ➢ **Interaction techniques for bimanual haptics**

# Objectives

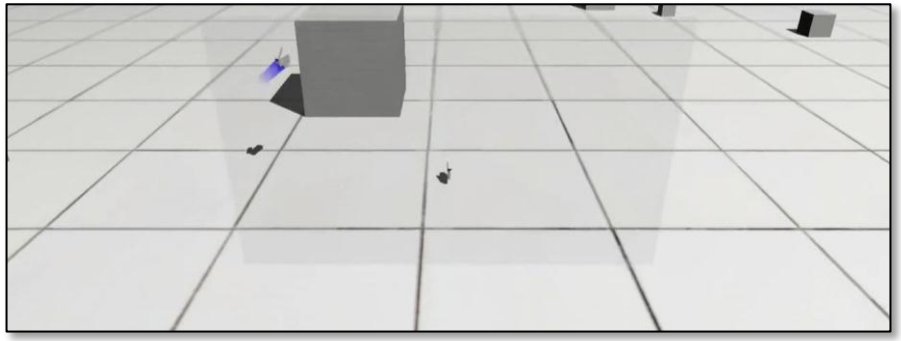
- Solving main issues with bimanual haptic interaction using single-point devices
  - Exploration of VEs with limited workspaces
  - Handling of virtual objects with simple rigid proxies
  - Simultaneous exploration and manipulation



# Double Bubble

- <u>Objective:</u>
  Exploration of VEs with two haptic devices
- <u>Principle:</u>
  Position/rate control scheme for each *bubble*

  [Dominjon et al., 2005]
- <u>Implementation:</u>
  - Non-spherical workspaces
  - Invisible plane to keep the hands from crossing

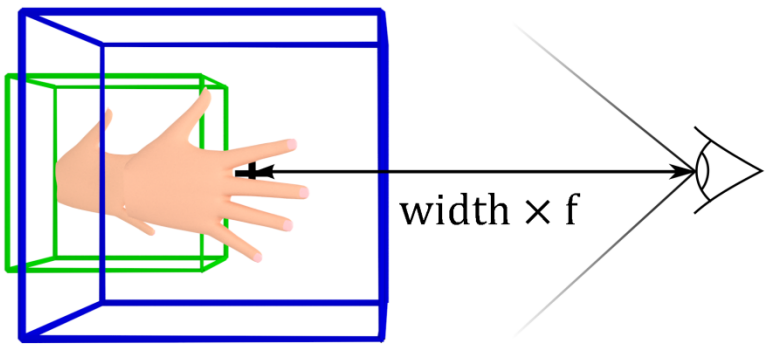


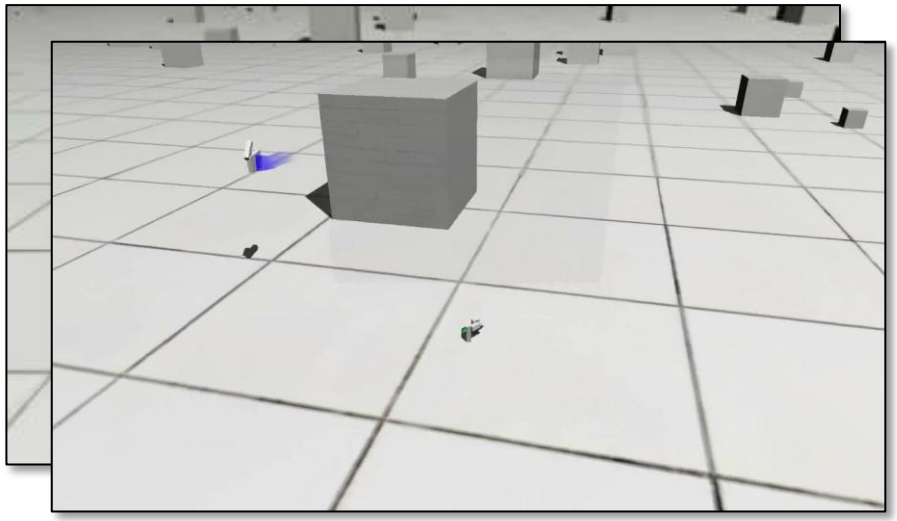
# Viewport Adaptation

- <u>Objective:</u>
  Keeping the proxies in the field of view

- <u>Principle:</u>
  Viewpoint adaptation

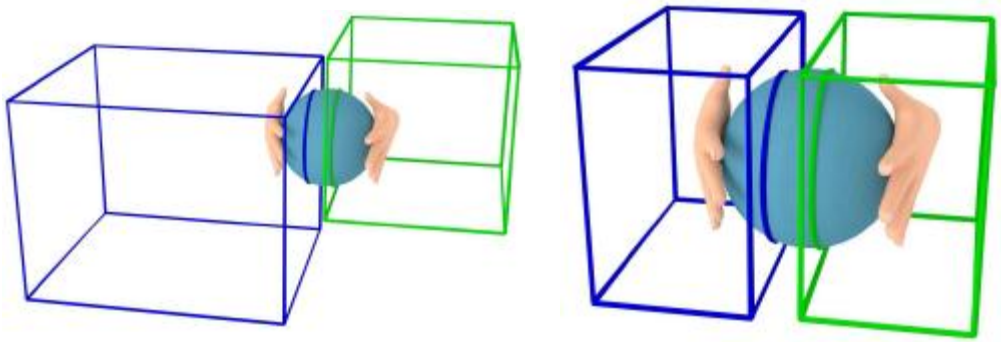
- <u>Implementation:</u>
  - Translation: adaptation to the *bubble* positions and widths
  - Rotation: Separation plane as a “revolving door”

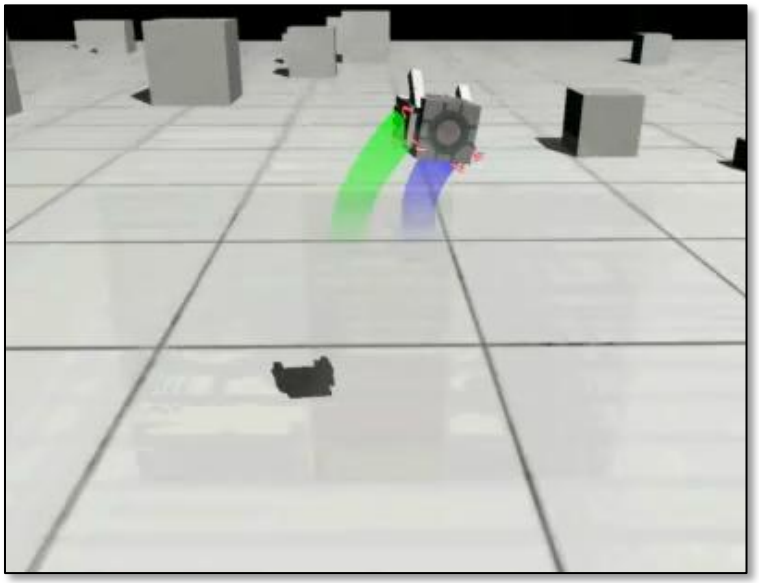


# Joint Control

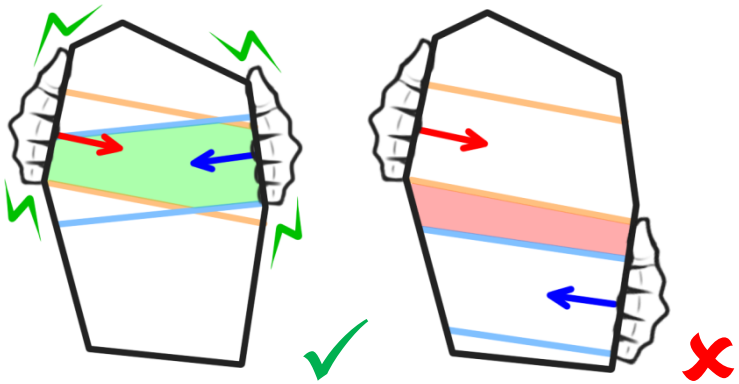
- <u>Objective:</u>
  Facilitating grasping with *bubbles*
- <u>Principle:</u>
  - Same bubble size
  - Same rate control velocities
- <u>Implementation:</u>
  - Intersection of *bubbles*
  - Average of velocities

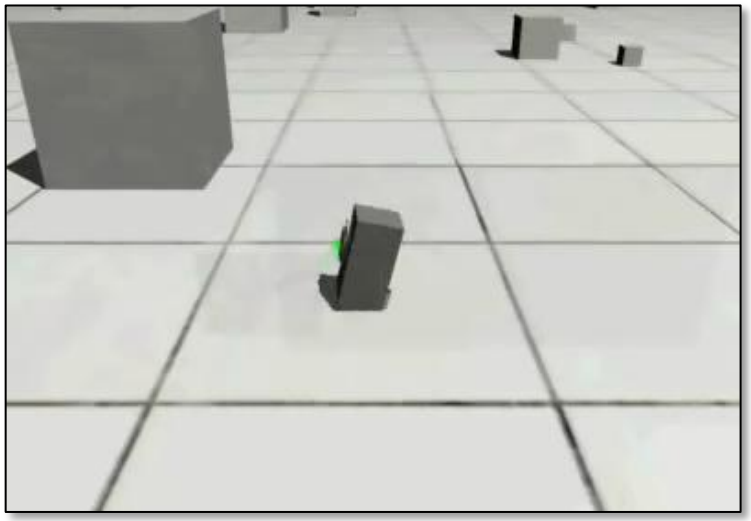




# Grasping Detection

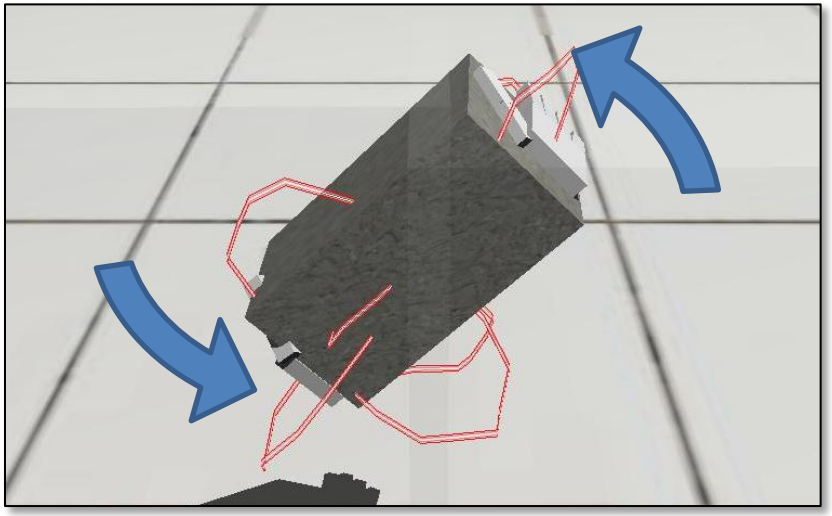
- <u>Objective:</u>
  Detect grasping attempts
- <u>Principle:</u>
  Detection based on:
  - Forces applied on the object
  - Relative position of the hands
- <u>Implementation:</u>
  - Force threshold on contacts
  - Ray casts between both hands with a tolerance





# Magnetic Pinch

- <u>Objective:</u>
  Providing assistance to the user when grasping objects
- <u>Principle:</u>
  Visual and haptic effect of “magnetism” between hands and object
- <u>Implementation:</u>
  - Springs: softer, 3DOF
  - Constraints: harder, 6DOF

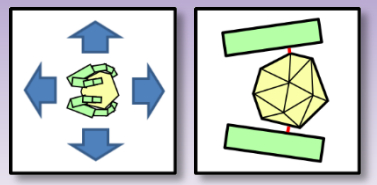


# Evaluation

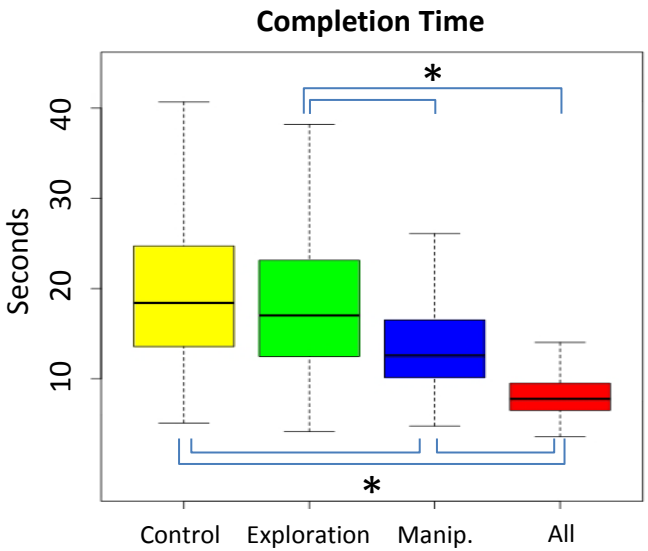
- Task: picking and carrying
- 4 conditions:
  - Control: *clutching* technique
  - Exploration: *double bubble*
  - Manipulation: *magnetic pinch*
  - All proposed techniques

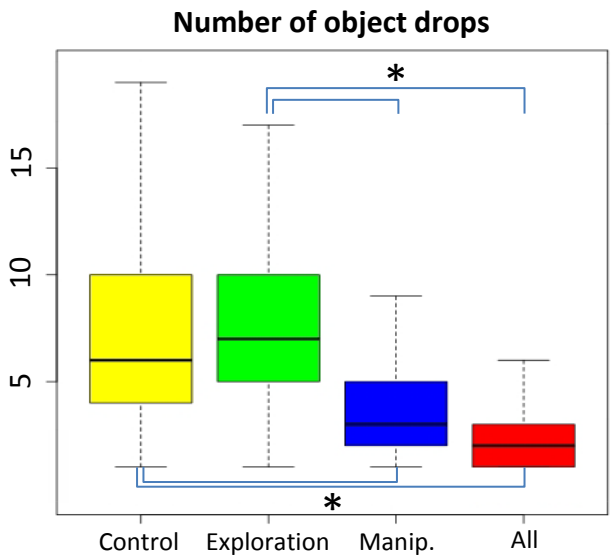
- 13 participants
- 4 conditions × 4 targets × 11 trials = 176 trials
- Collected data:
  Completion times, number of drops, subjective questionnaire

# Results



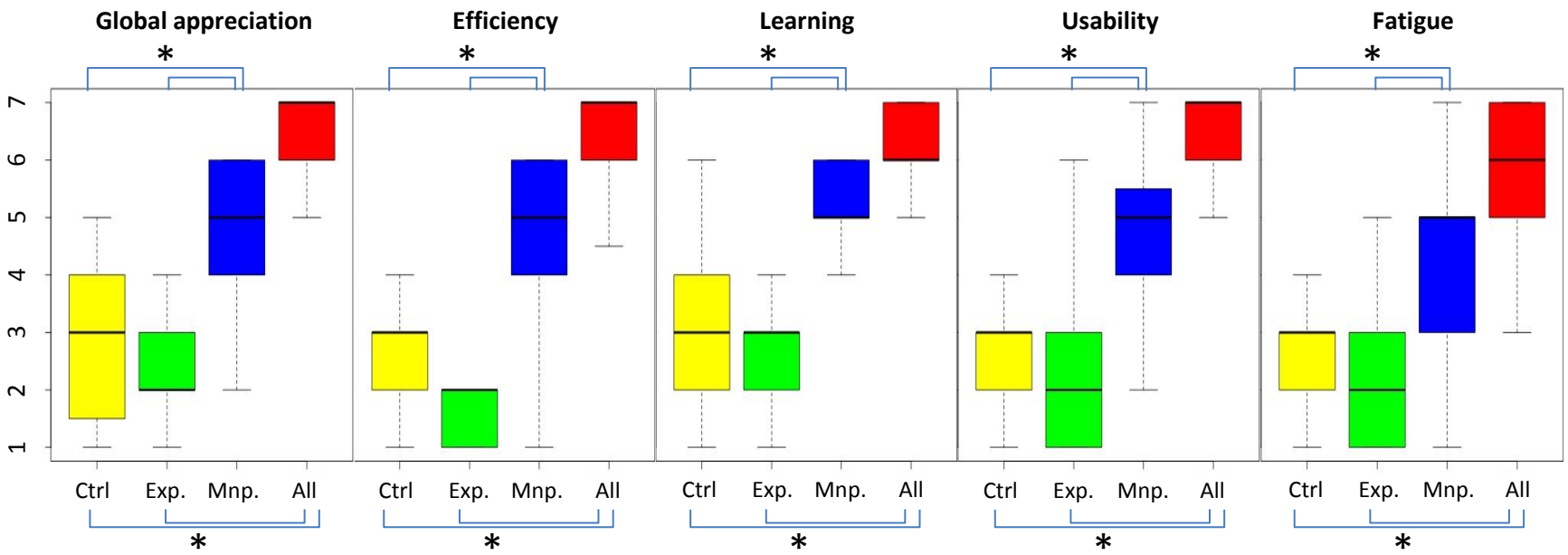
- Friedman test : significant effect of the techniques
- Completion times:
  - Manipulation-only improve over control and exploration-only
  - Further improvement with all techniques
- Object drops:
  - Improvement with both manipulation conditions



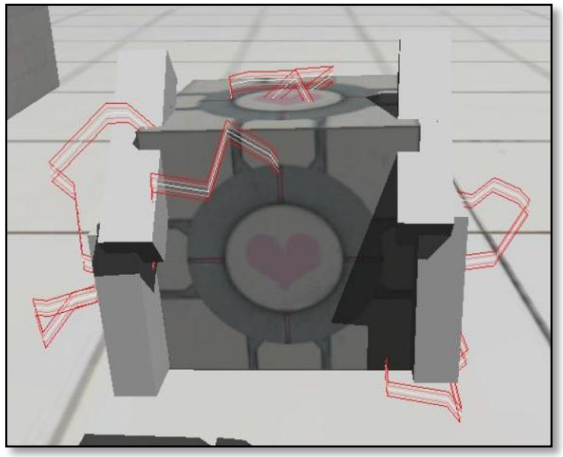
# Subjective Questionnaire

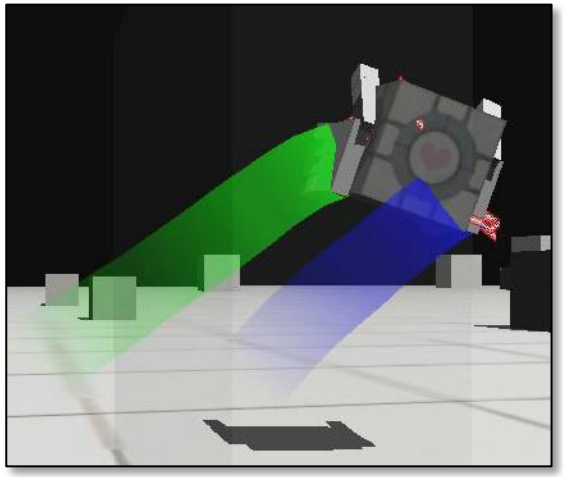
- The conditions with manipulation techniques were overall better appreciated by the participants
- The addition of the magnetic effect did not lead to significant changes in the Realism criterion



# Conclusion

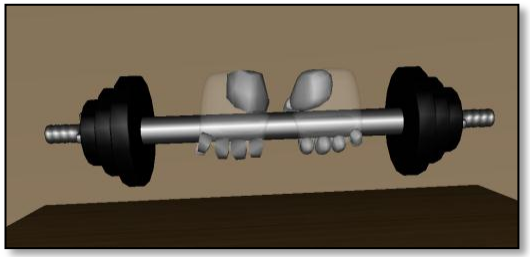
- *Double bubble* with viewport adaptation: **smooth bimanual exploration** of VEs
- J*oint control*: **easier grasping with the *double bubble***
- M*agnetic pinch*: **assistance** to the user when **manipulating objects**
- User experiment on carrying task: **faster completion, less drops, better user appreciation**

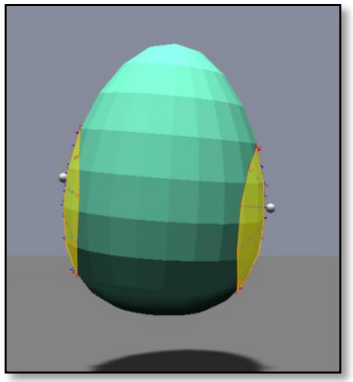


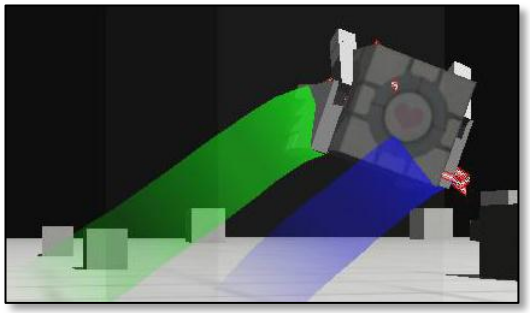


# Conclusion

- Objective: Improving interaction in VEs using two haptic devices
- Three main contributions:
  - Aggregate constraint method for improving contact resolution with deformable hands
  - Heuristic method for rendering of finger pad contact surfaces with point and rigid proxies
  - Novel interaction techniques for bimanual exploration in VEs and haptic manipulation with single-point haptic devices







# Perspectives

- Contact constraint formulation for soft hand grasping
  - Improving the hand model with the palm and non-linear deformation
  - Comparison against other contact reduction methods
- Rendering of finger pad contact surfaces
  - Generation of arbitrary-shaped surfaces (*e.g.* palm)
  - More realistic visual feedback (visual finger deformation, etc.)
- Interaction techniques for bimanual haptics
  - Adaptation for immersive interaction and multiple objects
  - Further evaluations on different tasks and between the variants
- Applications: virtual assembly, surgical training, rehabilitation

# Publications

- Journal papers
  - **A. Talvas**, M. Marchal, A. Lécuyer. A Survey on Bimanual Haptic Interaction. *IEEE ToH*, 99:285–300, 2014.
  - **A. Talvas**, M. Marchal, C. Duriez, M. A. Otaduy. Aggregate Constraints for Virtual Manipulation with Soft Fingers. *IEEE TVCG*, conditionally accepted.
- Book chapters
  - **A. Talvas**, M. Marchal, G. Cirio, A. Lécuyer. *Multi-finger Haptic Interaction*, chapter 3D Interaction Techniques for Bimanual Haptics in Virtual Environments, pages 31–53. Springer Series on Touch and Haptic Systems, 2013.
- International conferences
  - **A. Talvas**, M. Marchal, C. Nicolas, G. Cirio, M. Emily, A. Lécuyer. Novel Interactive Techniques for Bimanual Manipulation of 3D Objects with Two 3DOF Haptic Interfaces. In *Proc. of Eurohaptics*, pages 552–563, 2012.
  - **A. Talvas**, M. Marchal, A. Lécuyer. The God-finger Method for Improving 3D Interaction with Virtual Objects through Simulation of Contact Area. In *Proc. Of IEEE 3DUI*, pages 111–114, 2013.
  - M. Achibet, A. Girard, **A. Talvas**, M. Marchal, A. Lécuyer. Elastic-Arm: Human-Scale Elastic Feedback for Augmenting Interaction and Perception in Virtual Environments. *IEEE VR*, 2015, accepted.
- National conferences
  - **A. Talvas**, M. Marchal, C. Nicolas, G. Cirio, M. Emily, A. Lécuyer. Novel Interactive Techniques for Bimanual Haptic Manipulation in Virtual Environments. In *Proc. of the 7th annual conference of the AFRV*, 2012.

# Thank you for your attention

## Bimanual Haptic Interaction with Virtual Environments