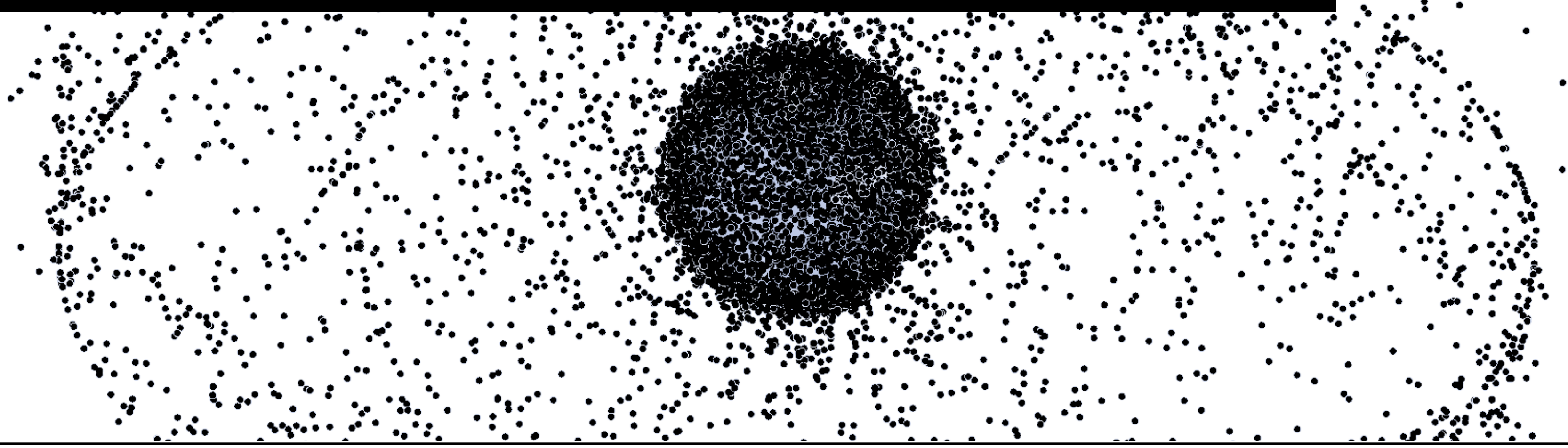
Rigid-Body Simulation With Gaming Engines

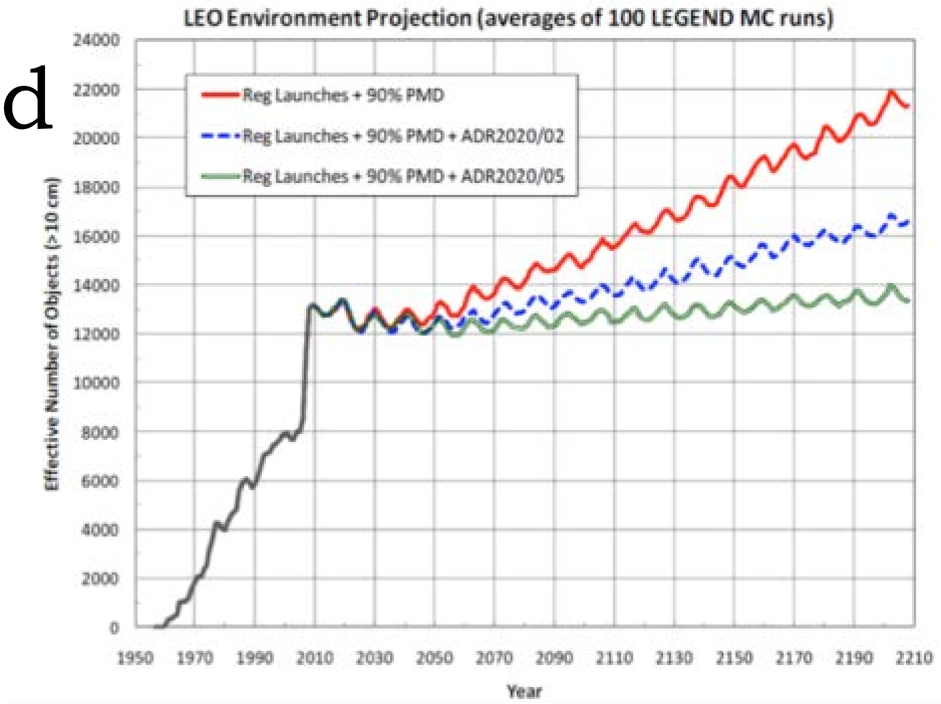
A study on the usability of gaming industry software for simulating engineering problems



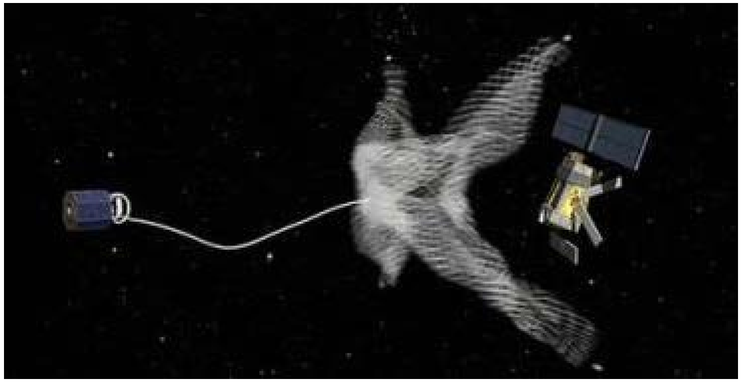
TU Delft esa

Project background

- Exponential increase in orbital debris (Kessler syndrome)
- Stabilize by de-orbiting several large objects per year
- Capture satellites with nets
- Simulations required for development
- Traditional tools expensive and not user-friendly



Source: J.C. Liou, NASA



Source: ESA

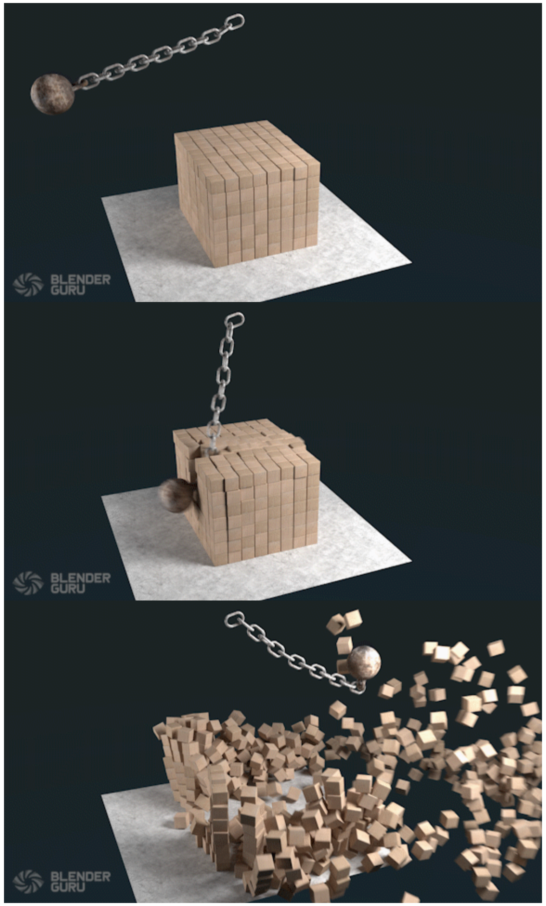
Project background

- Video games include complex physics

Physics engine ⟷ Video game ⟷ 

- Suspected advantages
  - Flexible & free
  - Ease of use
  - Fast

- Net simulations with **Bullet** physics engine & 3D-modelling tool **Blender**

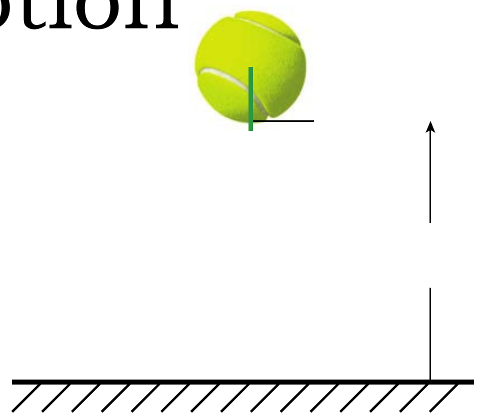


Research objectives

- Assess gaming engine ***accuracy***
- Verify suspected ***advantages***
- Identify possible engineering ***applications***
- Suggest ***implementation*** of an engineering tool

Theoretical Analysis

Time integration of free motion



- Newton-Euler equations

$$\sum F = m\ddot{q}$$

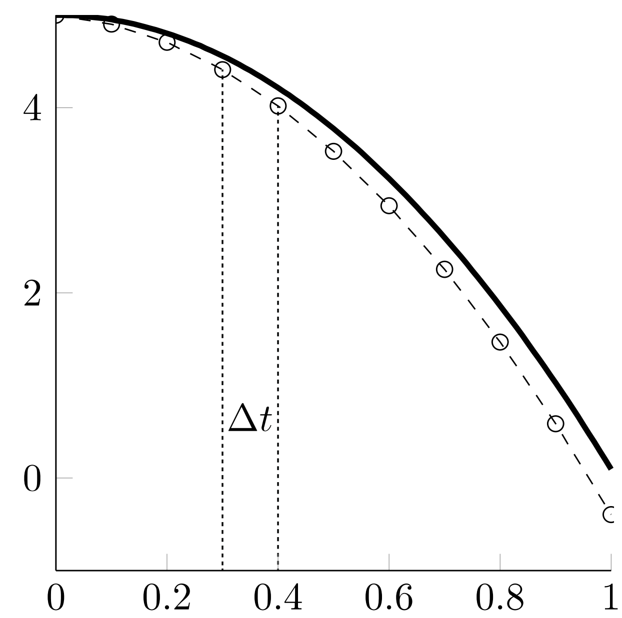
- Forward Euler

$$\dot{q}^{n+1} = \dot{q}^{n} + \Delta t \ddot{q}^{n}$$
$$q^{n+1} = q^{n} + \Delta t \dot{q}^{n}$$

- Semi-implicit Euler

$$\dot{q}^{n+1} = \dot{q}^{n} + \Delta t \ddot{q}^{n}$$
$$q^{n+1} = q^{n} + \Delta t \dot{q}^{n+1}$$

- Symplectic integrator (conserves energy)



Contact model

- Rigid-bodies and geometry simplified to contact points
- Penalty based method (Adams)

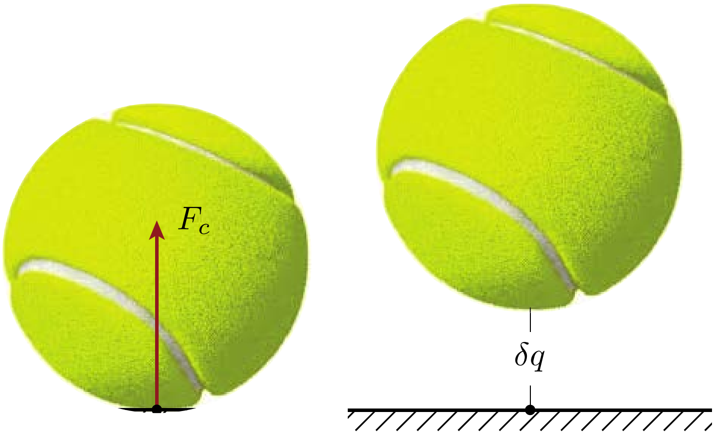
$$F_c = f(\delta q, \delta \dot{q}) \geq 0$$

- Constraint based method (Bullet)

$$\text{find} \quad F_c \geq 0 \quad \text{such that} \quad \delta \dot{q} \geq 0$$

- Complementarity condition

$$F_c \delta \dot{q} = 0$$



The complementarity problem

- Including friction & joints yields linear complementarity problem (LCP)

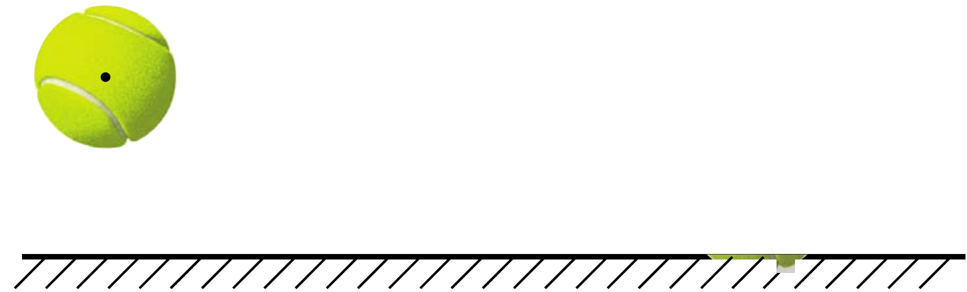
$$\underbrace{\begin{bmatrix} \boldsymbol{M} & -\boldsymbol{J}_e^T & -\boldsymbol{J}_c^T & -\boldsymbol{D} & 0 \\ \boldsymbol{J}_e & 0 & 0 & 0 & 0 \\ \boldsymbol{J}_c & 0 & 0 & 0 & 0 \\ \boldsymbol{D}^T & 0 & 0 & 0 & \boldsymbol{E} \\ 0 & 0 & \mu & -\boldsymbol{E}^T & 0 \end{bmatrix}}_{\boldsymbol{A}} \underbrace{\begin{bmatrix} \boldsymbol{u}^{n+1} \\ \lambda_e \\ \lambda_c \\ \boldsymbol{\lambda}_f \\ \gamma \end{bmatrix}}_{\boldsymbol{x}} - \underbrace{\begin{bmatrix} \boldsymbol{M}\boldsymbol{u}^n + h\boldsymbol{f}_{\text{ext}} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}}_{\boldsymbol{b}} = \underbrace{\begin{bmatrix} 0 \\ 0 \\ a \\ \boldsymbol{\sigma} \\ \zeta \end{bmatrix}}_{\boldsymbol{w}}$$

$$\begin{bmatrix} a \\ \boldsymbol{\sigma} \\ \zeta \end{bmatrix} \geq 0 \quad , \quad \begin{bmatrix} \lambda_c \\ \boldsymbol{\lambda}_f \\ \gamma \end{bmatrix} \geq 0 \quad , \quad \begin{bmatrix} a \\ \boldsymbol{\sigma} \\ \zeta \end{bmatrix}^T \begin{bmatrix} \lambda_c \\ \boldsymbol{\lambda}_f \\ \gamma \end{bmatrix} \geq 0$$

- Solved at every time-step of the simulation
- Iterative solvers

Inaccurate behavior

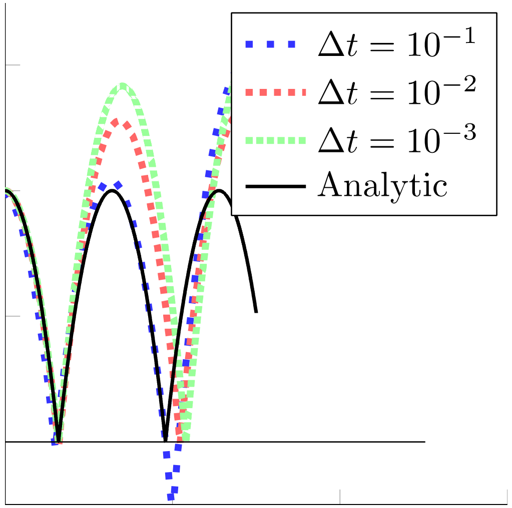
Constraint stabilization & elastic collisions



- Penetration errors
- Baumgarte stabilization

$$\delta \dot{q} \geq 0$$

$$\delta \dot{q} \geq -\frac{k_{\text{erp}}}{\Delta t} \delta q$$



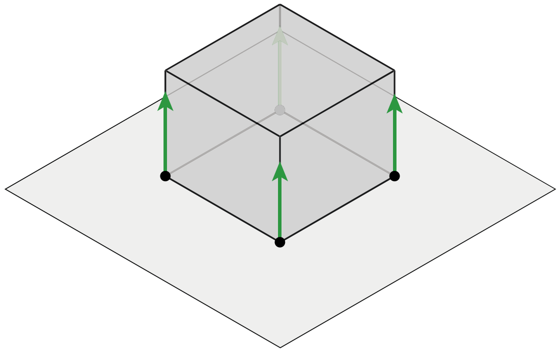
- Pseudo random energy creation in collisions
- No convergence

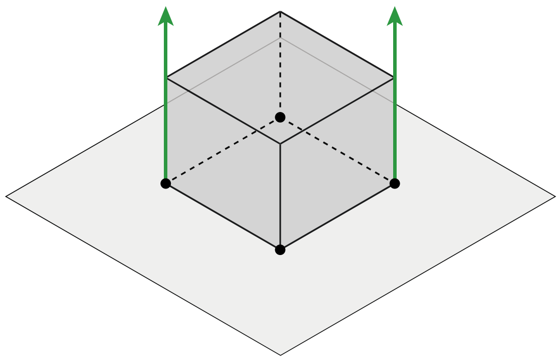
Inaccurate behavior

MNCP solver convergence & uniqueness

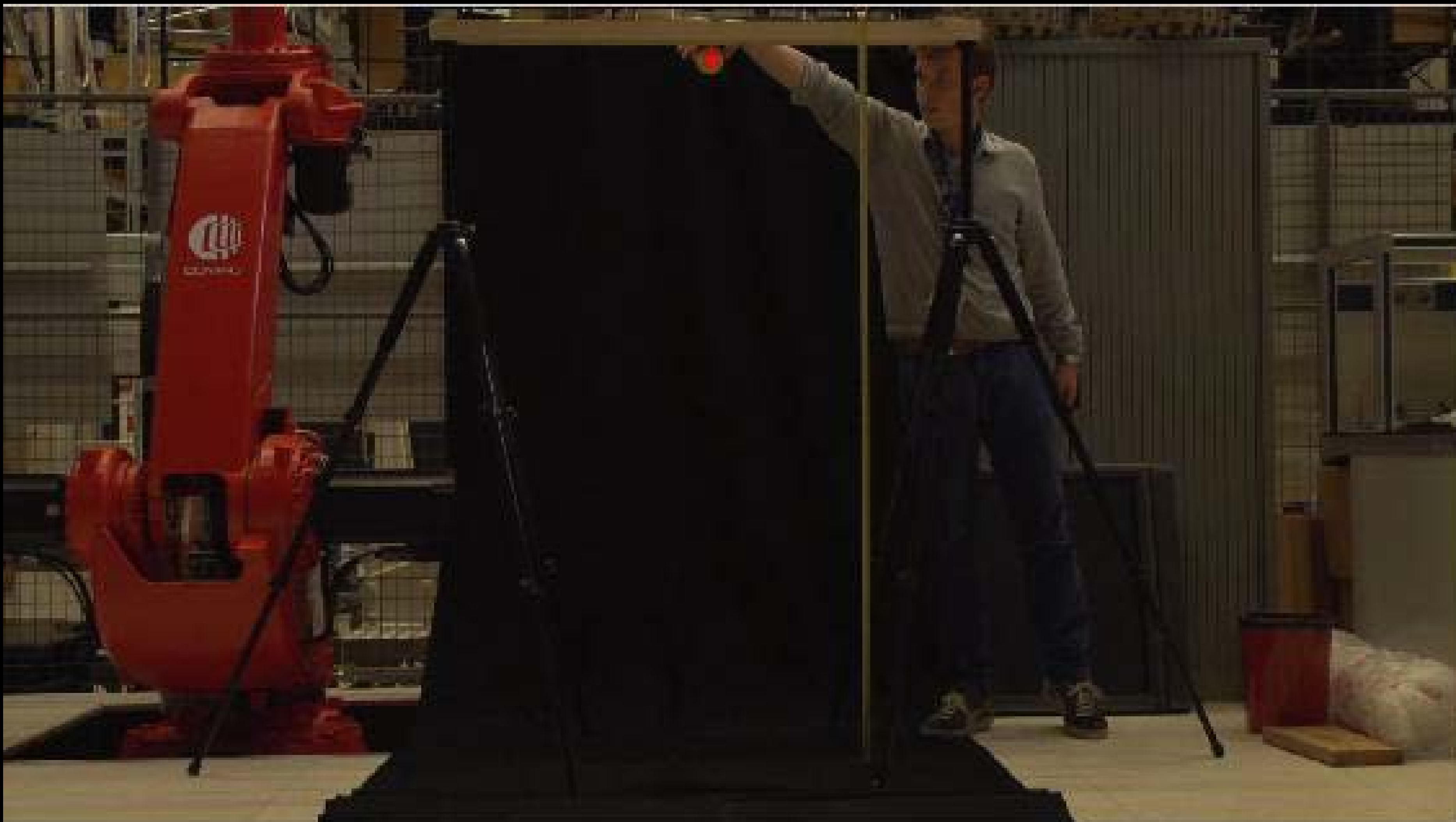
- Projected Gauss-Seidel (PGS) solver often used
  - Fast initial convergence, slow afterwards
  - No error based convergence criterion
  - Fixed number of iterations

- Uniqueness not guaranteed



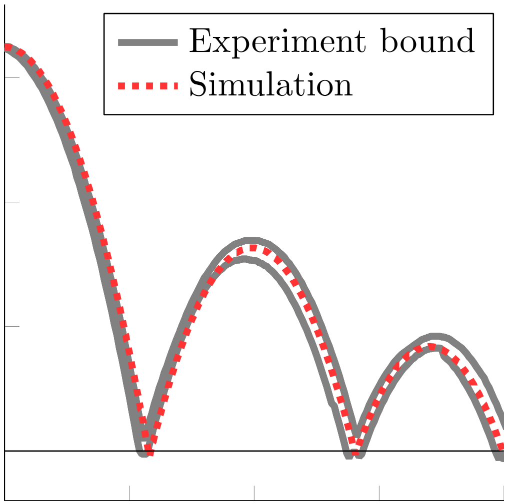


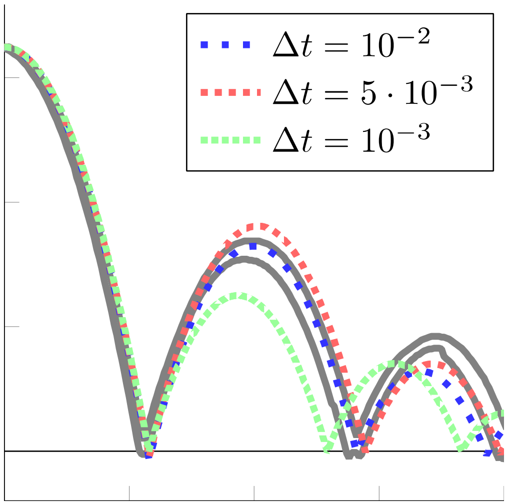
Experimental Analysis

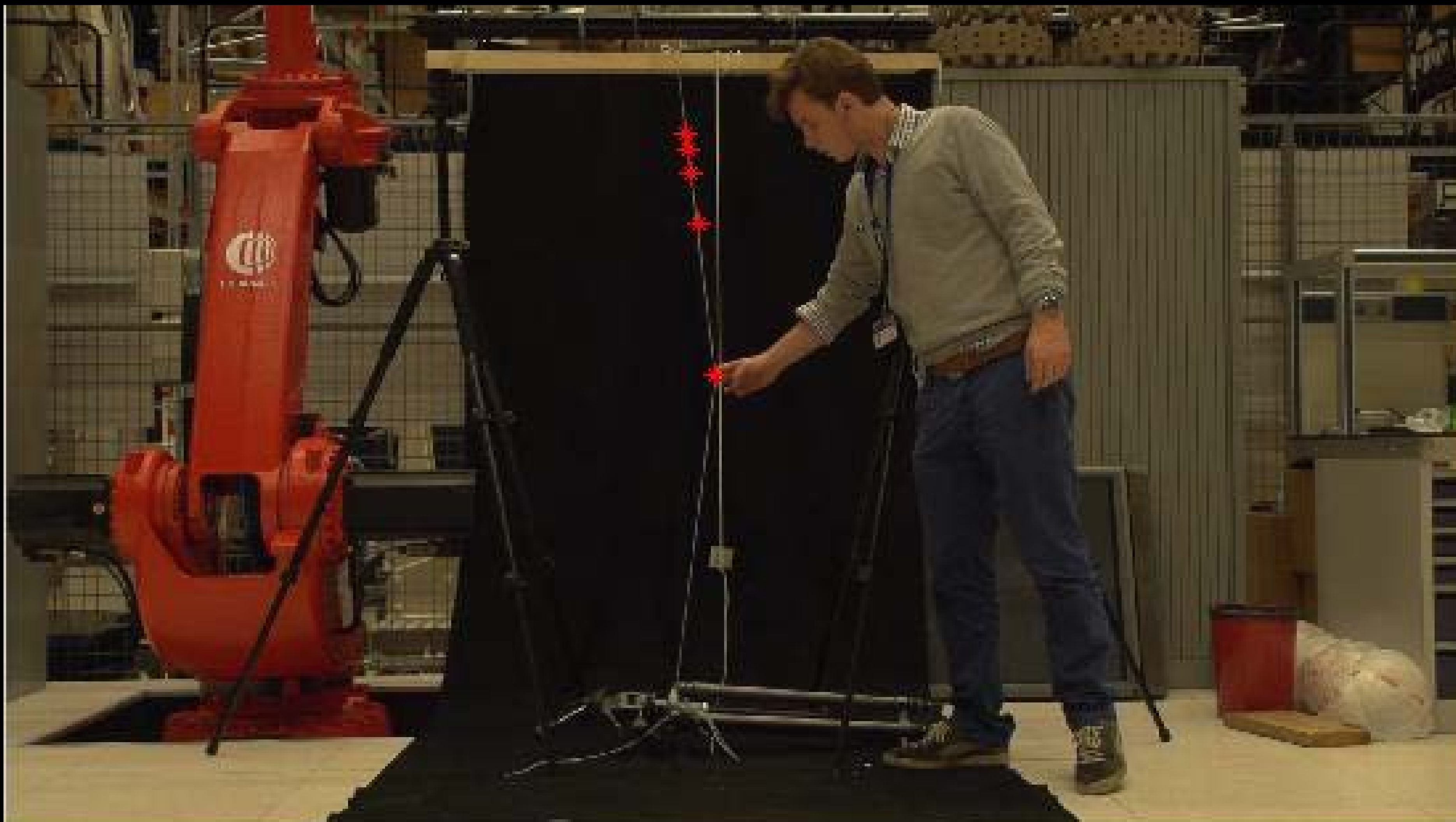


Tennis ball experiment

- High-speed camera & video tracking
- Pseudo-random behavior too large

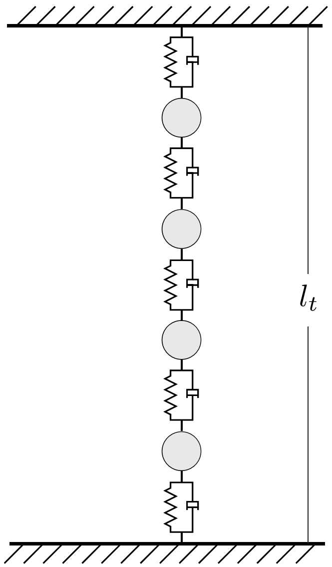




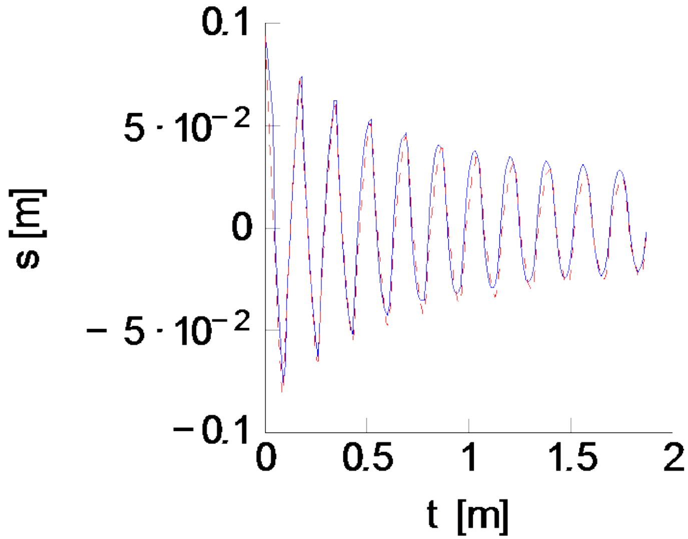


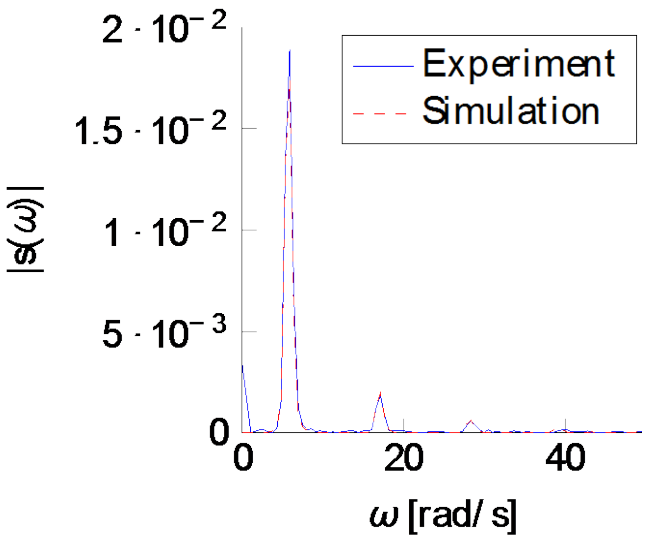
String experiment

- Lumped mass model
  - Experimentally determined stiffness
  - Estimated aerodynamic damping



- Accurate for simple excitations





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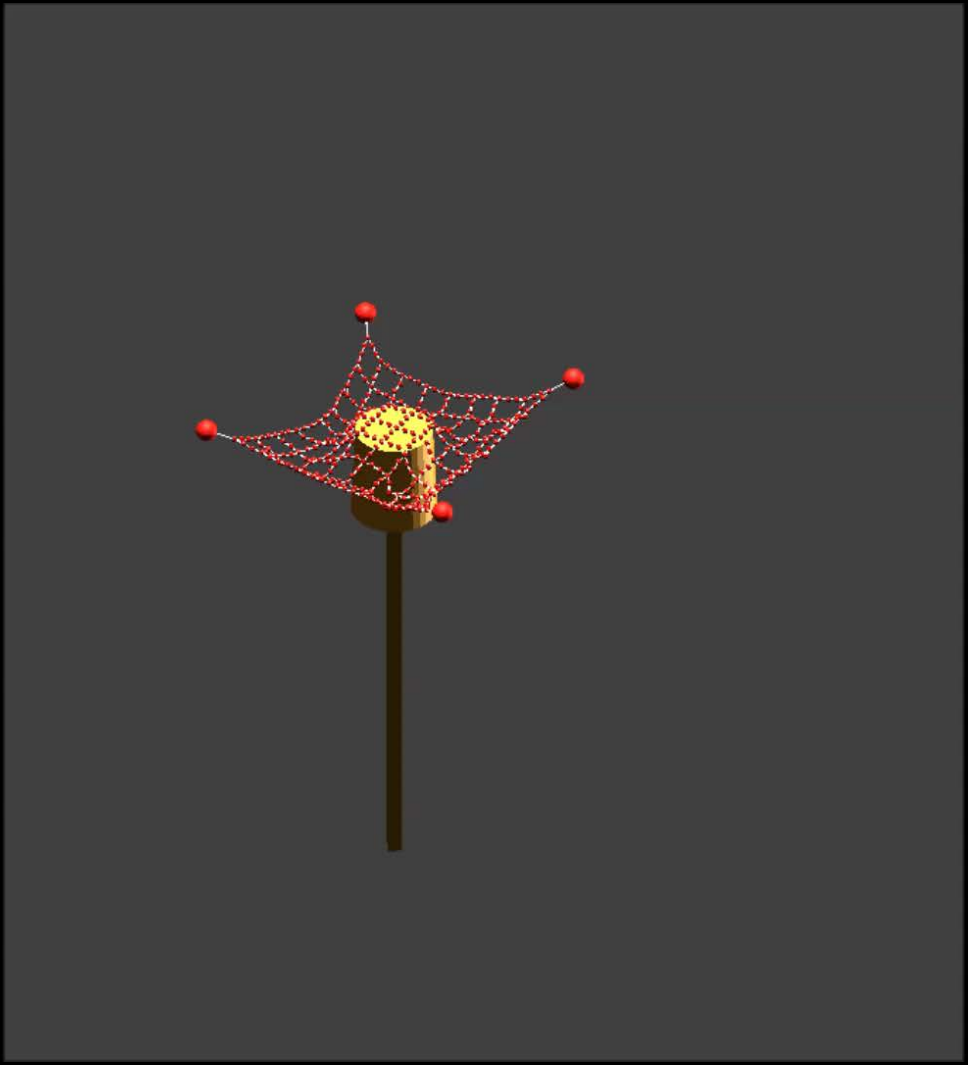
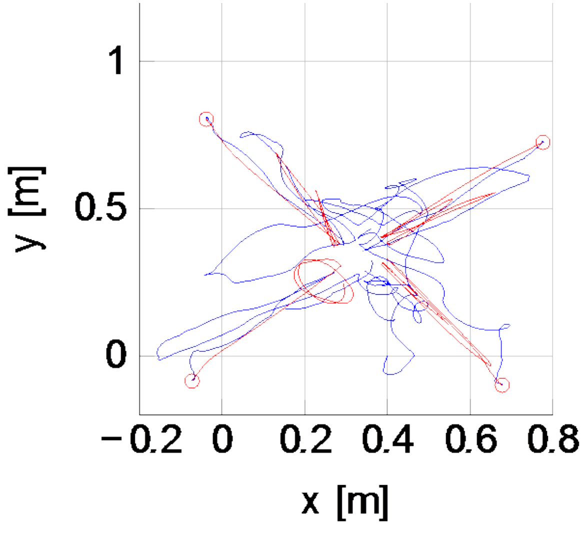
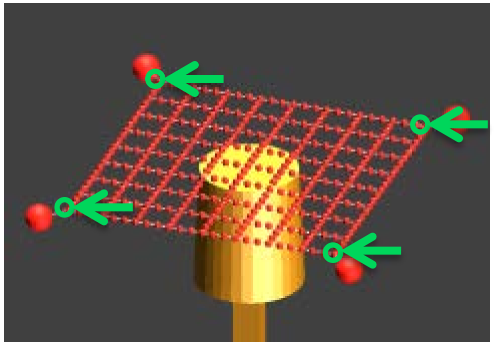
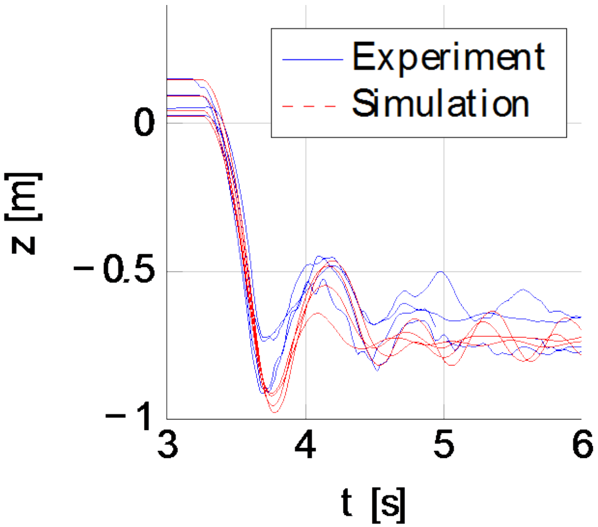
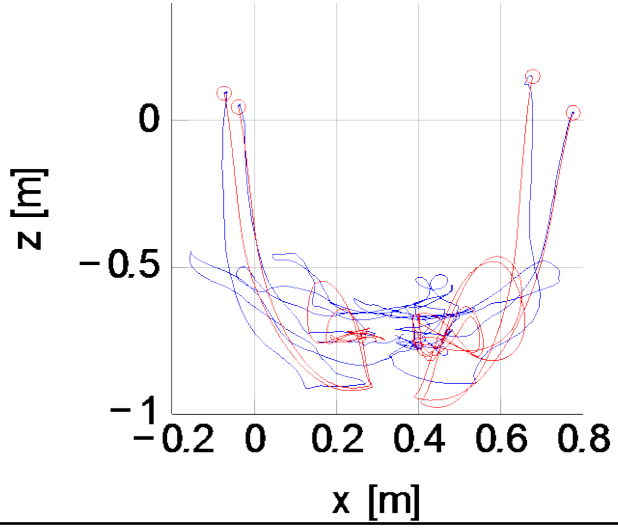


Net experiment

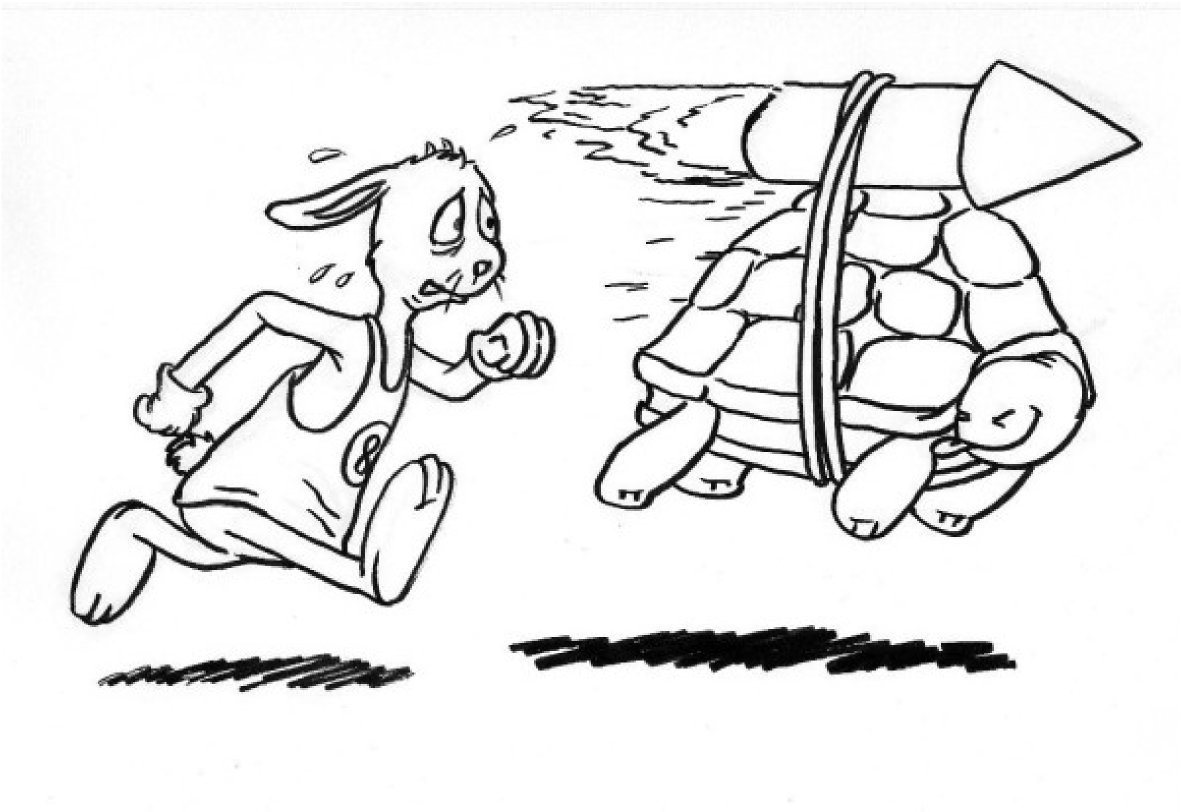




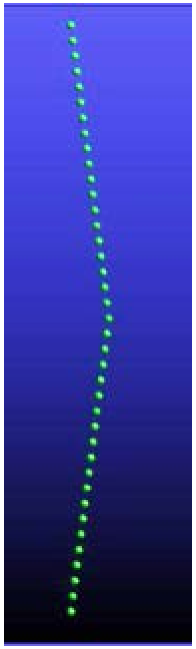


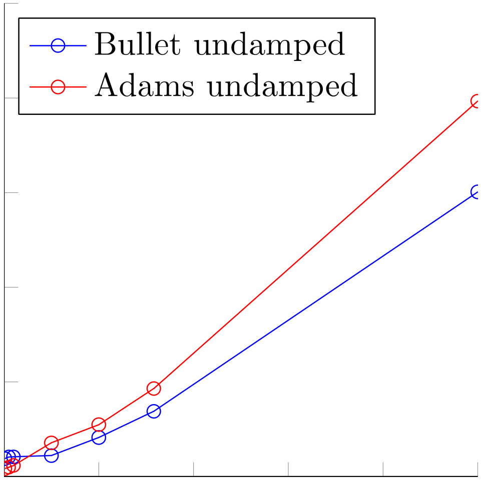


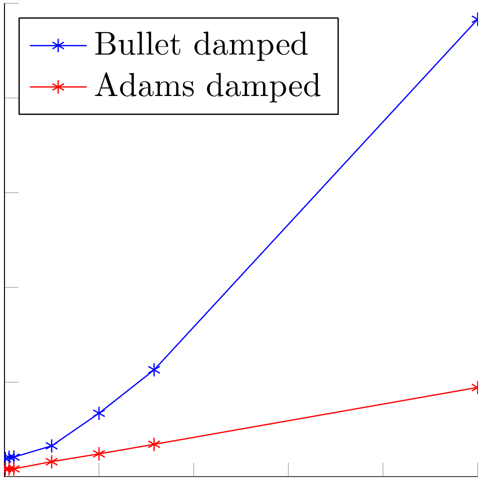
Computational efficiency



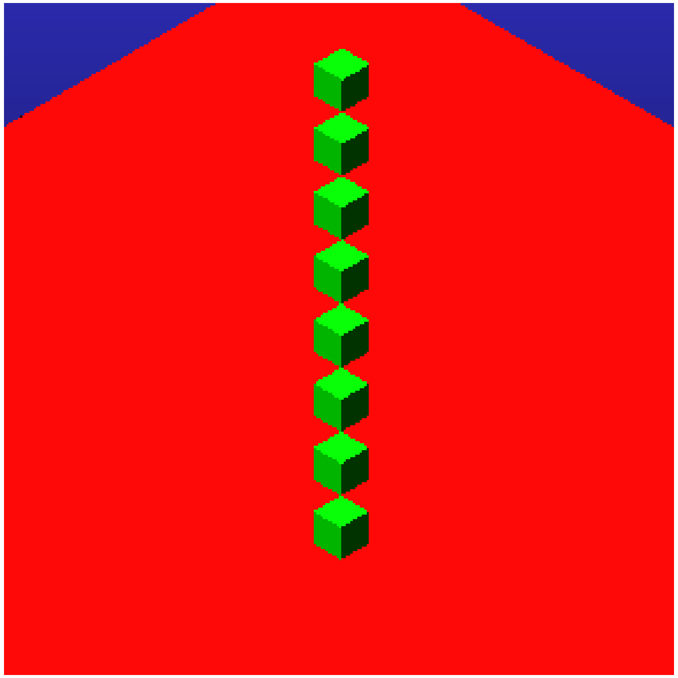
Computational efficiency

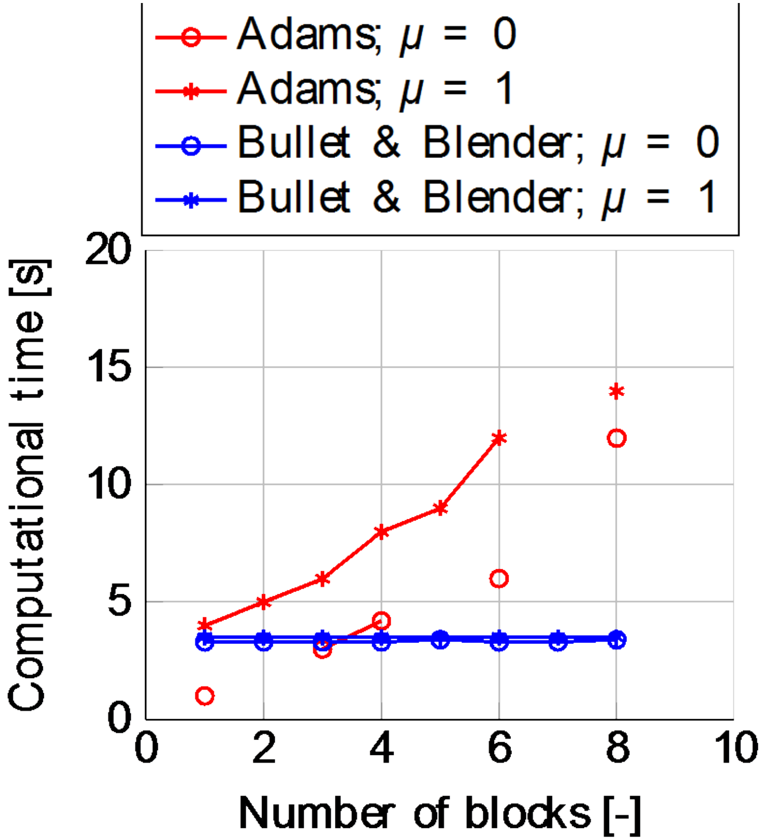






Computational efficiency





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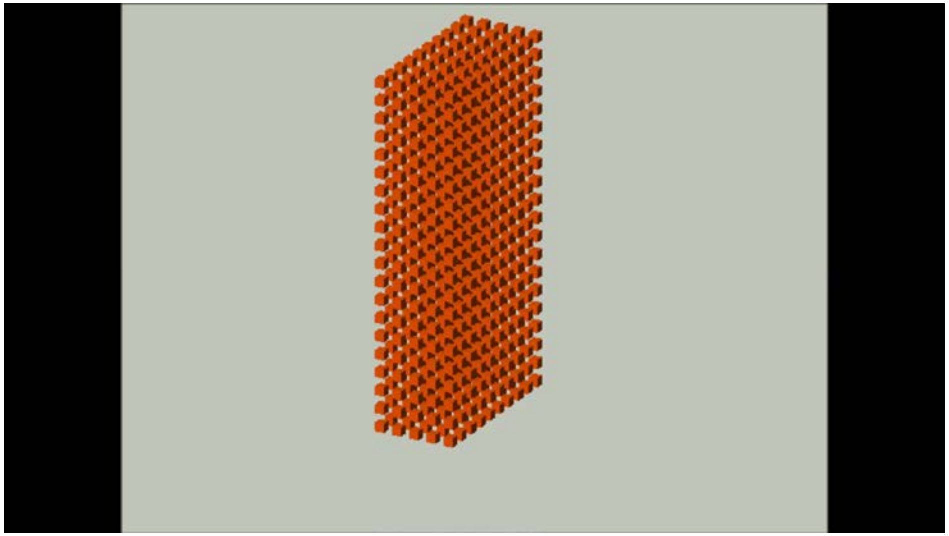
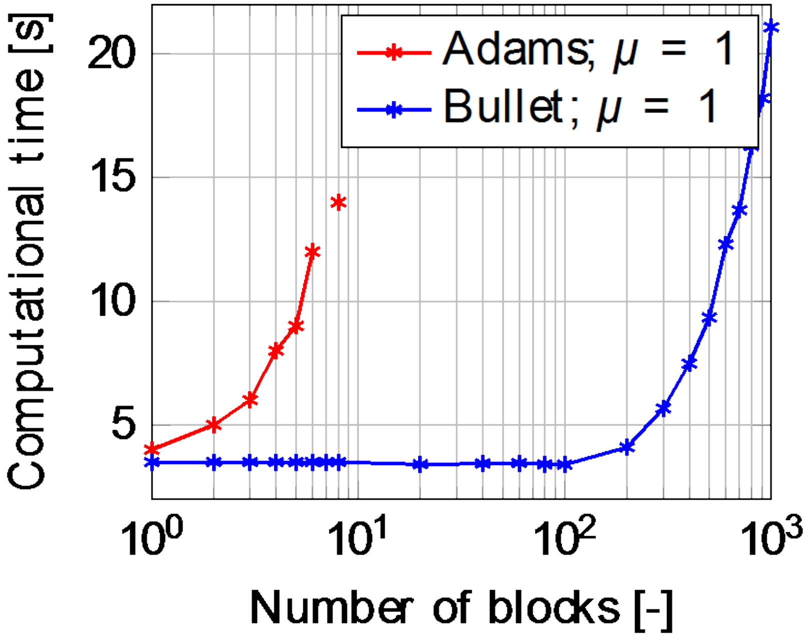




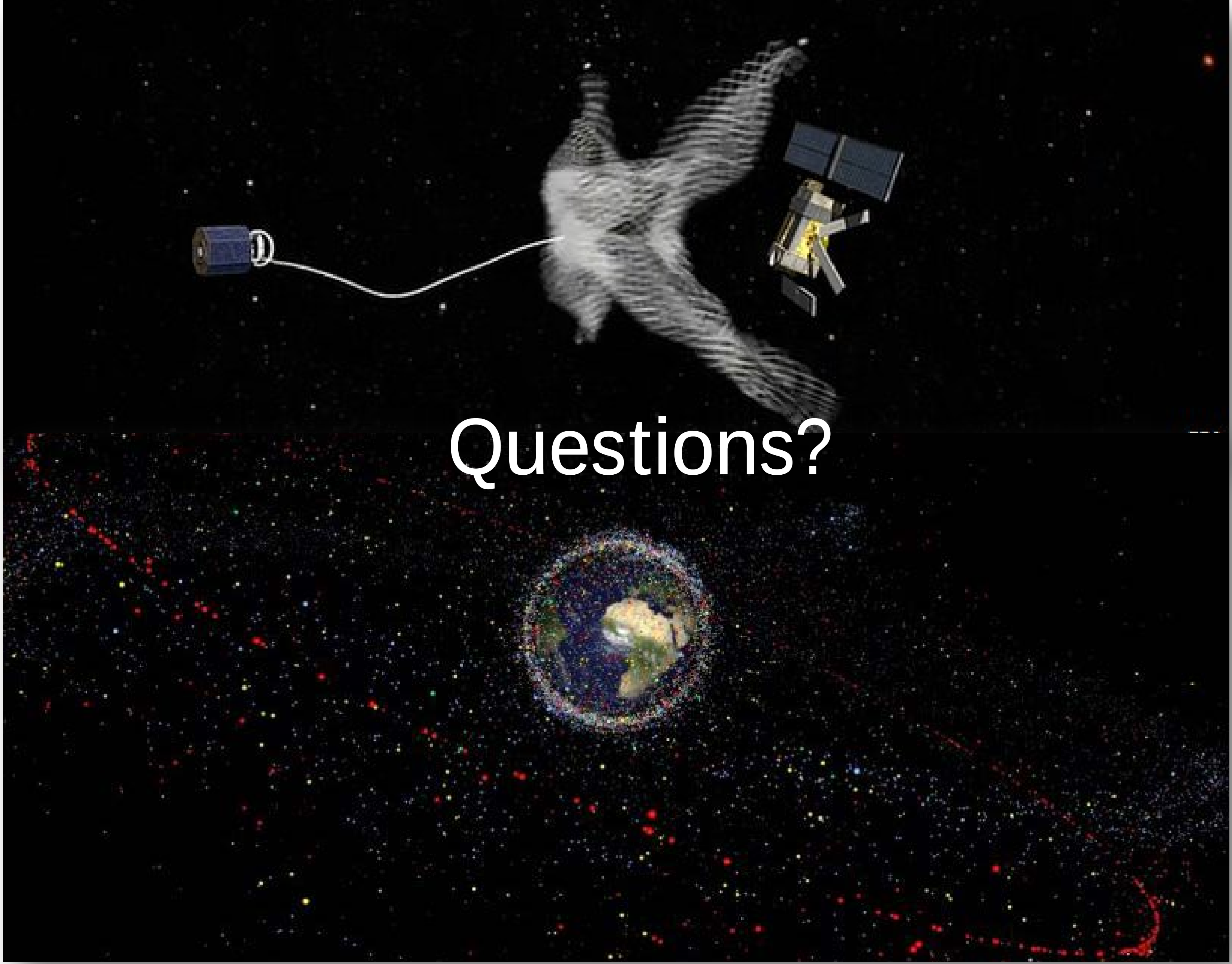
Conclusions

- Assess gaming engine ***accuracy***
  - Simple models, but can be accurate
  - Important to select proper combination of algorithms
- Verify suspected ***advantages***
  - Much faster in handling contact
- Identify possible engineering ***applications***
  - Rigid-body simulations with many contacting bodies
  - Real-time applications
- Suggest ***implementation*** of an engineering tool
  - Use Bullet & Blender as a basis

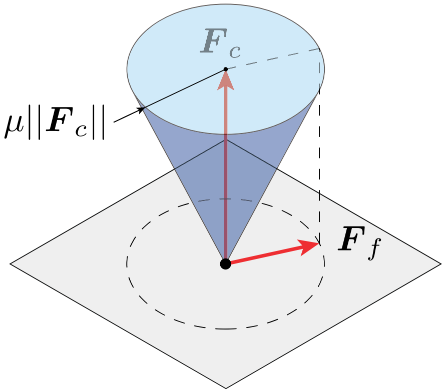
Recommendations

- Making a useful tool from Bullet & Blender
  - More control over Bullet from Blender
  - Add additional modules for post-processing

- Future research
  - Thorough investigation on string & net dynamics
  - Adaptive time-stepping methods to improve efficiency of simulation of stiff systems


Questions?

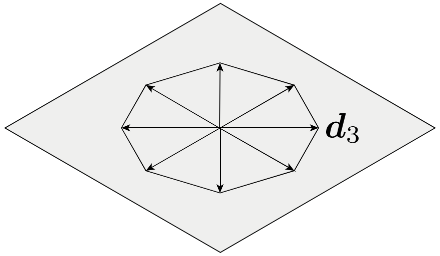
Friction



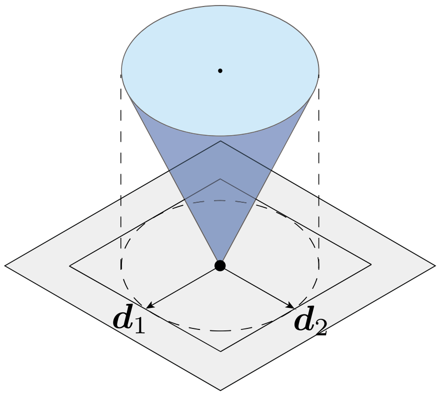
- Coulomb friction model

$$||\boldsymbol{F}_f|| \leq \mu||\boldsymbol{F}_c||$$

- Simplifications for simulators
  - Linearized friction model
  - Decoupled friction model

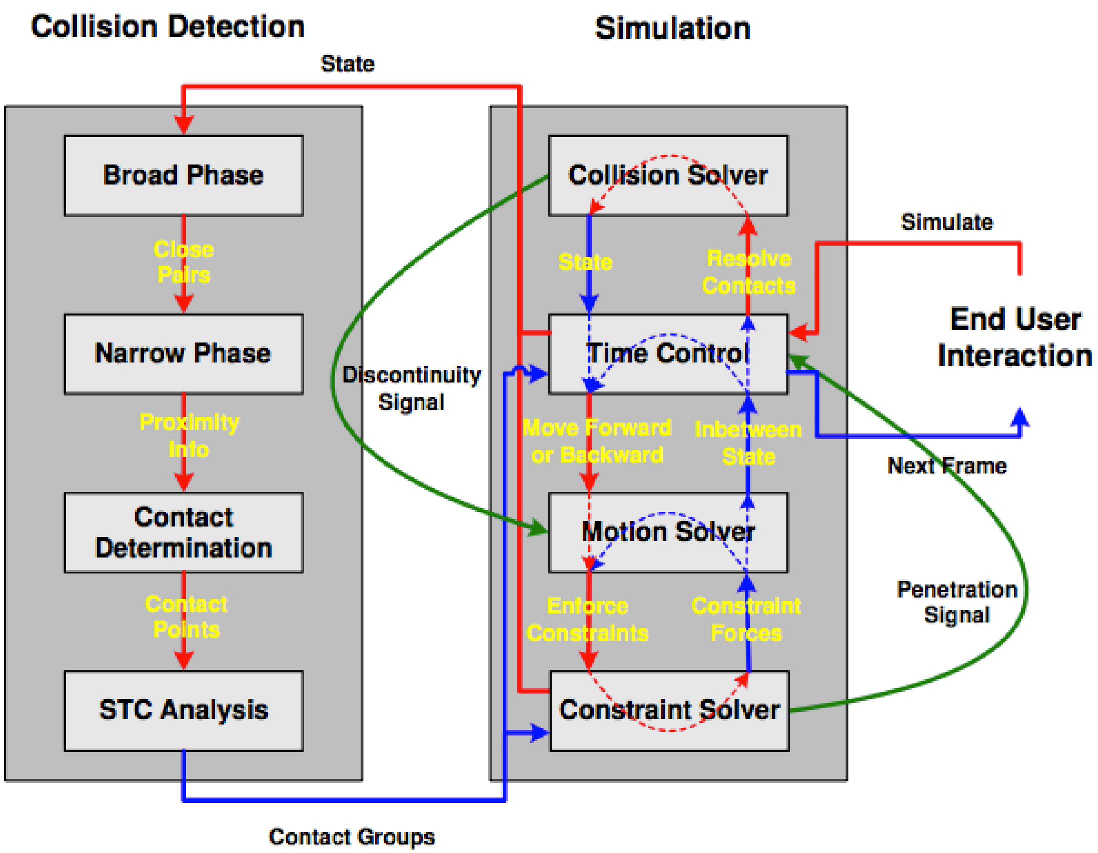


- Linearized model converges with more vectors but slower
- Static friction in decoupled model overestimated by √2



Back-up slides

Tennis ball experiment



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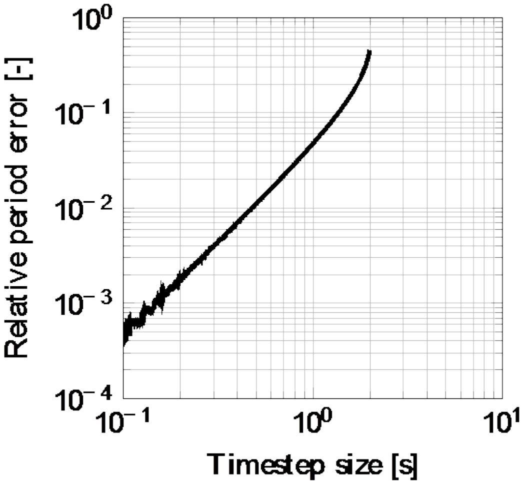
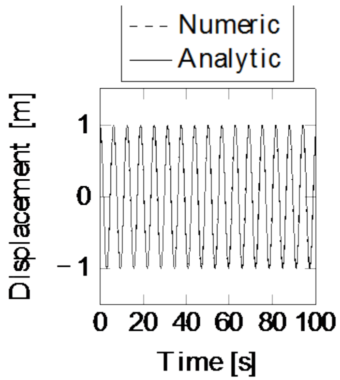
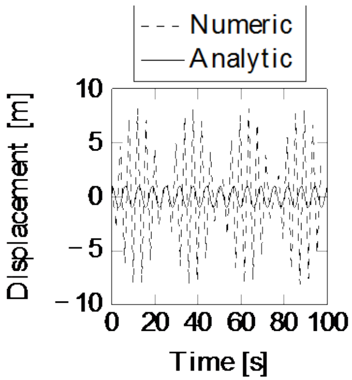
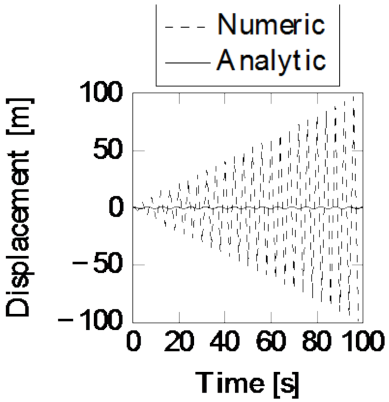
Semi-implicit Euler integration

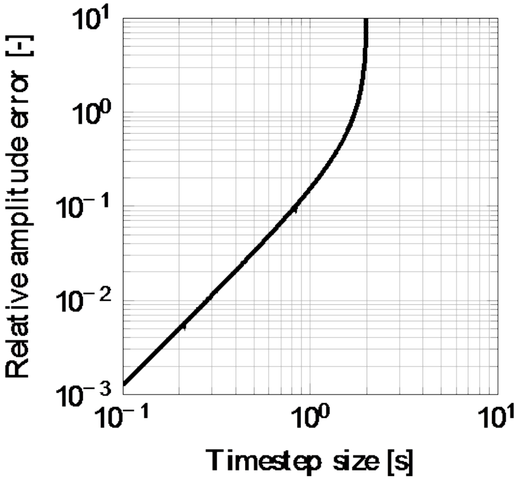


$$\Delta t \ll \frac{1}{\omega} \qquad \frac{1}{\omega} < \Delta t < \frac{2}{\omega} \qquad \Delta t \geq \frac{2}{\omega}$$









Back-up slides

Friction models

- Coulomb friction model

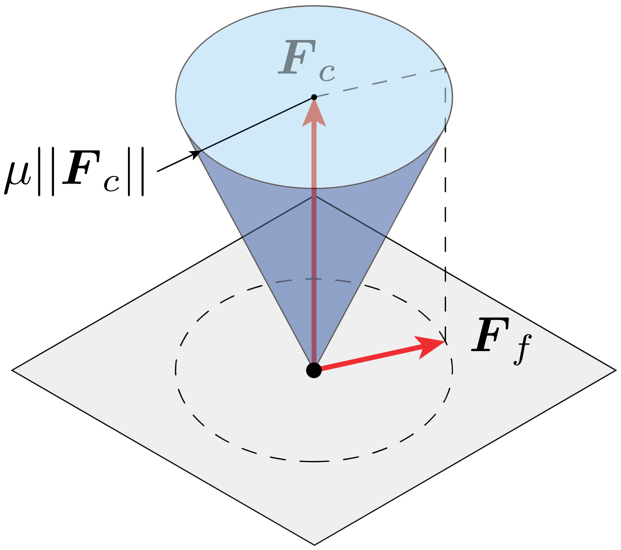
$$||\boldsymbol{F}_f|| \leq \mu||\boldsymbol{F}_c||$$

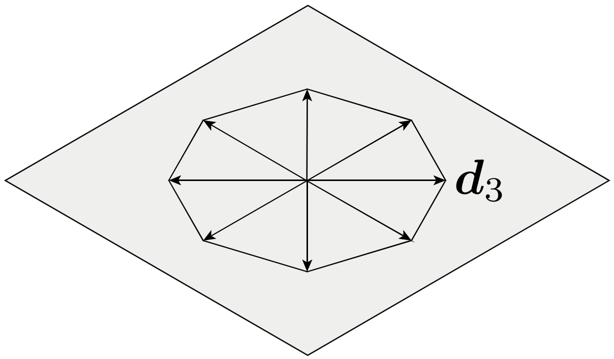
- Linearized friction model

$$\boldsymbol{F}_f = \boldsymbol{D}\boldsymbol{\lambda}$$

$$\text{where} \quad \boldsymbol{D} = [\boldsymbol{d}_1, \ldots, \boldsymbol{d}_\eta]$$

$$\text{and} \quad \sum_i \lambda_i \leq \mu||\boldsymbol{F}_c||$$





Back-up slides

Friction models

- Coulomb friction model

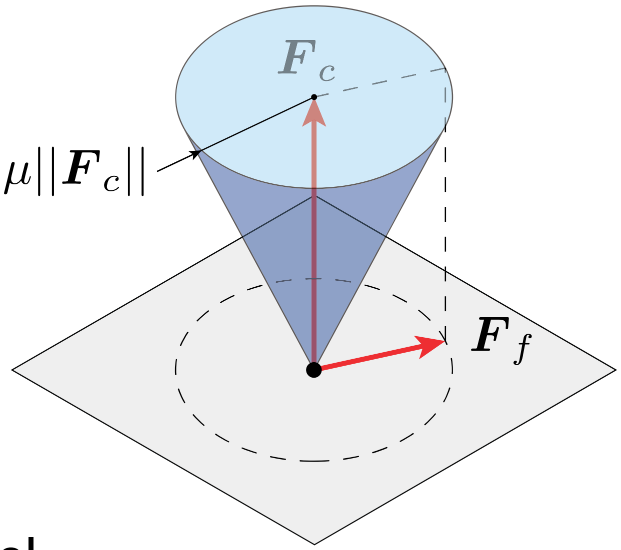
$$||\boldsymbol{F}_f|| \leq \mu||\boldsymbol{F}_c||$$

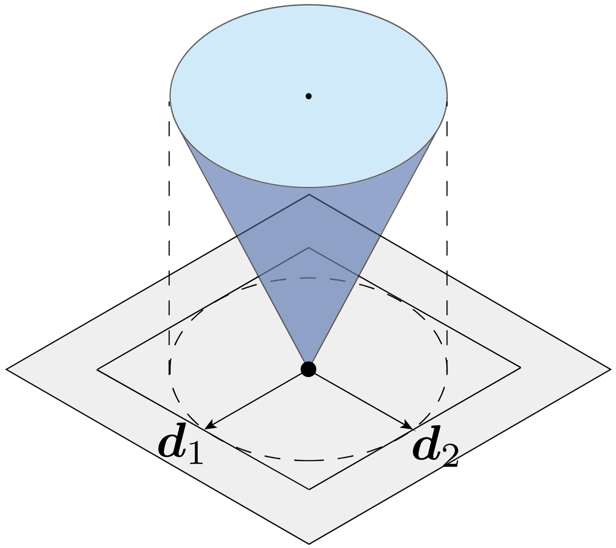
- Linearized & decoupled friction model

$$\boldsymbol{F}_f = \boldsymbol{D}\boldsymbol{\lambda}$$

where $\boldsymbol{D} = [\boldsymbol{d}_1, \boldsymbol{d}_2]$

and $-\mu||\boldsymbol{F}_c|| \leq \lambda_i \leq \mu||\boldsymbol{F}_c||$





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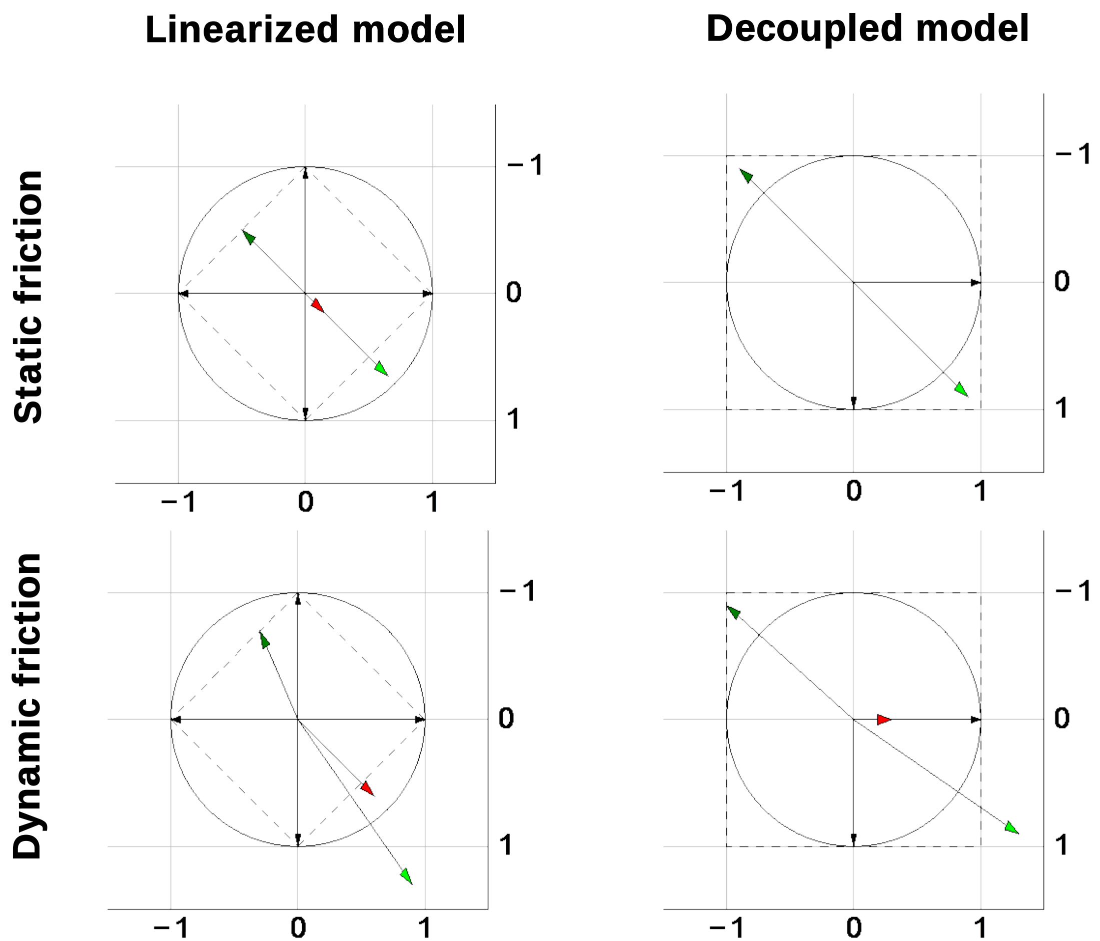
Friction models



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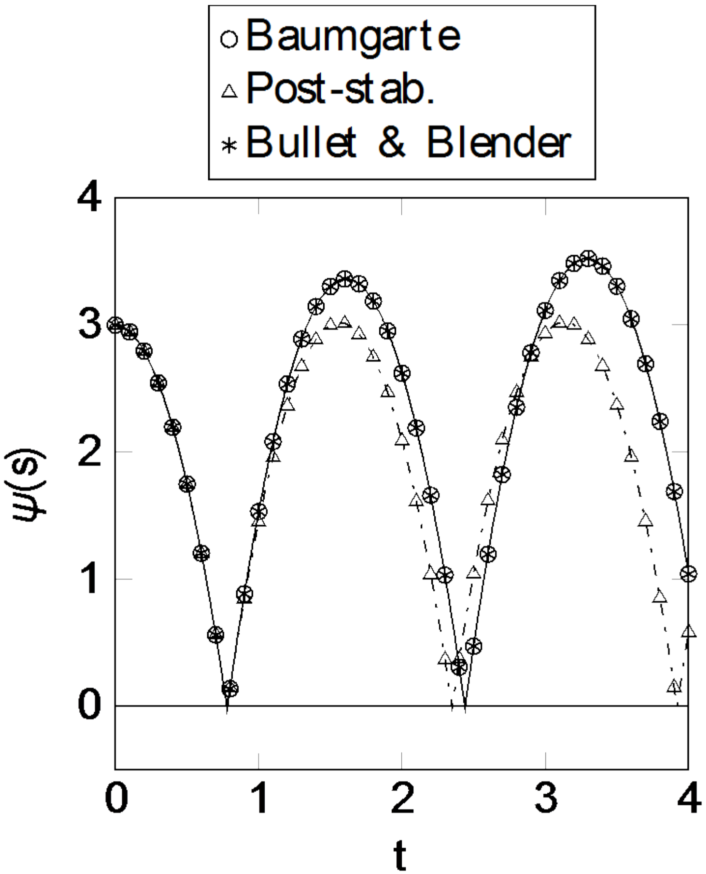
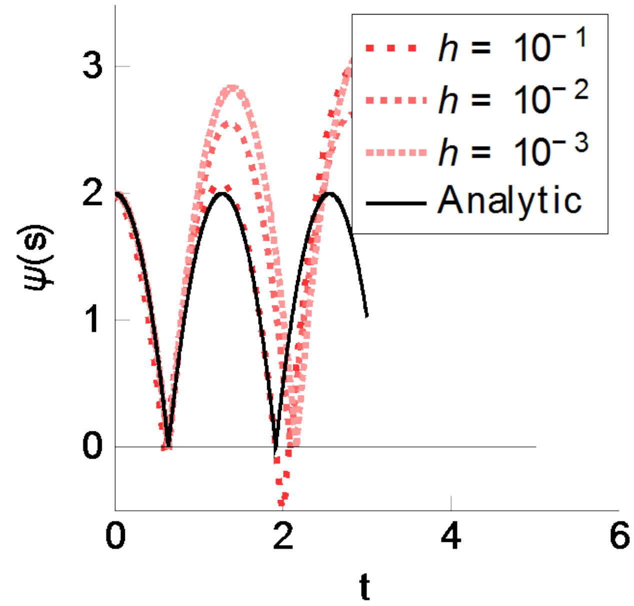
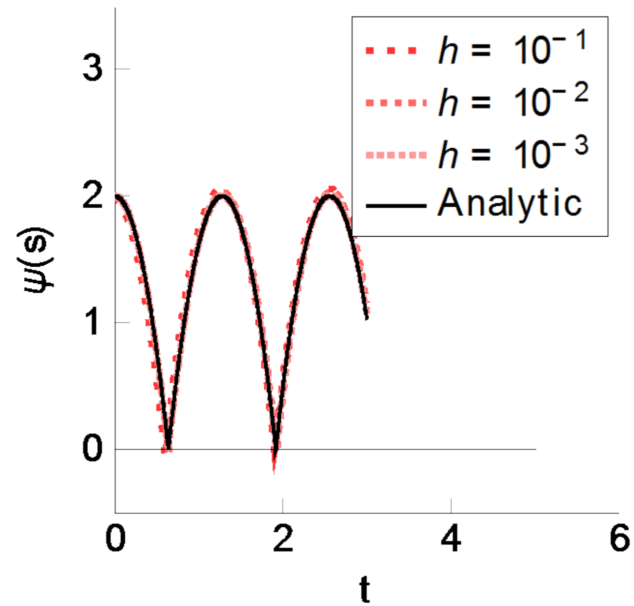
Error redution



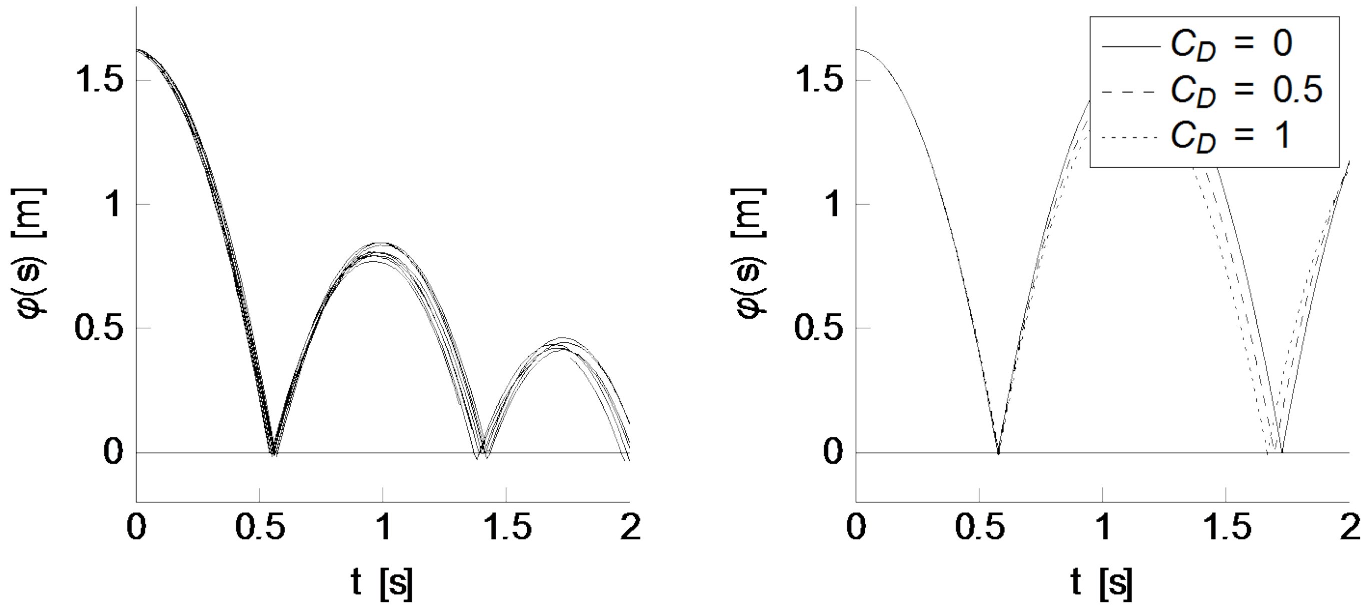




Back-up slides

Tennis ball experiment

$$\boldsymbol{F}_d = -\frac{1}{2} A C_D \rho (\boldsymbol{u} \cdot \boldsymbol{u}) \left(\frac{\boldsymbol{u}}{||\boldsymbol{u}||} \right)$$



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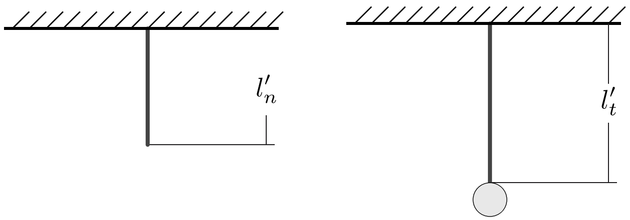
String experiment

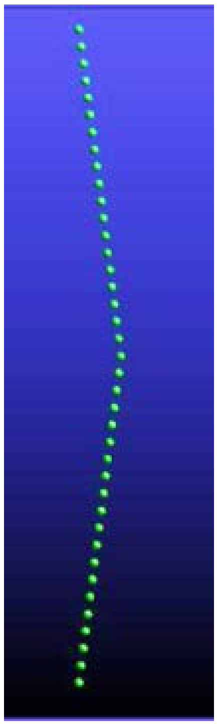


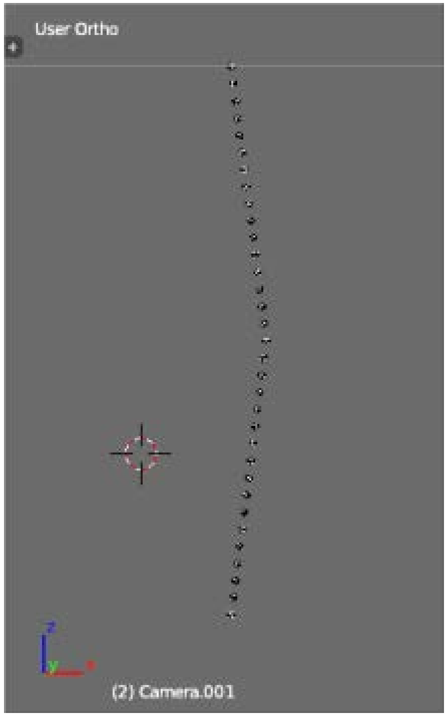
$$\boldsymbol{F}_{s,ij} = k_e(||\delta_{ij}\boldsymbol{r}|| - l_e)\delta_{ij}\hat{\boldsymbol{r}}$$

$$\boldsymbol{F}_{d,ij} = c_e(\delta_{ij}\boldsymbol{v} \cdot \delta_{ij}\hat{\boldsymbol{r}})\delta_{ij}\hat{\boldsymbol{r}}$$

$$\boldsymbol{F}_{ij} = \begin{cases} \boldsymbol{F}_{s,ij} + \boldsymbol{F}_{d,ij} & \text{if } ||\delta_{ij}\boldsymbol{r}|| - l_e \geq 0 \\ 0 & \text{if } ||\delta_{ij}\boldsymbol{r}|| - l_e < 0 \end{cases}.$$

$$\boldsymbol{F}_{D,i} = \frac{1}{2}\rho_{\text{air}} \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \boldsymbol{v}_i C_D A_h,$$





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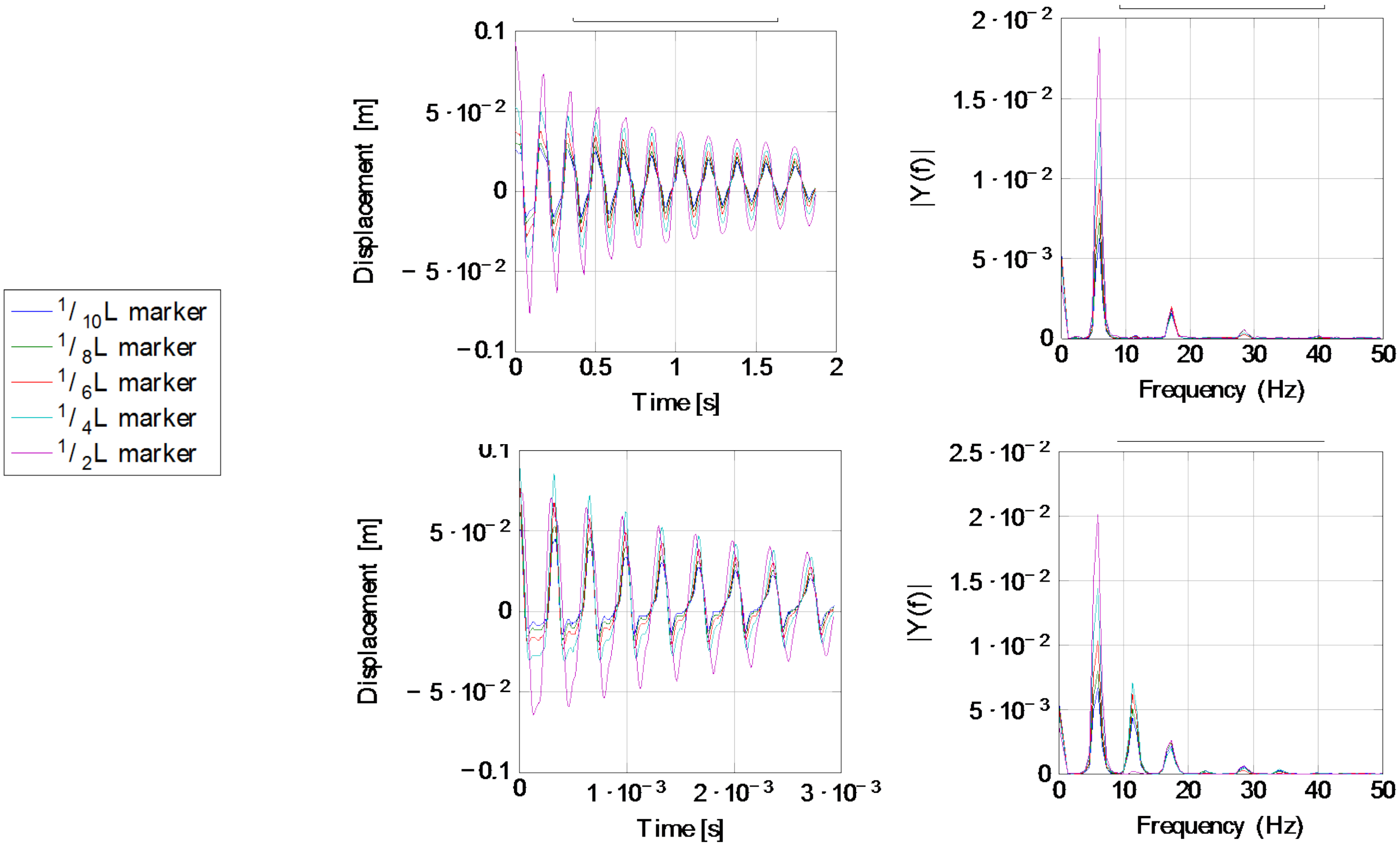

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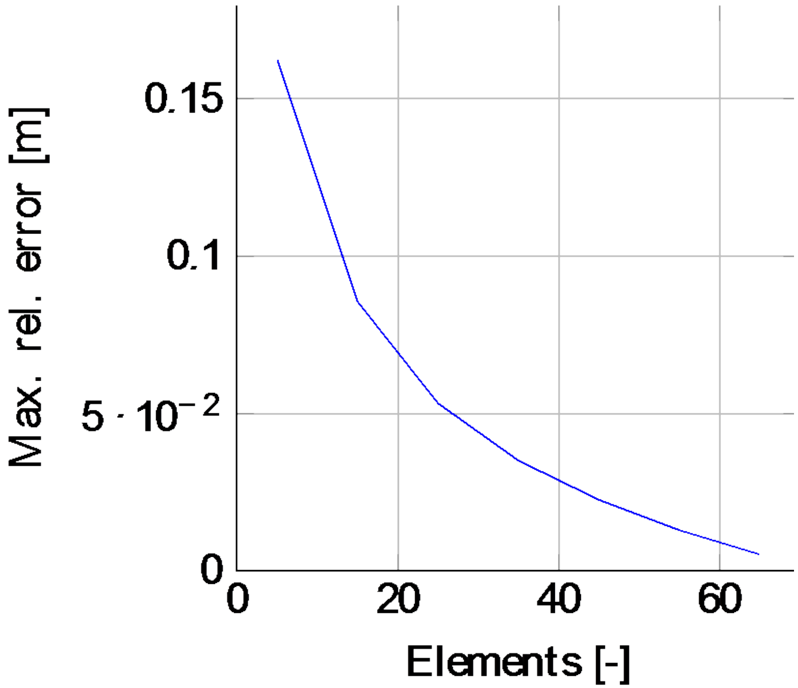

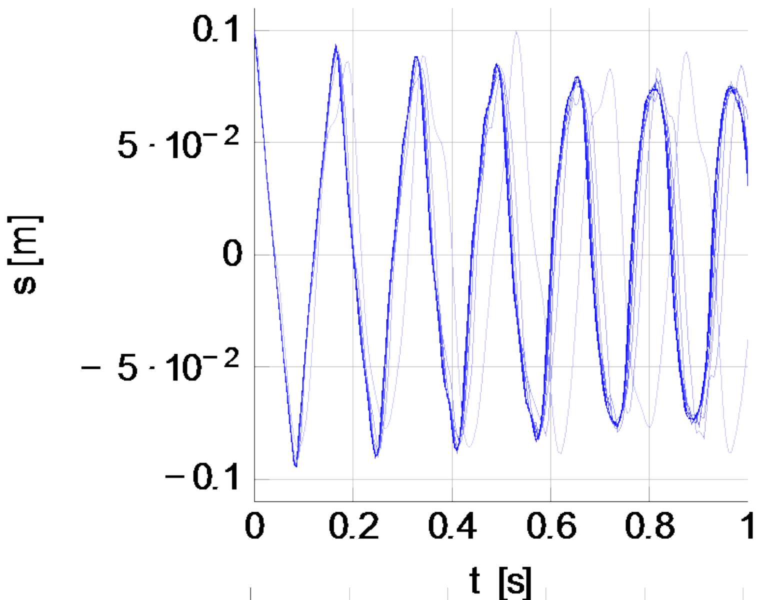

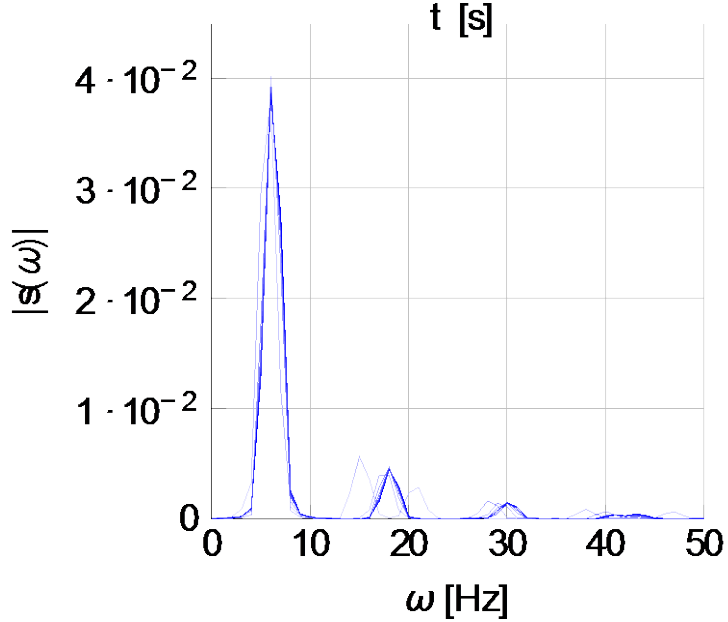

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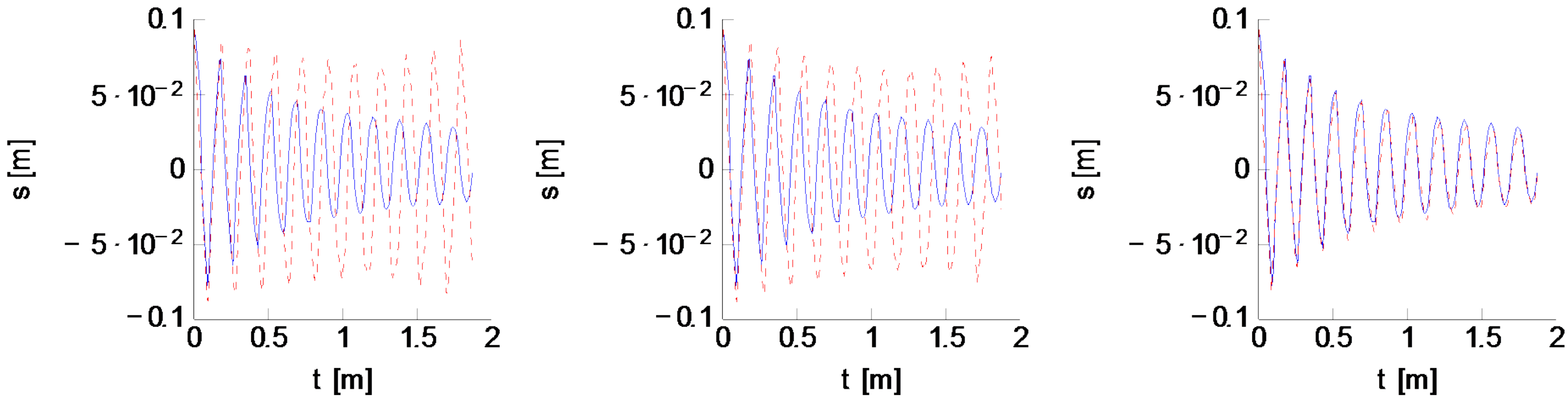
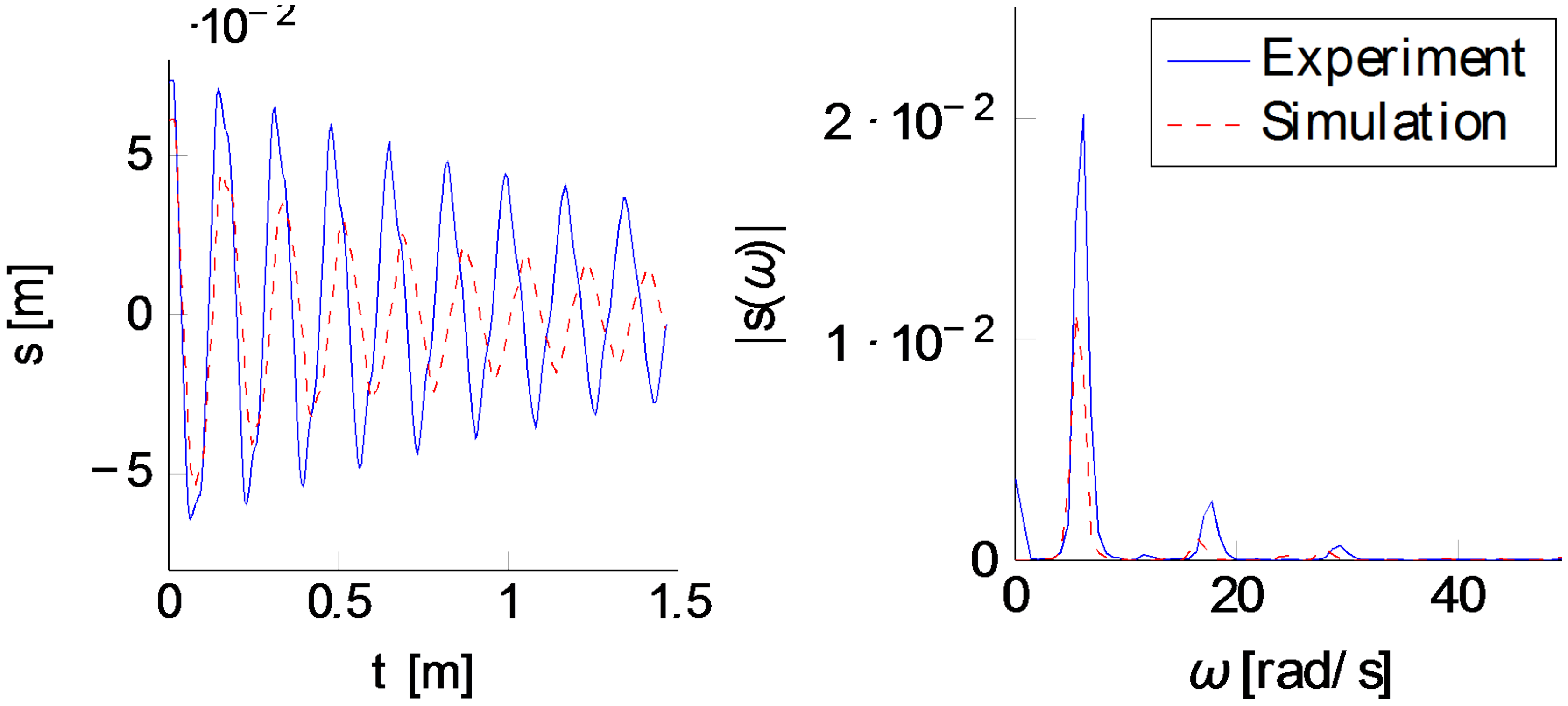
String experiment



Back-up slides

String experiment

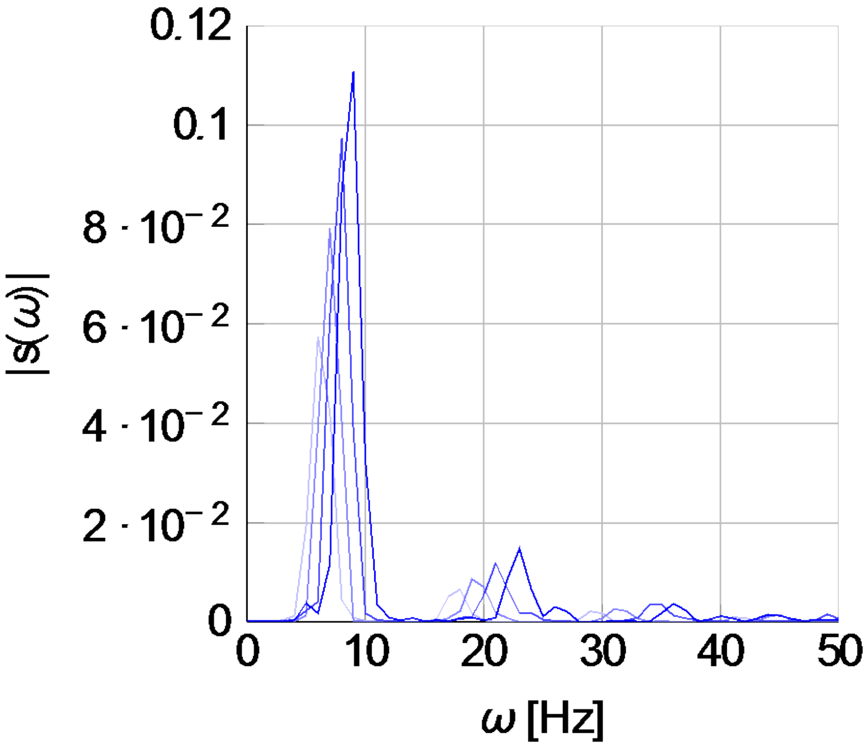


Back-up slides

String experiment

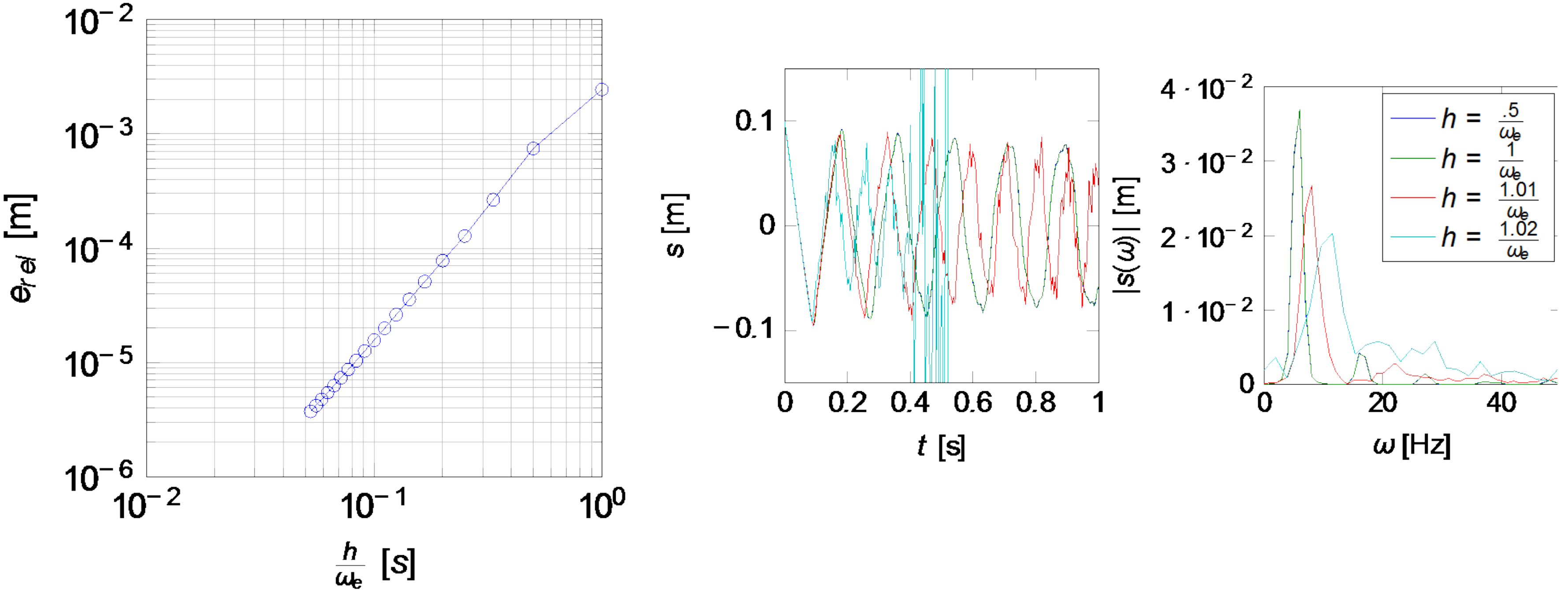
$$\boldsymbol{F}_{s,ij} = k_e(||\delta_{ij}\boldsymbol{r}|| - l_e)\delta_{ij}\hat{\boldsymbol{r}}$$

$$\boldsymbol{F}_{d,ij} = c_e(\delta_{ij}\boldsymbol{v} \cdot \delta_{ij}\hat{\boldsymbol{r}})\delta_{ij}\hat{\boldsymbol{r}}$$



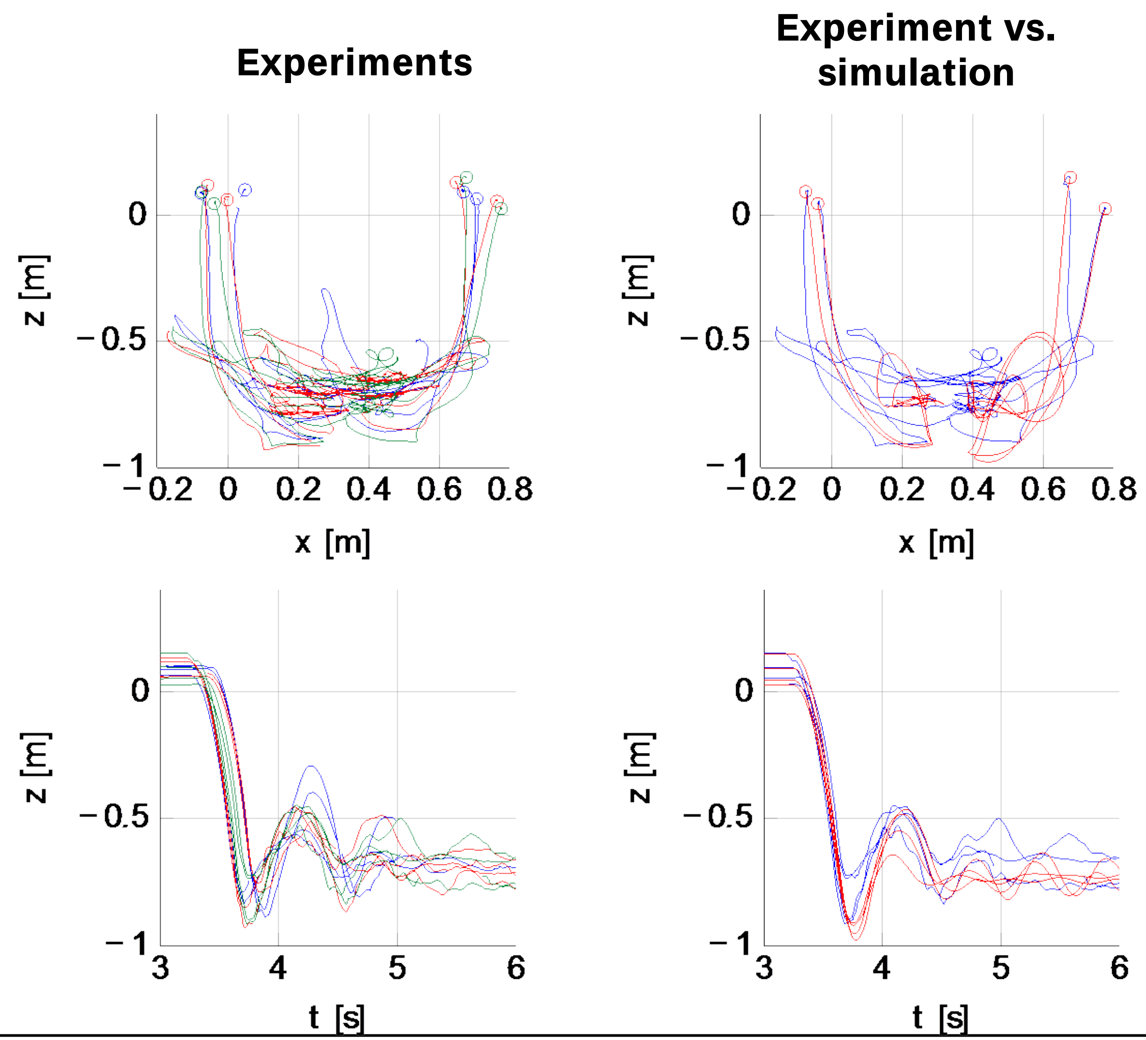
Back-up slides

String experiment



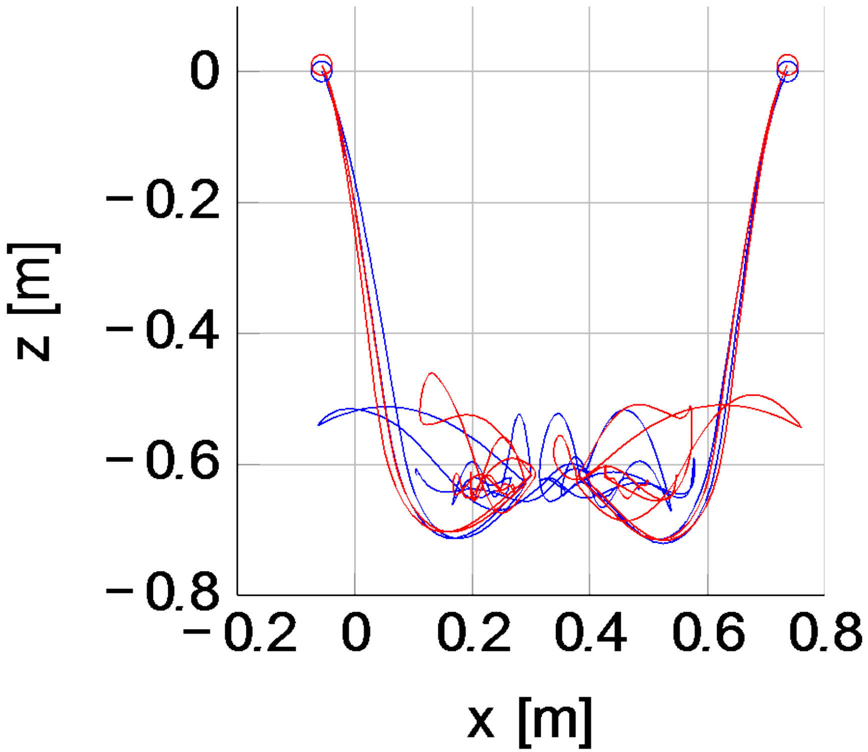
Back-up slides

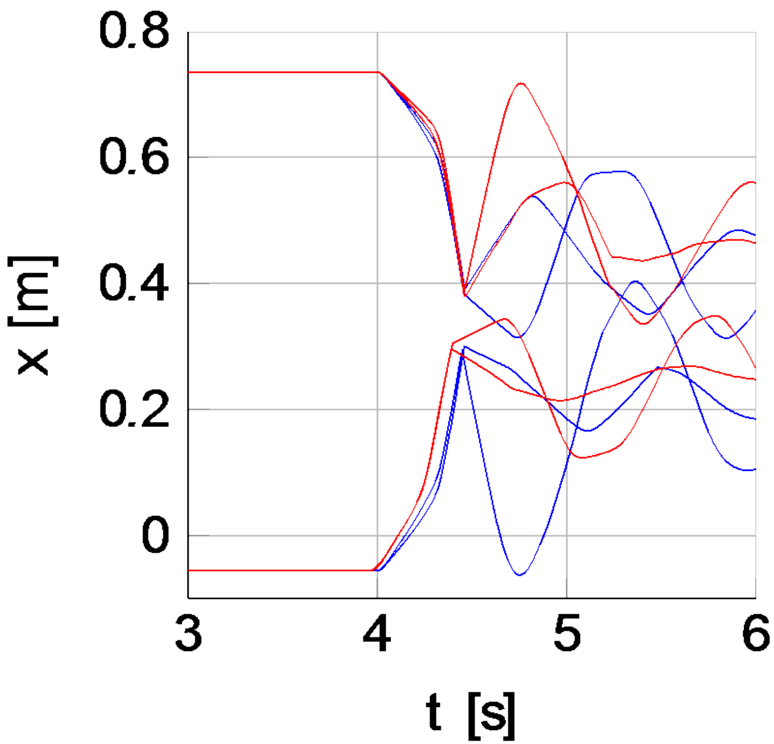
Net experiment



Back-up slides

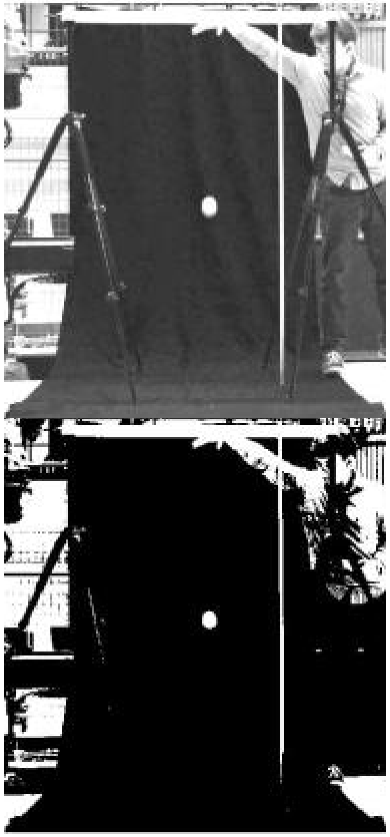
Net experiment

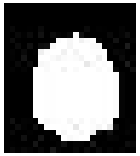




Back-up slides

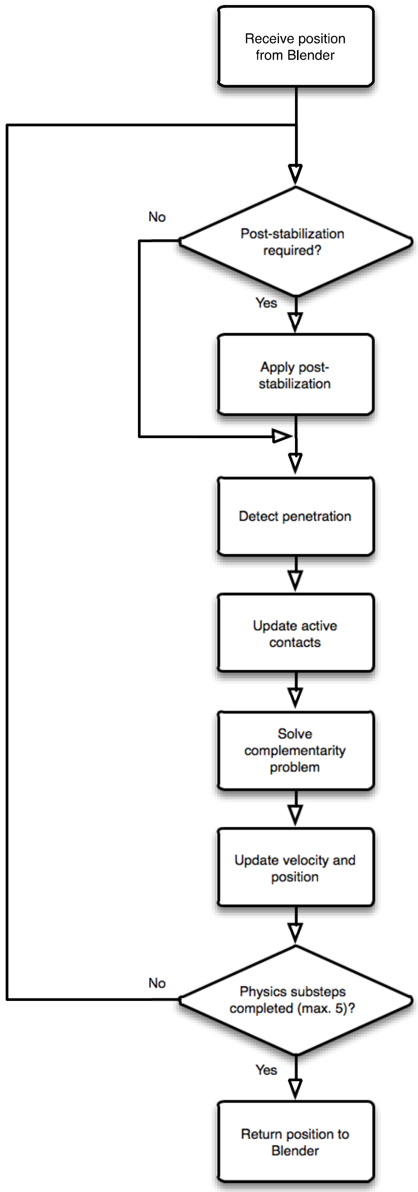
Image processing

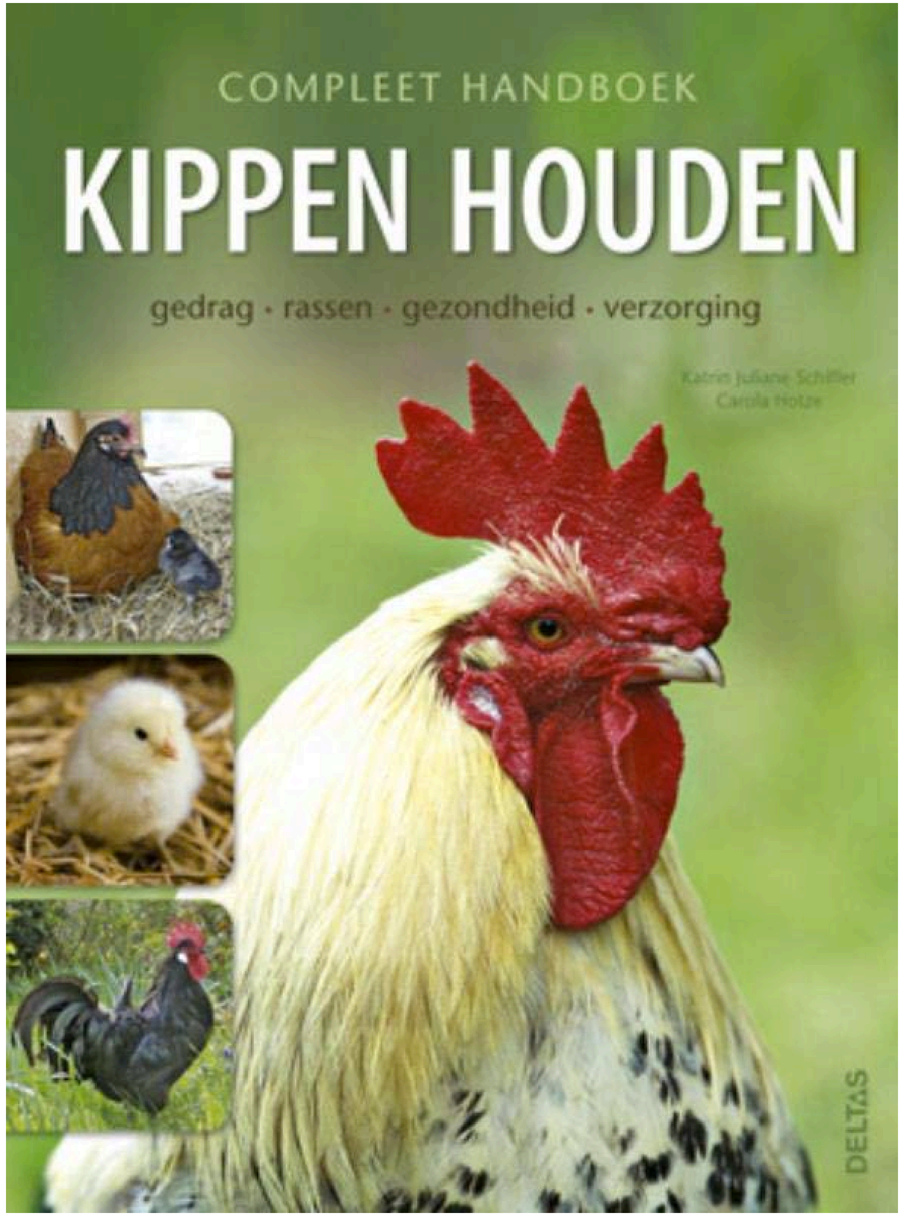




Back-up slides

Bullet algorithm overview




COMPLEET HANDBOEK
KIPPEN HOUDEN
gedrag · rassen · gezondheid · verzorging
DELTAS