Modeling and Identification of Rheological Deformation

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Workshop on
Modeling, Identification, and Control of Deformable Soft Objects
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in conjunction with
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Introduction

- **Modeling rheology object** is a younger field.
- The model is useful to manipulate an object **by a robot arm in a real world**.
- The model is useful to feel its reactive force **by a haptic device** or to watch shape deformation **in a 3-D graphics world of PC**.

Food

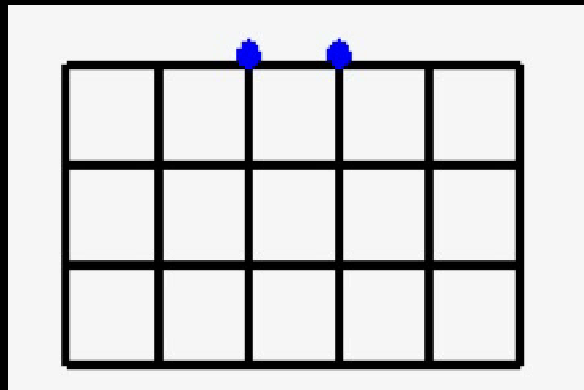
Fabric

Biomedical tissue

Introduction (cont'd)

- Twin goals are the most important:
  - Shape reality for visualization
  - Force reality for tactile feeling

By mixing wheat flour and water.



By digitalized particle model

Basic Framework

- Modeling and Calculating
  - by many algorithms (e.g., FEM, MSD, …)
- Calibrating for reality
  - by many algorithms (e.g., RA, GA,…)
- Evaluating for repeatability
  - by captured data (e.g., shape, force,…)
  - by human operator's feeling

Our related papers located in http://www.noblab.jp/ja/

- Haruyuki Yoshida, Fumiaki Ujibe and Hiroshi Nobor, “Force/Shape Reappearance of MSD Rheology Model Calibrated by Force/Shape Sequence,” Proc. of the International Conference Virtual Reality and Telexistence, 2007 (to appear).
- Takeshi Ikawa and Hiroshi Noborio, “On the Precision and Efficiency of Hierarchical Rheology MSD Model,” Proc. of the IEEE/RSJ Int. Conf. Intelligent Robots and Systems, pp.376-383, 2007.
- Haruyuki Yoshida, Yasuyuki Murata and Hiroshi Noborio, "A Smart Rheologic MSD Model Pushed/Calibrated/Evaluated by Experimental Impulses, " Proc. of the IEEE/RSJ Int. Conf. Intelligent Robots and Systems, pp.1614-1621, 2005.
- Ryo Nogami, Fumiaki Ujibe, Hiroki Fujii and Hiroshi Noborio, "Precise Deformation of Rheologic Object under MSD Models with Many Voxels and Calibrating Parameters," Proc. of the IEEE Int. Conf. on Robotics and Automation, pp.1919-1926, 2004.

Our related papers located in http://www.noblab.jp/ja/ (cont'd)

- Ryo Nogami, Hiroshi Noborio, Seiji Tomokuni and Shinichi Hirai, "A Comparative Study of Rheology MSD Models whose Structures are Lattice and Truss," IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.3809-3816, 2004.
- Hiroshi Noborio, Ryo Enoki, Shohei Nishimoto and Takumi Tanemura, "On the Calibration of Deformation Model of Rheology Object by a Modified Randomized Algorithm, " Proceeding of the IEEE International Conference on Robotics and Automation, pp.3729-3736, Taipei, September 15-18, 2003.
- Hiroshi Noborio, Ryo Nogami, Ryo Enoki, "Precise Deformation of Rheology MSD Model Calibrated by Randomized Algorithm," Eurographics 2003, Short Presentations, Granada Spain, pp.171-178, 2003.

Shape Outline (Part 1)

- Introduction and Research purpose
- Model 1 – A voxel/lattice model under many basic MSD elements
- Models 2 and 3 by adding each of local and global volume constant conditions into the Model 1
- Calibrating unknown parameters of each model by RA (Randomized Algorithm) and GA (Genetic Algorithm)
- Experimental comparisons
- Conclusions and future works

Research Purpose

- Elastic and Visco-elastic objects have been modeled by Mass Spring Damper (MSD) Method, Finite Differential Method (FDM), Boundary Element Method (BEM), Finite Element Method (FEM)

Concerning to FEM

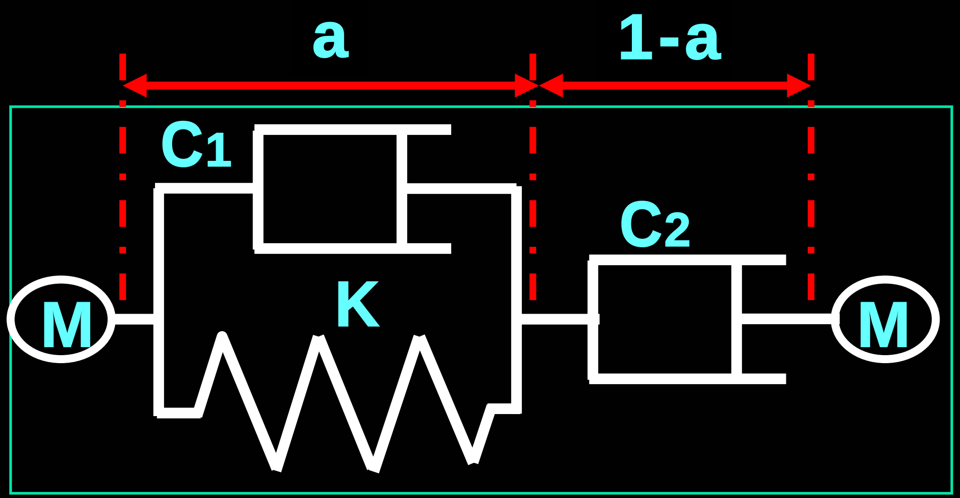
- Force propagation and shape deformation are precise.
- Calculation time is enormous.

Concerning to MSD

- Calculation time is small enough.
- Force propagation and shape deformation are not so precise.

MSD Basic Element

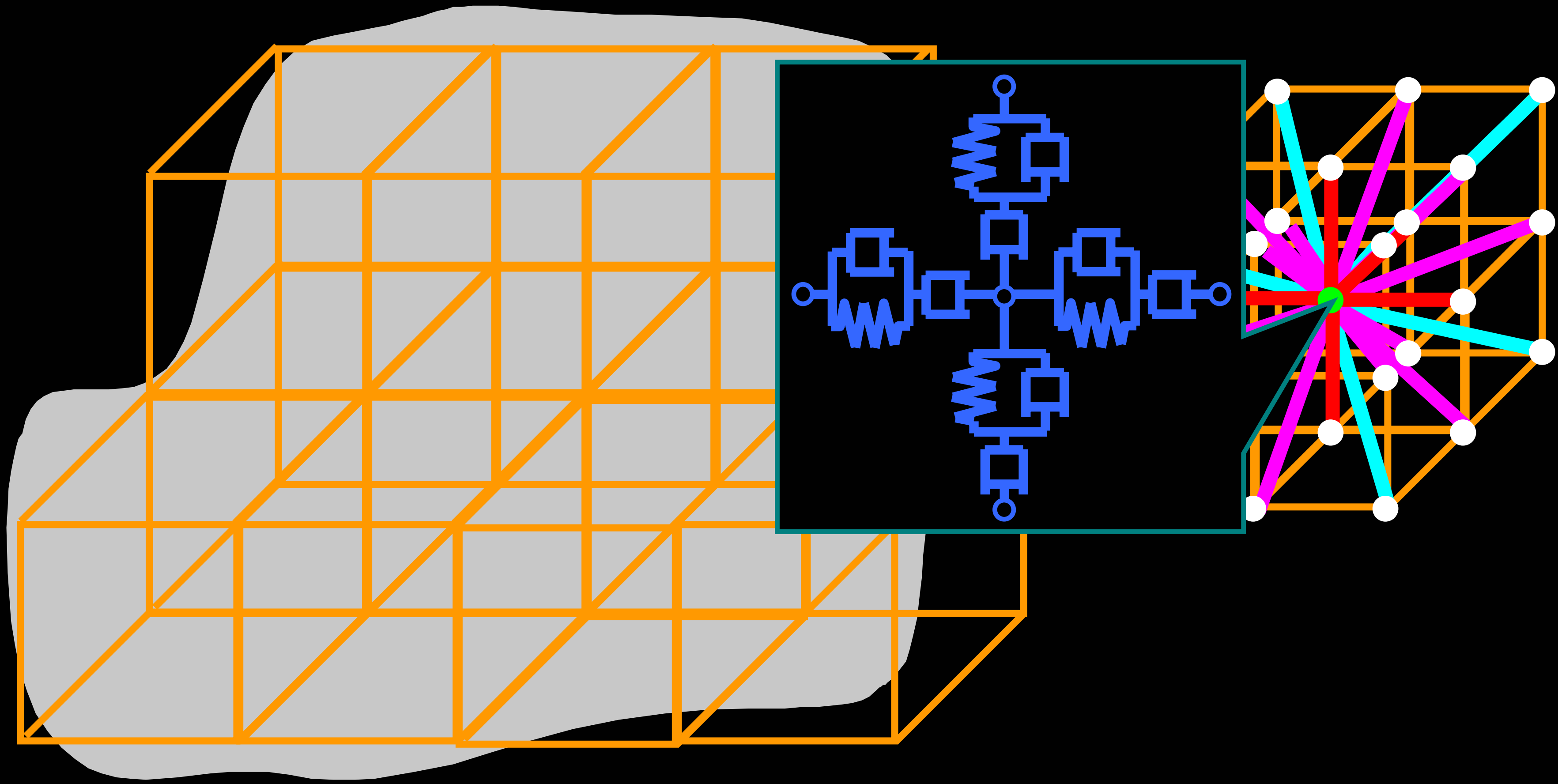
Basic element consists of Voigt model and damper.



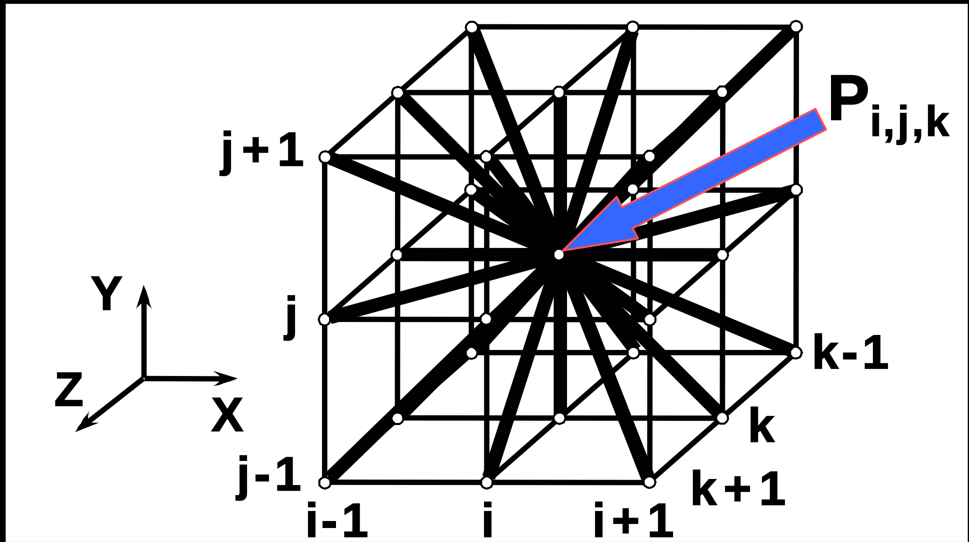
Basic element

Rheology property (e.g., residual displacement) is flexibly condensed.

Voxel/Lattice Basic Model



Constructing Dynamic Equation



$$M = M_{object} \,/\, N$$

M_{object} : Mass of object

N : Number of mass points

$P_{i+\alpha,j+\beta,k+\gamma}$: $P_{i,j,k}$ Neighbors for the mass point

Internal forces between $P_{i,j,k}$ and its neighbor masses

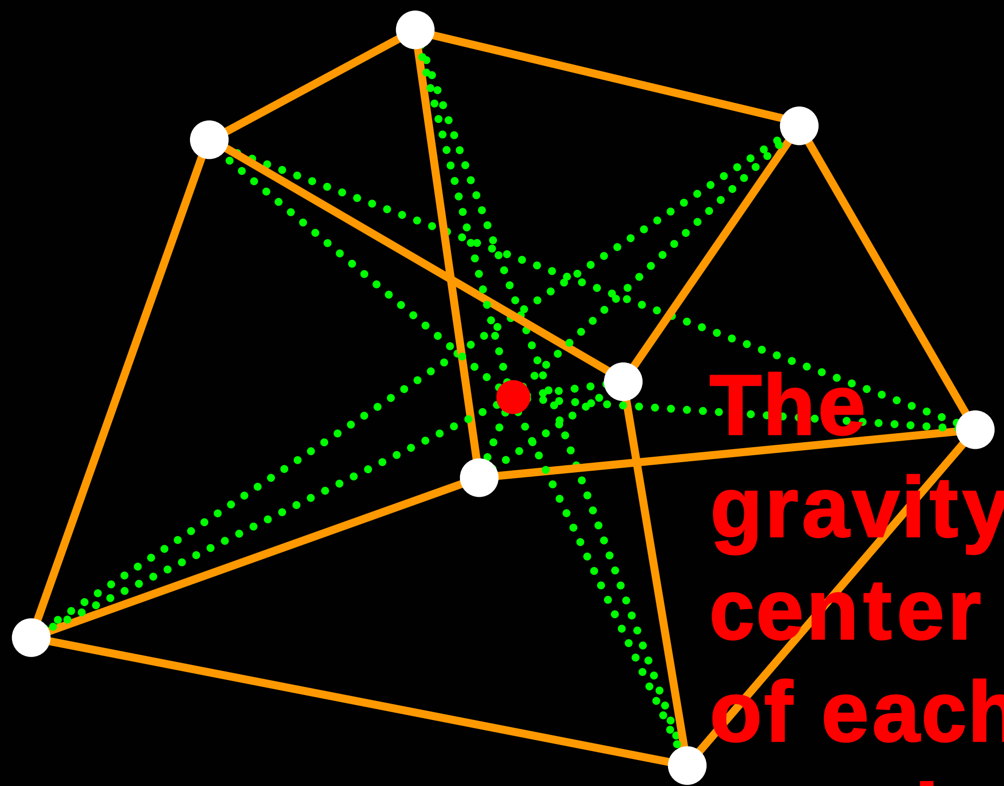
$$F^{int}_{i,j,k} = \sum_{\substack{\alpha,\beta,\gamma \in \{-1,0,1\} \\ (\alpha,\beta,\gamma) \neq (0,0,0)}} F^{\alpha,\beta,\gamma}_{i,j,k}$$

$$M\ddot{P}_{i,j,k} = F^{int}_{i,j,k} + F^{ext}_{i,j,k}$$

External forces directly

The equation is solved by integration methods, e.g., RK, Midpoint, Euler, BDF methods.

Local Volume Constant Condition



The gravity center of each voxel

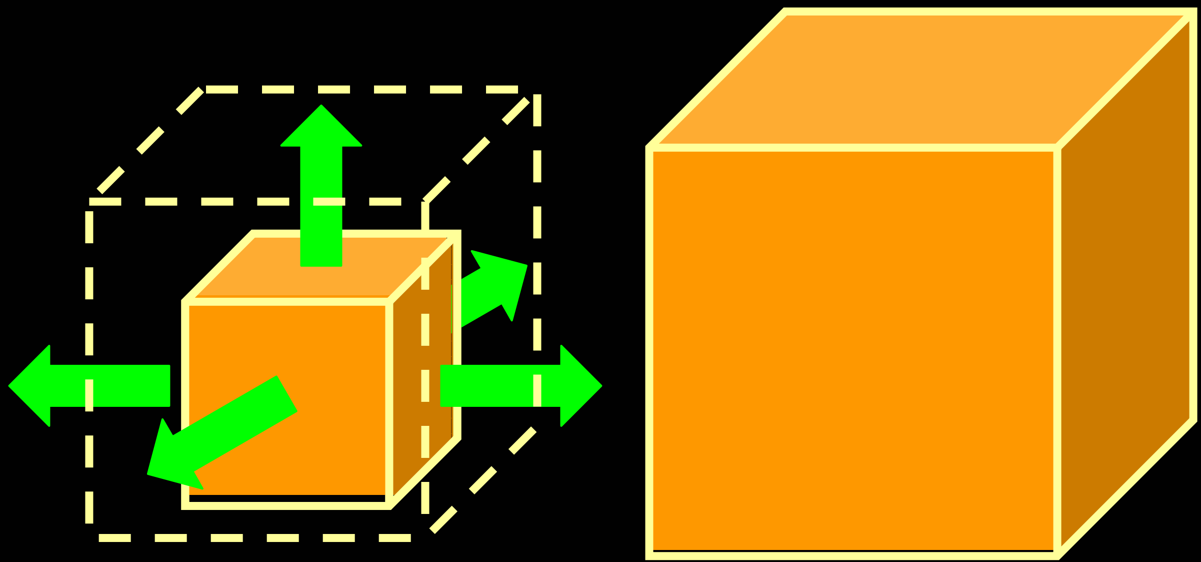
This feed-forward approach **converges** a virtual volume to a real one indirectly.

Global Volume Constant Condition

In order to converge virtual volume to real one, we always give an external force p around virtual object.

Feedback force under Pascal's principle

$$p = -k_{vol}(\dot{V} - V_{int}) - c_{vol}V$$



$V < V_{int}$ $\quad V_{int} < V$

Elastic coefficient : k_{vol}

Viscous coefficient : c_{vol}

Present volume : V

Initial volume : V_{int}

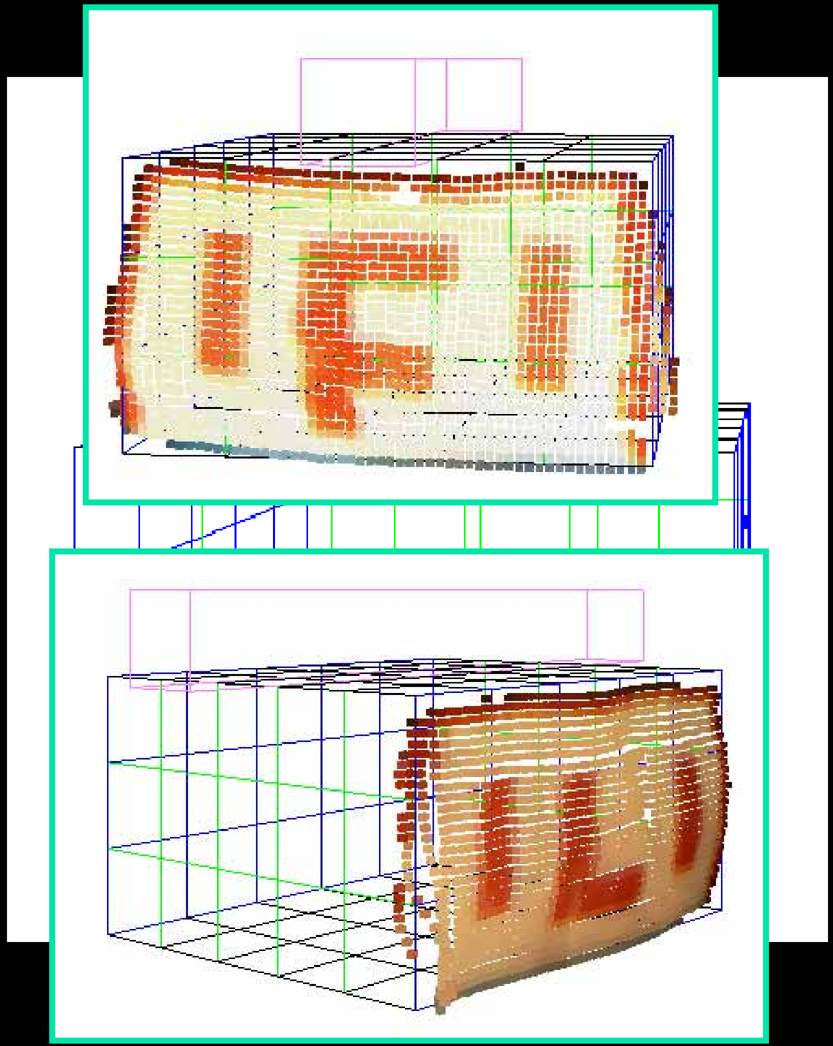
Difference of $\dot{V}$: V

Measuring Real Shape Deformation

- **Real Rheology Object**
  - A real rheology object is made by mixing wheat flour and water.
  - The volume of rheology object is 10× 6× 10 = 600[cm^3].

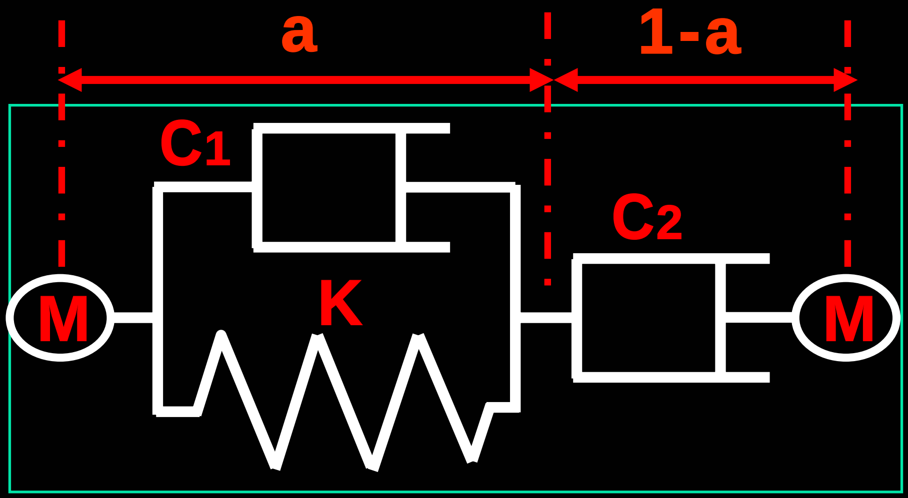
- **Real-time stereo visions**
  - A set of surface points whose number is about 1000 is captured in real-time manner.

Virtual Rheology Object



- **How to measure the difference between virtual and real objects**
  - **A set of captured points are initially located on a virtual object.**
  - **The minimum distance from a captured point to a virtual object is calculated by a modified Lin-Canny algorithm.**
  - **The sum S of distances from captured points at four times are calculated.**

Parameters to Calibrate



Our MSD basic element

- Elastic coefficient K
- Viscous coefficient C1, C2
- Length ratio between Voigt and the other parts a

In order to minimize the sum S of distance errors at four times, we calibrate uncertain parameters.

Randomized Algorithm (RA)
Genetic Algorithm (GA)

Randomized Algorithm (RA)

1. Initialize all the uncertain parameters K,C1,C2 and a within their intervals.
2. We select a local minimum by the steepest descendent method.
3. If the past time amounts to a threshold T_{cal} (=168[hour]), this finishes.
4. Otherwise, after Δ(=10) is randomly added into one of many parameters T_{ran} (=100[number]) times, return to step 2.

Genetic Algorithm (GA)

1. Initialize G_{ind}, G_{gen}, G_{eli} and G_{mut}.
2. G_{ind} is the number of individuals. Each consists of calibrating parameters. P_{gen} and G_{gen} are present and threshold generations.
3. If P_{gen} amounts to G_{gen}, GA finishes.
4. We calculate shape differences S_n ($n=1,2,\ldots,G_{ind}$) between real and virtual objects.

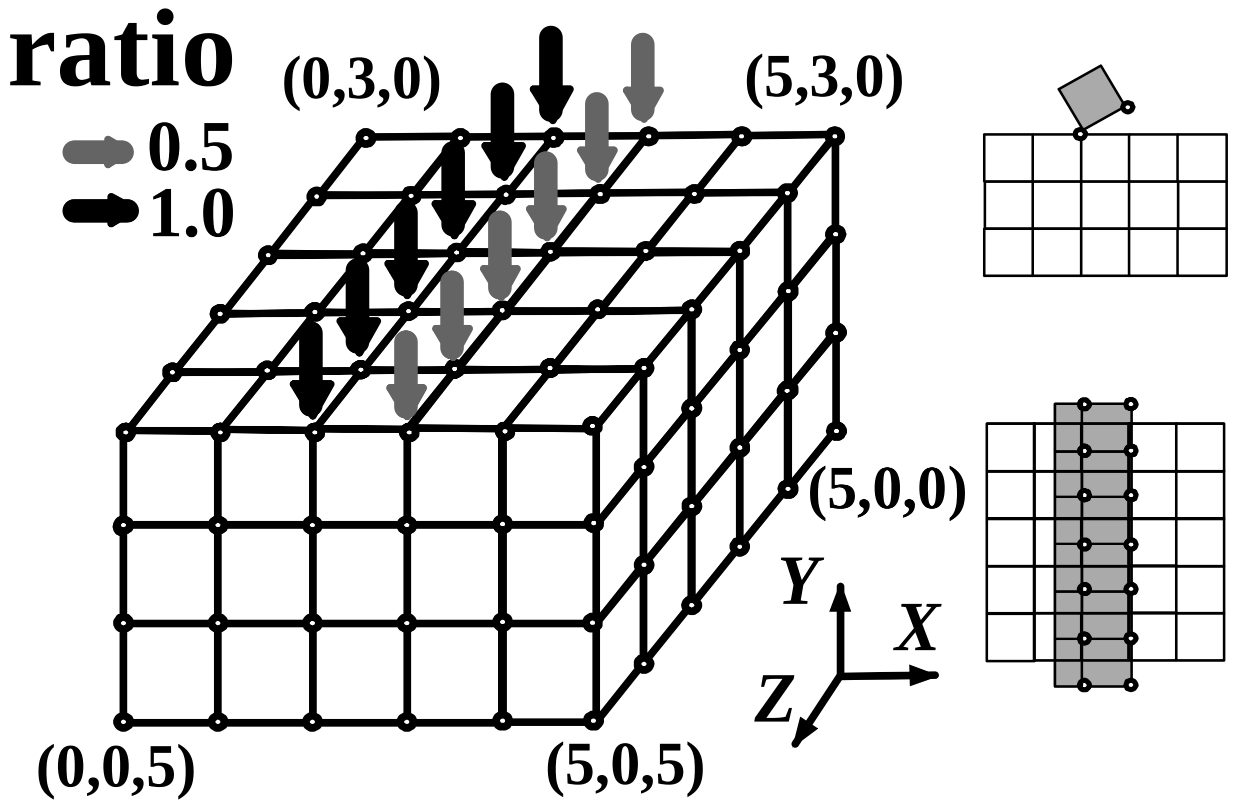
Genetic Algorithm (GA)

5. [Selection] After sorting individuals by S_n. we select better individuals whose number is $G_{ind} \times G_{eli}$ $(0.6 < G_{eli} < 1.0)$.
6. [Mutation] We generate individuals by reversing bits of their originals. whose number is $G_{ind} \times G_{mut}$ $(0.0 < G_{mut} < 0.05)$.
7. [Crossing] We cut and combine parts of two individuals to make the other ones.
8. After increasing P_{gen} by 1, we return to 2.

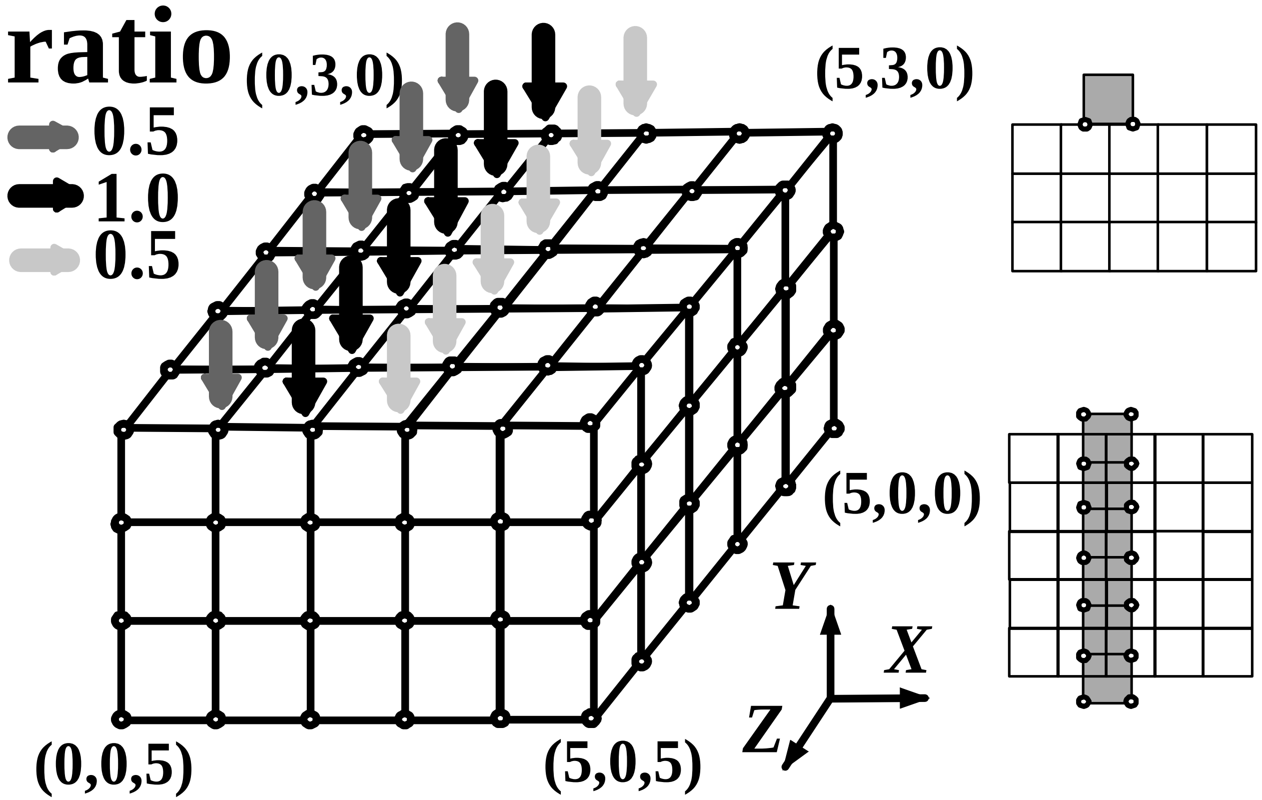
PC Circumstance

- **3-D graphics acceleration board GeForce FX 5600, 128MB**
- **PC (CPU : Pentium4 3.00GHz, Memory : 2048MB)**
- **3-D graphics software Open-GL**

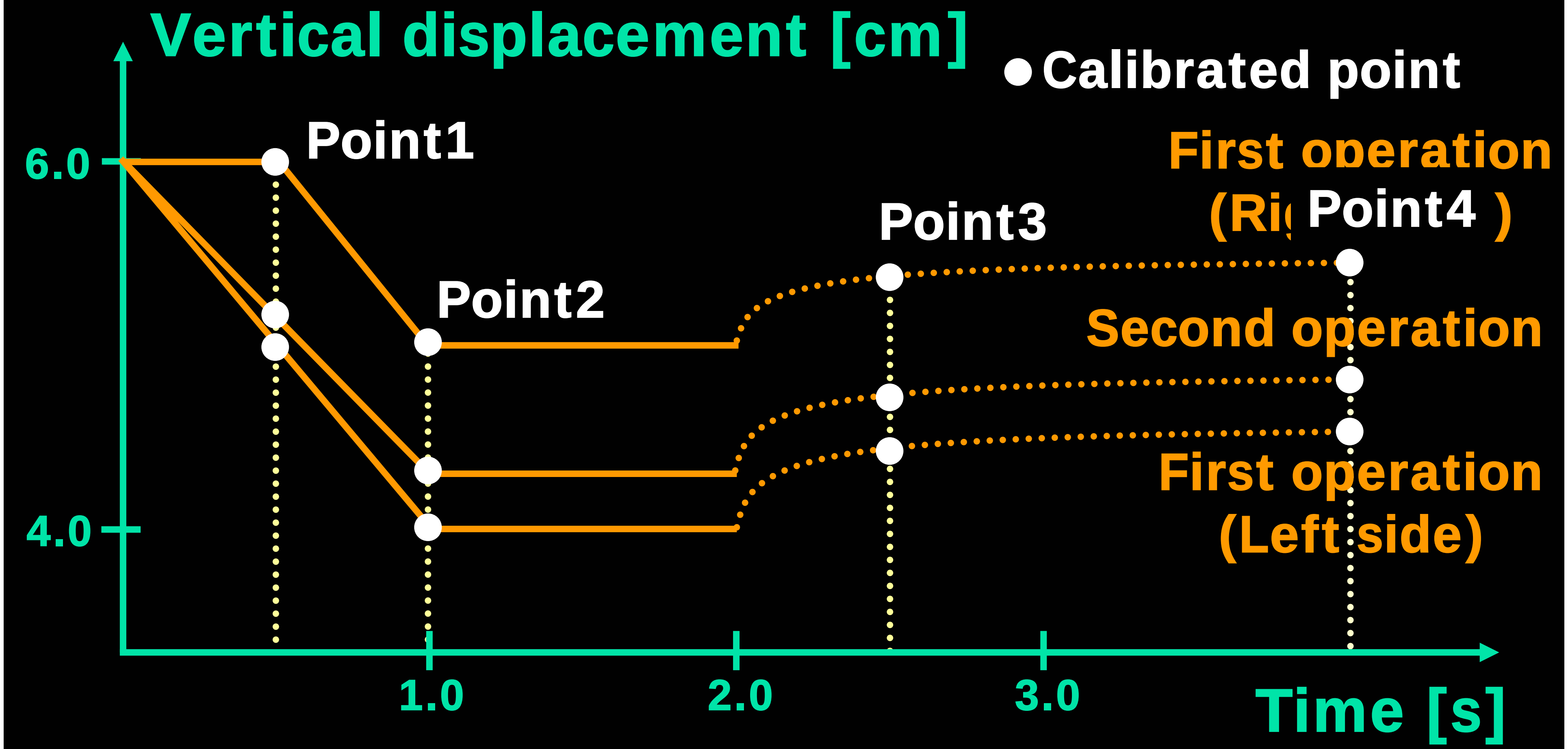
First Operation



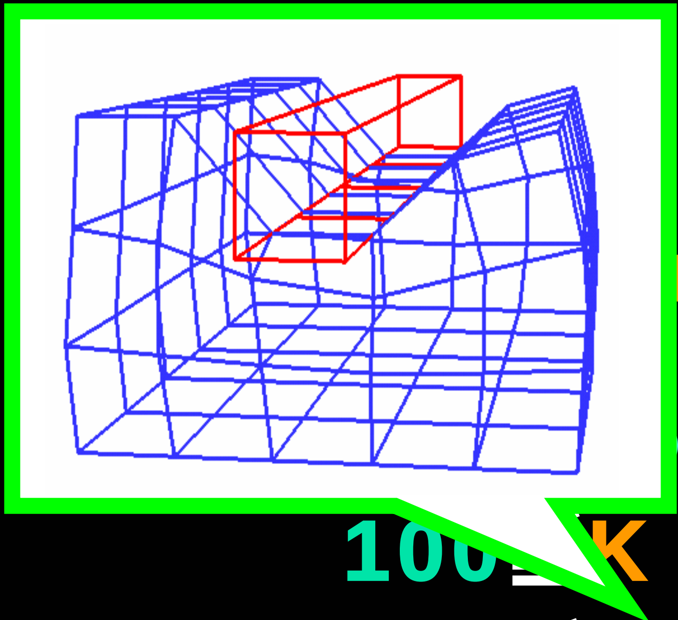
Second Operation



Time Schedule of Two Operation



Stable Parameter Intervals



Otherwise, deformation shapes are almost destroyed.

msec]

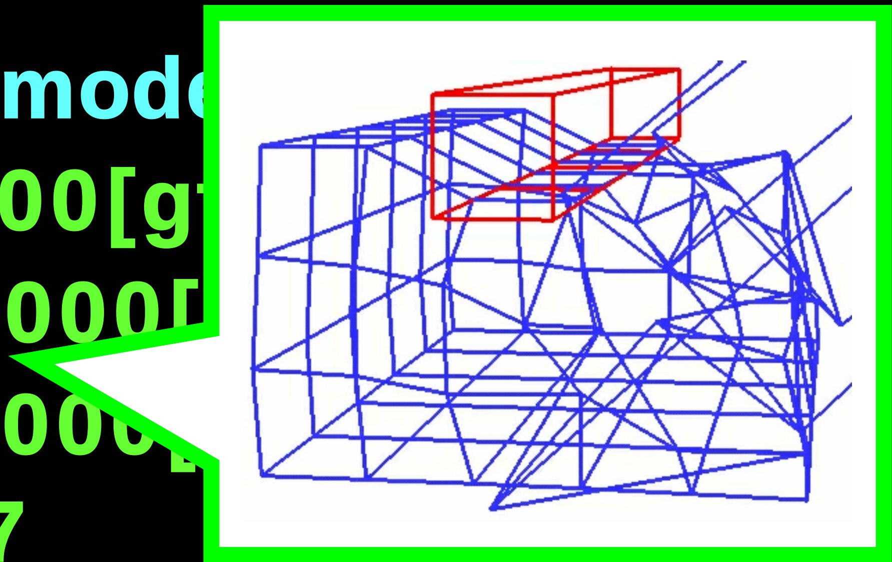
r all mode

100 ≦ K ≦ 3000[g

500 ≦ C_1 ≦ 10000[

500 ≦ C_2 ≦ 2000

0.3 ≦ a ≦ 0.7



Search Space

RA Δ = 10
T_{ran} = 100 [number]

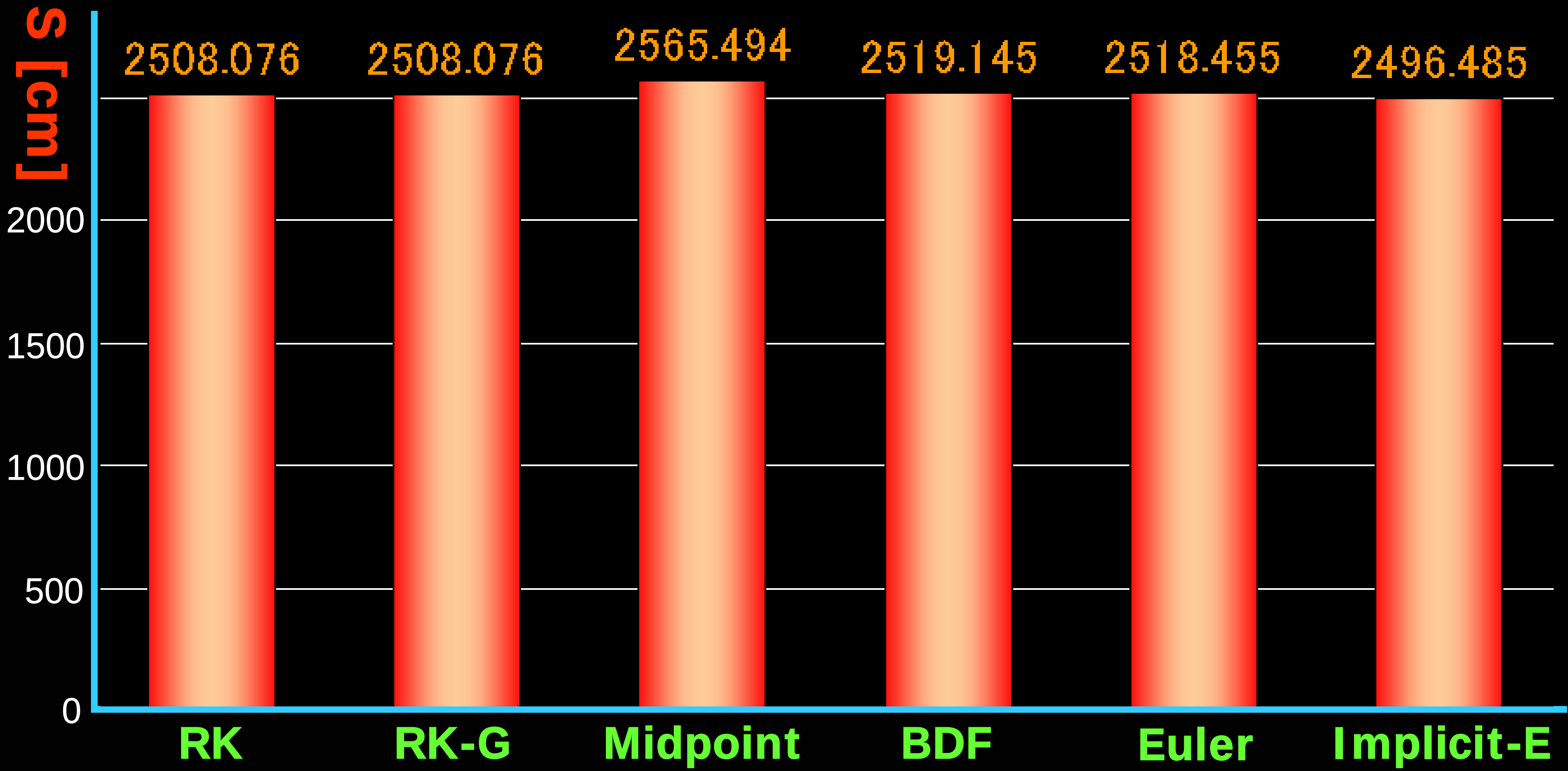
GA G_{ind} = 50
G_{eli} = 0.2
G_{mut} = 0.01

Calculation time is always the same.

To keep comparative fairness of RA and GA, we synchronously select G_{gen} and T_{cal}.

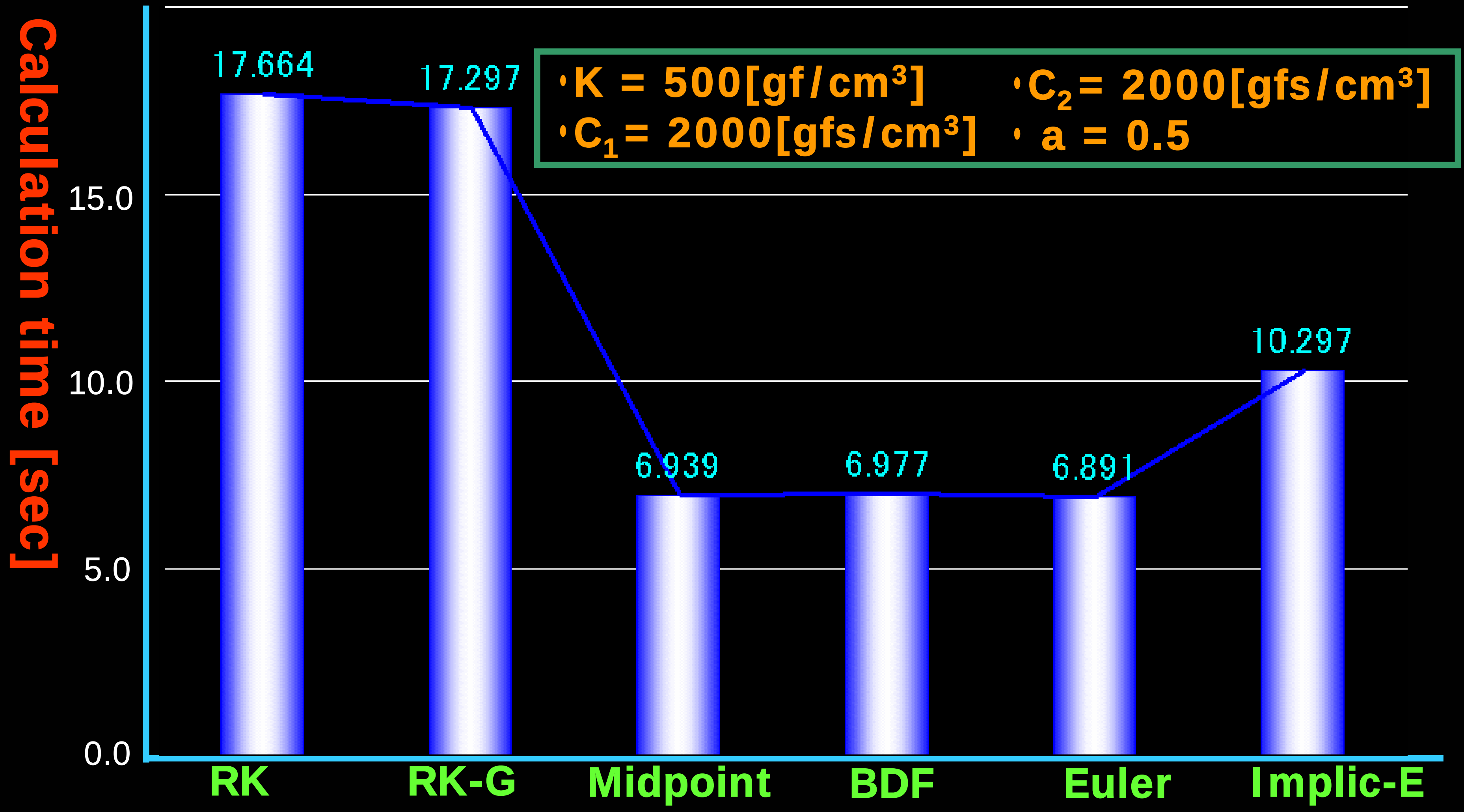
Model1: G_{gen} = 1900 (T_{cal} = 168 [hour])

Shape Difference



- $K = 500 [gf/cm^3]$
- $C_2 = 2000 [gfs/cm^3]$
- $C_1 = 2000 [gfs/cm^3]$
- $a = 0.5$

Integration Time



Four kinds of MSD models

- Model1：without volume constant condition
- Model2：with local volume condition
- Model3：with global volume condition
- Model4：with both volume conditions

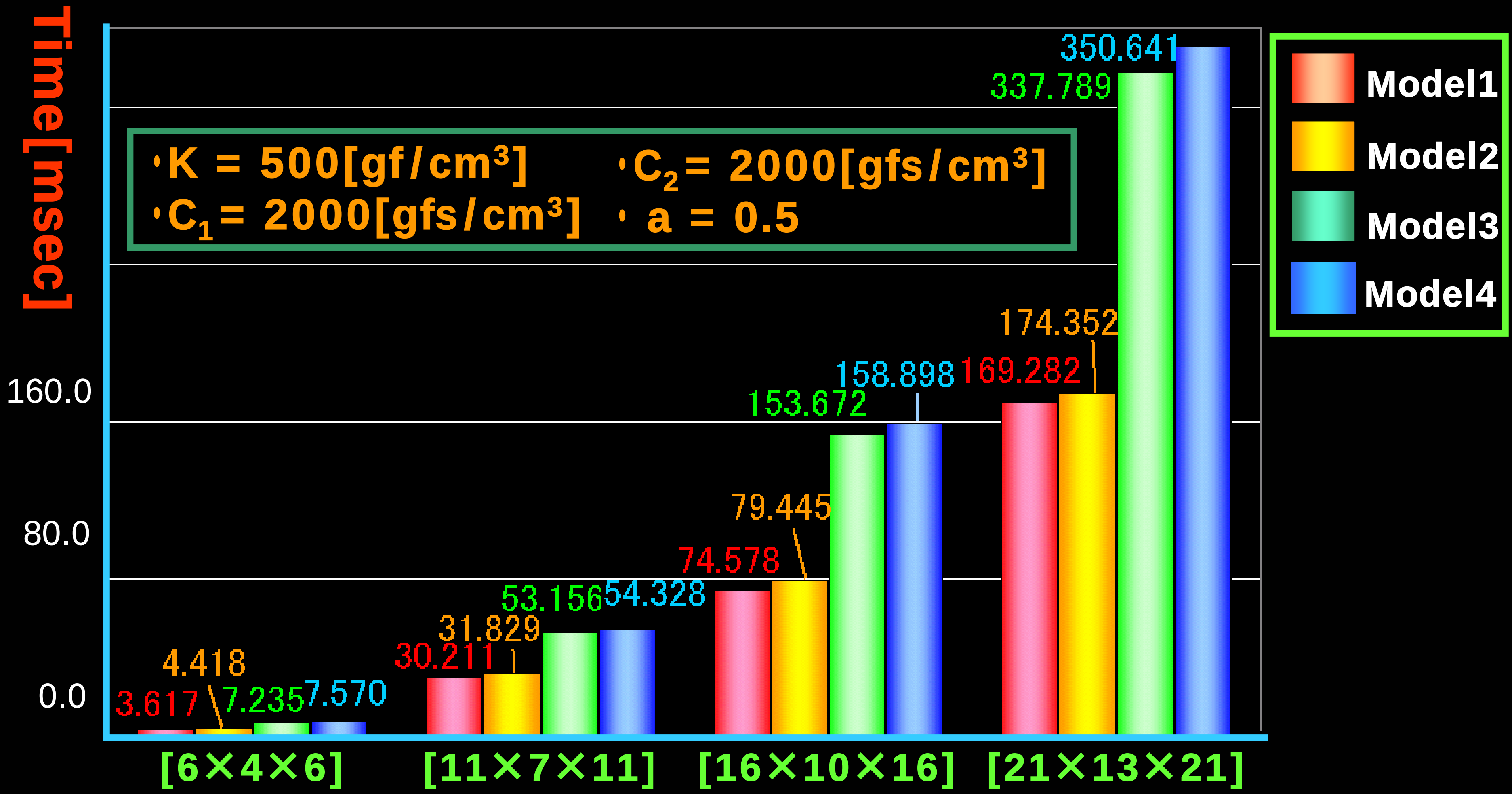
- Fast calculation because the number of basic elements is slightly larger
- Hard calibration of shortest elements in each voxel

Four kinds of MSD models

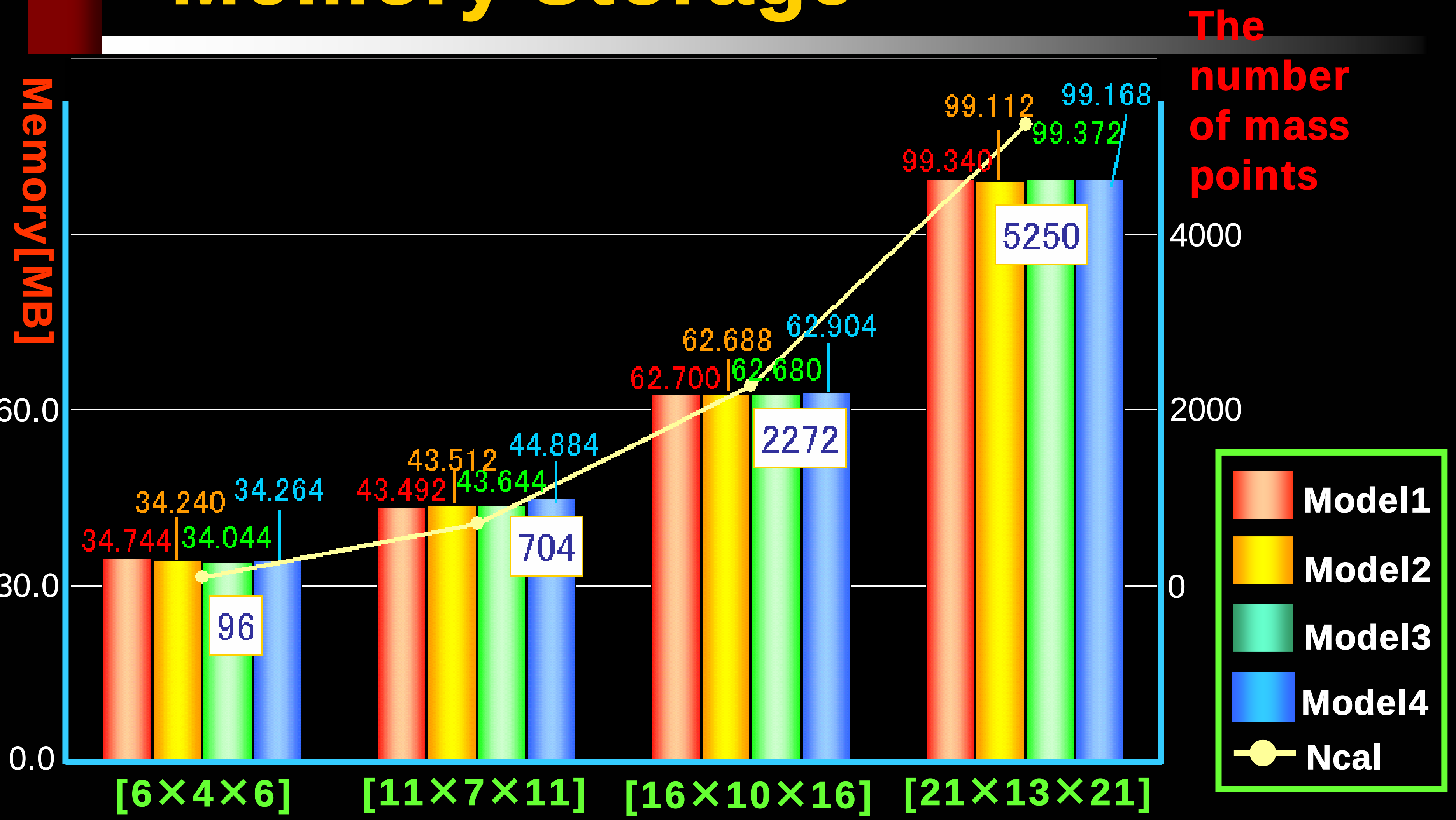
- Model1：without volume constant condition
- Model2：with local volume condition
- Model3：with global volume condition
- Model4：with both volume conditions

- Few calibration because of feedback property
- Hard calculation since volume should be always calculated

Calculation Time



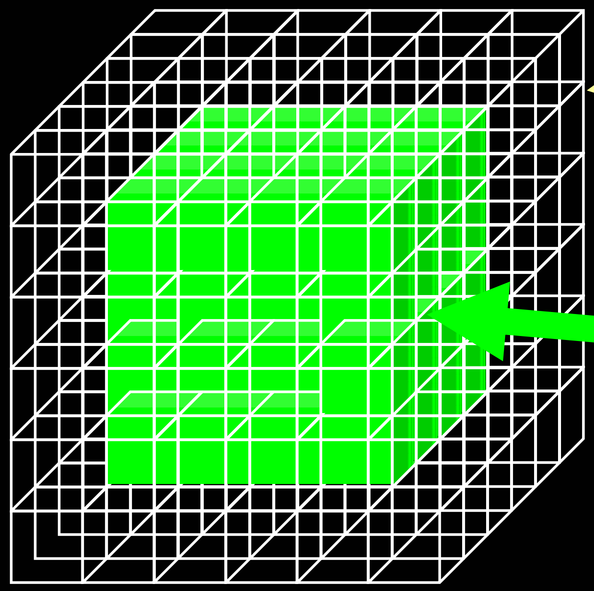
Memory Storage



- K = 500[gf/cm³]
- C_2 = 2000[gfs/cm³]
- C_1 = 2000[gfs/cm³]
- a = 0.5

Surface and Core Areas

Different force propagations in surface and core areas are assumed. Surface parameters K^{surf}, C_1^{surf}, C_2^{surf}, a^{surf} and core ones K^{core}, C_1^{core}, C_2^{core}, a^{core} should be calibrated.



A set of voxels facing object surface is defined as surface area.

A set of the other voxels is defined as core area.

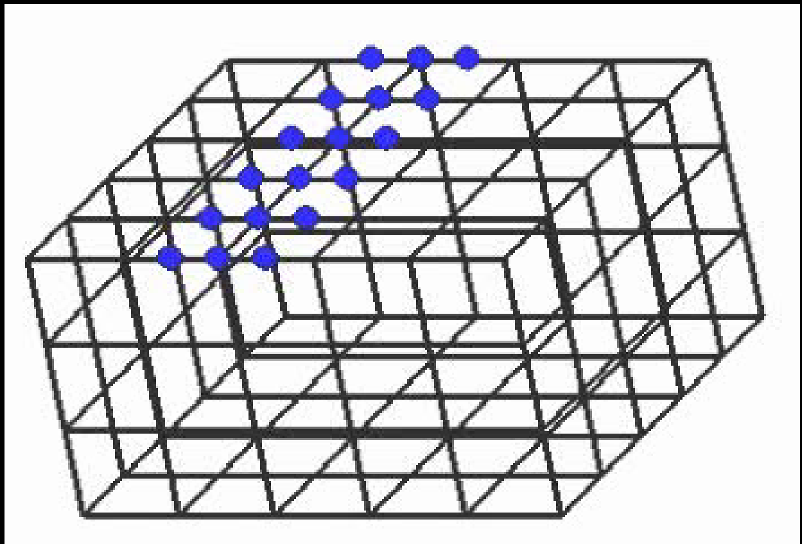
The number of masses：6×6×6

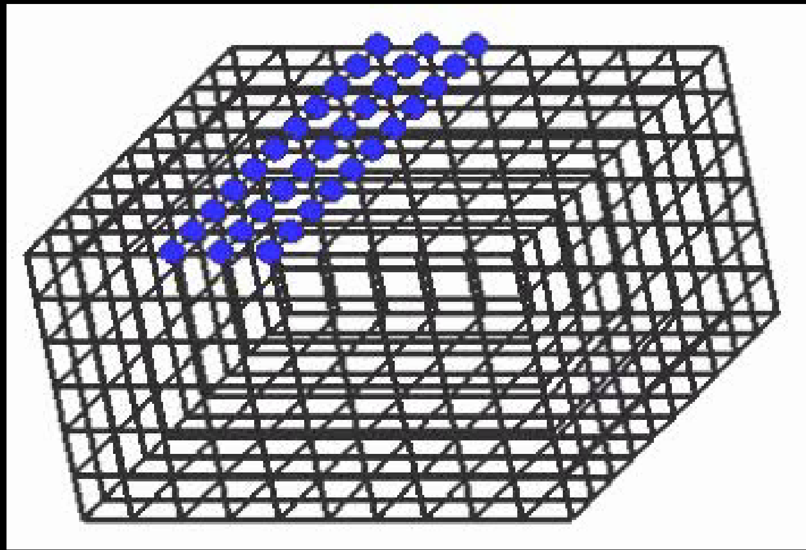
Shape Comparison between RA and GA in the Model 1

The number of captured points is N = 14551						
4 Parameters						
	S	Volume	K	C_1	C_2	a
RA	2481	67.99	2256	648	15944	0.59
GA	2463	67.87	3000	3691	20000	0.70
8 Parameters						
	S	Volume	K^{core}	C_1^{core}	C_2^{core}	a^{core}
RA	2442	67.35	2245	4970	4277	0.68
GA	2350	67.85	293	9988	19961	0.63
			K^{surf}	C_1^{surf}	C_2^{surf}	a^{surf}
		RA	1870	3026	2526	0.47
		GA	2477	561	4454	0.63

External Force Transfers in sparse and dense models

Virtual Rheology Object





Mass number: 6×4×6
Lattice length: 1.0[cm]
●: Pushed masses

Mass number: 11×7×11
Lattice length: 0.5[cm]
●: Pushed masses

Number of individuals in GA when model calculation is changed

Ggen is selected while keeping the same calibration time T_{cal}=168 [hour]. Thus, comparison fairness against RA is maintained.

- Model 2 as Sparse Model : G_{gen}=1900
- Models 3, 4 as Sparse Model : G_{gen}=1100
- Model 2 as Dense Model : G_{gen}= 270
- Models 3, 4 in Dense Model : G_{gen}= 140

If the volume is always calculated, calculation increases and generation decrease in calibration.

Number of individuals in GA when model calculation is changed

Ggen is selected while keeping the same calibration time T_{cal}=168 [hour]. Thus, comparison fairness against RA is maintained.

- Model 2 as Sparse Model : G_{gen}=1900
- Models 3, 4 as Sparse Model : G_{gen}=1100
- Model 2 as Dense Model : G_{gen}= 270
- Models 3, 4 in Dense Model : G_{gen}= 140

If resolution increases,
calculation increases and generation
decrease in calibration.

Calibrate Parameters in Local Volume Constant Condition (Models 2 and 4)

$50 \leqq K^{surf\text{-}in}, K^{core\text{-}in}, \leqq 3000[gf/cm^3]$

$100 \leqq K^{surf\text{-}on}, K^{core\text{-}on}, \leqq 3000[gf/cm^3]$

$250 \leqq C_1^{surf\text{-}in}, C_1^{core\text{-}in} \leqq 10000[gfs/cm^3]$

$500 \leqq C_1^{surf\text{-}on}, C_1^{core\text{-}on} \leqq 10000[gfs/cm^3]$

$250 \leqq C_2^{surf\text{-}in}, C_2^{core\text{-}in} \leqq 20000[gfs/cm^3]$

$500 \leqq C_2^{surf\text{-}on}, C_2^{core\text{-}on} \leqq 20000[gfs/cm^3]$

$0.3 \leqq a^{surf}, a^{core}, a^{surf}, a^{core} \leqq 0.7$

Sixteen parameters should be calibrated.

Parameters in each voxel

$K^{surf\text{-}in}, C_1^{surf\text{-}in},$
$C_2^{surf\text{-}in}, a^{surf\text{-}in},$
$K^{core\text{-}in}, C_1^{core\text{-}in},$
$C_2^{core\text{-}in}, a^{core\text{-}in}$

Parameters on each voxel

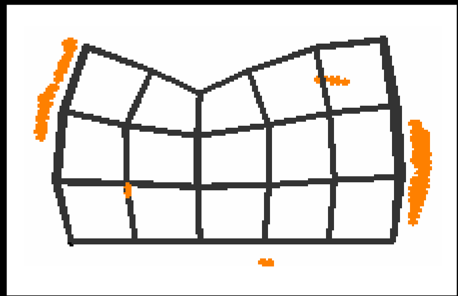
$K^{surf\text{-}on}, C_1^{surf\text{-}on},$
$C_2^{surf\text{-}on}, a^{surf\text{-}on},$
$K^{core\text{-}on}, C_1^{core\text{-}on},$
$C_2^{core\text{-}on}, a^{core\text{-}on}$

Comparative Shape Results

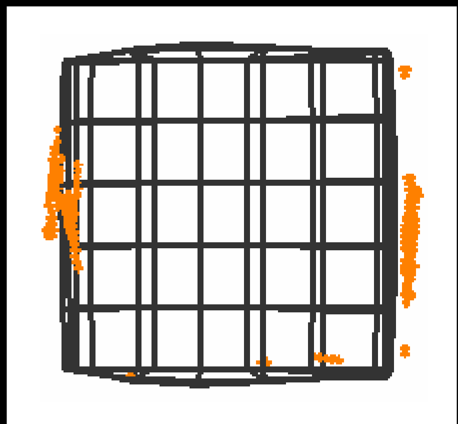
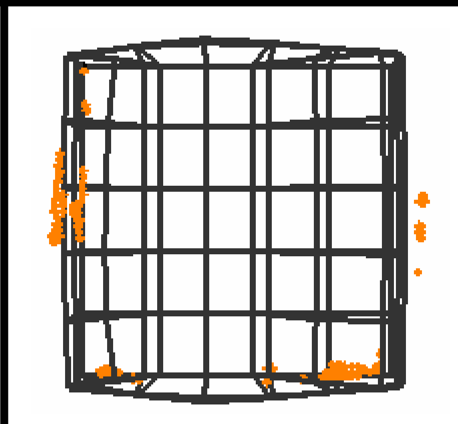
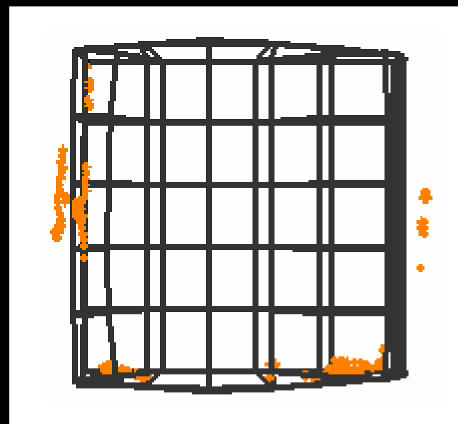
The number of captured point is N = 15732				
	S (Sparse)	S (Dense)	Volume (Sparse)	Volume (Dense)
Model 2'	1831	1506	76.30	72.88
Model 3	1724	1663	74.97	75.16
Model 4'	1835	1352	75.94	75.64

The number of points whose errors are larger than 0.25cm						
		First	Second	Third	Fourth	Total
Model 2'	Sparse	187	395	415	393	1390
	Dense	219	167	232	267	885
Model 3	Sparse	361	265	299	267	1192
	Dense	523	263	199	212	1197
Model 4'	Sparse	215	331	480	567	1390
	Dense	258	188	168	147	761

Comparative Shape Results (cont'd)

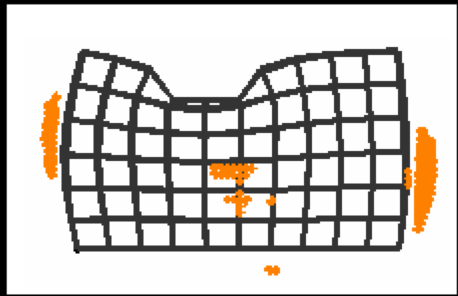
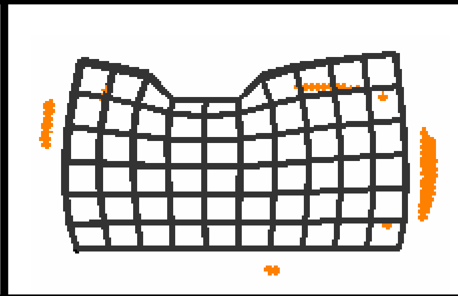
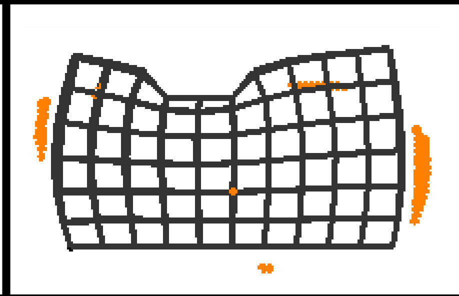
Real Rheology Object	Model 2'	Model 3	Model 4'
			

Front side

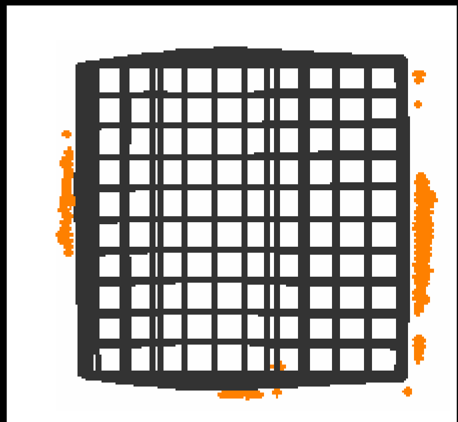
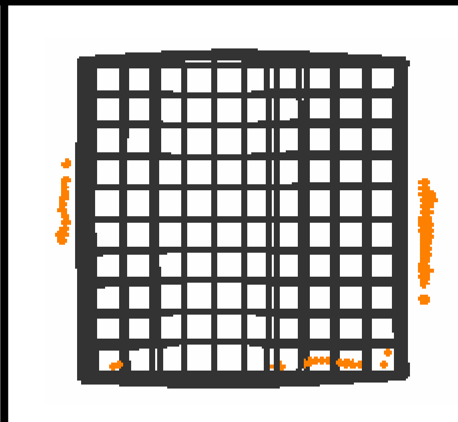
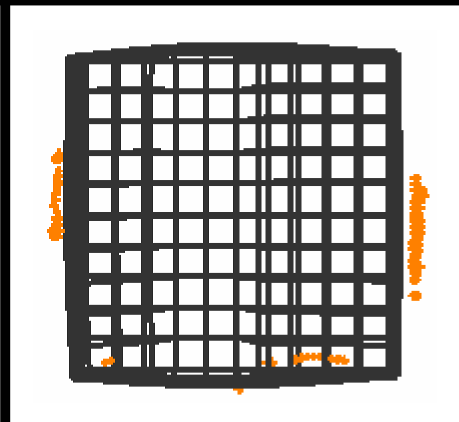
			

Upper side

Comparative Shape Results (cont'd)

Real Rheology Object	Model 2'	Model 3	Model 4'
			

Front side

Upper side

Conclusions

- By using MSD voxel/lattice models and two volume constant conditions, we build a virtual rheology object.
- Euler Method whose time step is 2 ms is selected concerning to computational efficiency and shape stability.
- If the number of uncertain parameters is larger, GA is better than RA.
- The larger the numbers of calibrating parameters and discrete voxels are, the better precision of deformation shape is.

Force Outline (Part 2)

- Research purpose
- **Model1** - Cell/lattice structure with many basic **MSD** (**M**ass-**S**pring-**D**amper) elements
- **Model2** & **3** by adding each of **local** & **global** **volume constant conditions** into **Model1**
- Classic force models

  such as **Pull-off** & **Friction forces**
- **Calibrating** uncertain parameters of each model **by** **shape deformation** & **force impulses**
- Experimental Comparisons
- Conclusion & future works

Research Purpose

- Comparison of several types of MSD model with/without conservation lows of volume

... by giving displacement at surrounding masses

... by calibrating & evaluating **Shape difference** between real & virtual objects

Shape Precision

The model **including conservation lows of volume** is **effective** for obtaining **precise shape deformation**.

Research Purpose (cont'd)

- Comparison of several types of MSD model with/without conservation lows of volume

... by giving displacement at surrounding masses

... by calibrating & evaluating **Shape difference** between real & virtual objects

Force Precision

All calibrations **based on** **Shape difference** are **not enough** for feeling **reactive force** from deformed virtual rheology object.

Based on Force impulses

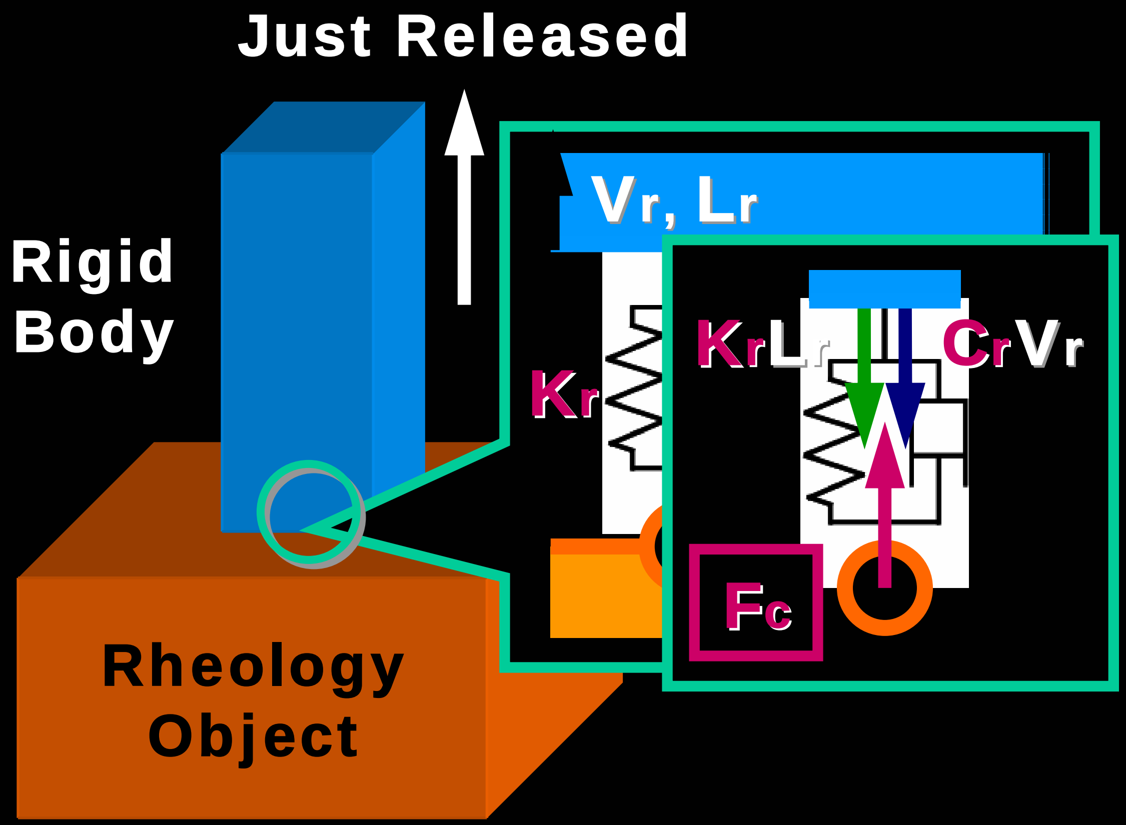
We applied **a multiple combination** of pushing, calibrating & evaluating operations to MSD models

➡ **to investigate the best one** & **its properties**

Pull-off Force

- Pull-off force : F_c [N]

If a rigid is slowly left from the rheology object, we should consider a pull-off force as follows :



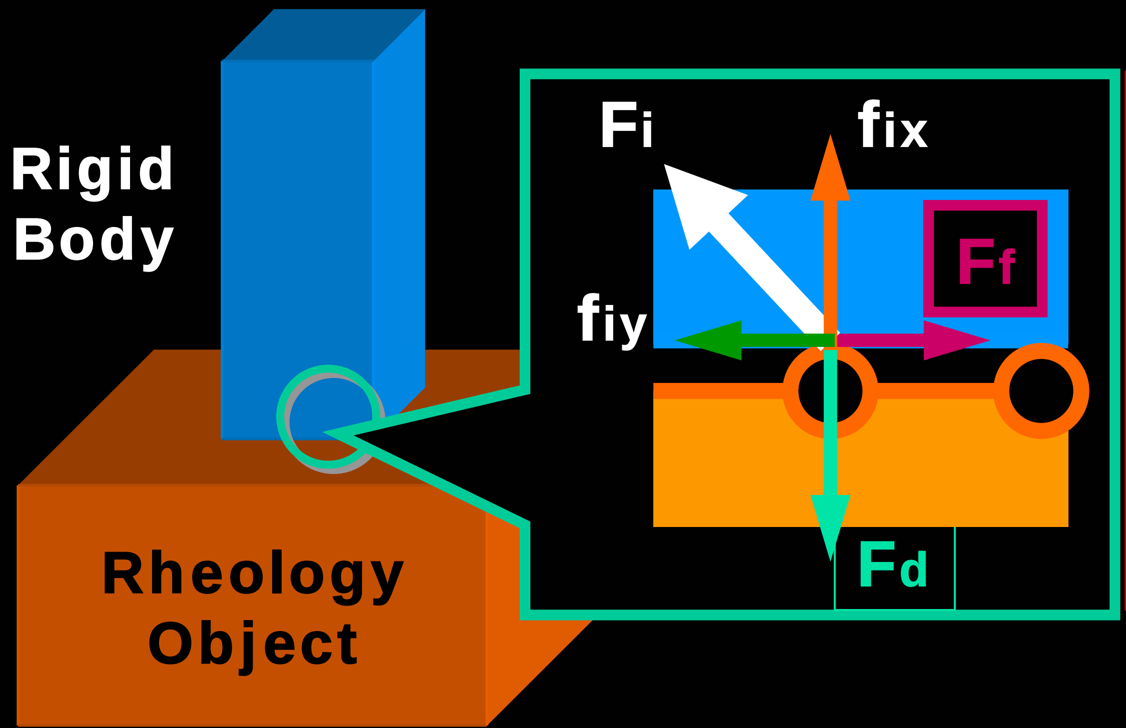
Voigt model is located at each mass point between rigid and rheology object.

Its force is neglected if the relative velocity is over a given threshold (V_t).

Friction Force

- Friction force : F_f [N]

  If two object are encountered, static ($\mu_s F_d$) or kinetic ($\mu_k F_d$) friction appears between rigid body and rheology object.



$f_{iy} \leqq \mu_s F_d$

$\Rightarrow F_f = f_{iy}$

$f_{iy} > \mu_s F_d$

$\Rightarrow F_f = \mu_k F_d$

Shape Measuring System

- **Real Rheology Object**
  - A real object is made by mixing wheat flour and water.
  - The volume is 10×6×10=600[cm^3].

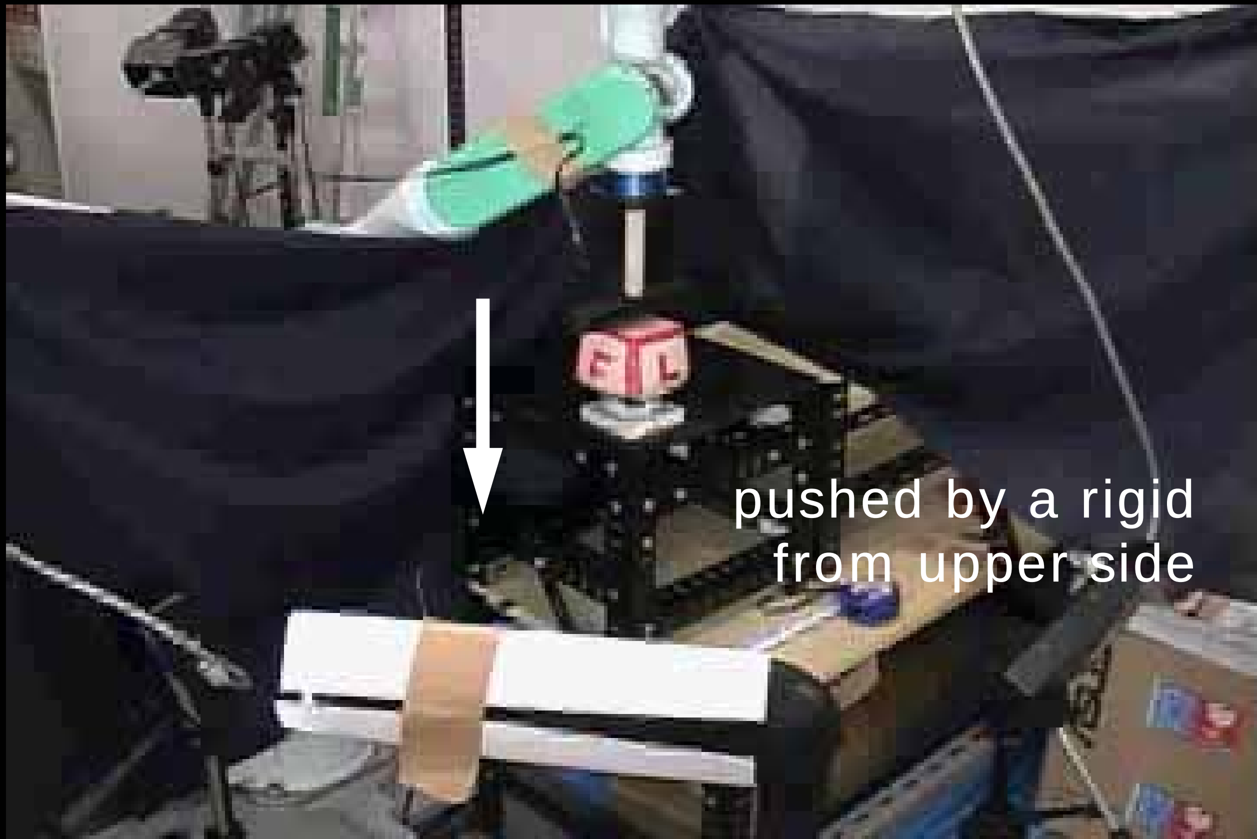
- **Real-time stereo visions :** A set of surface points whose number is about 1000 is captured at least ten times per second.
- **Difference calculation :** The sum of errors is quickly cauculated by Lin-Canny algorithm.

Force Measuring System

- **Real Rheology Object**
  - A real object is made by mixing wheat flour and water.
  - The volume is 10×6×10=600[cm^3].

- **Real-time force sensors :** 3 DOF forces and 3 DOF moments are captured by the sampling is 8 [kHz].

Video

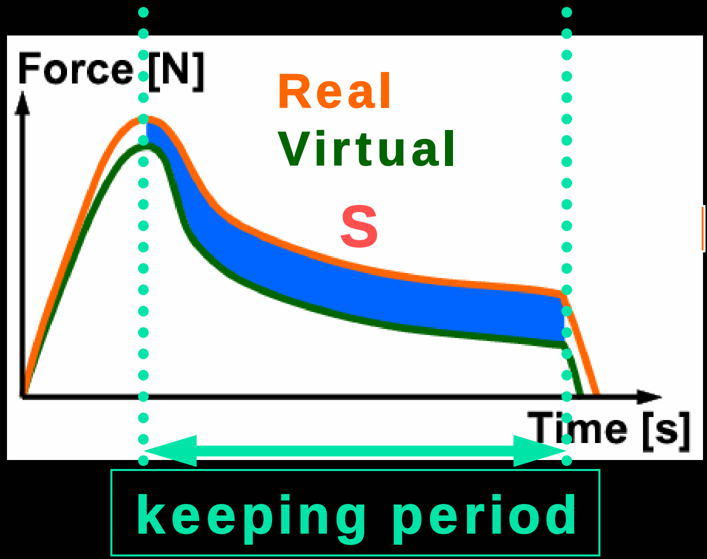


Pushing : 0.0 – 1.0 [sec]
Keeping : 1.0 – 3.0 [sec]
Releasing : 3.0 – [sec]

Parameters to calibrate

In order to calibrate many uncertain parameters of MSD models, we define **S** which is the sum of {force or shape} differences during the keeping period.

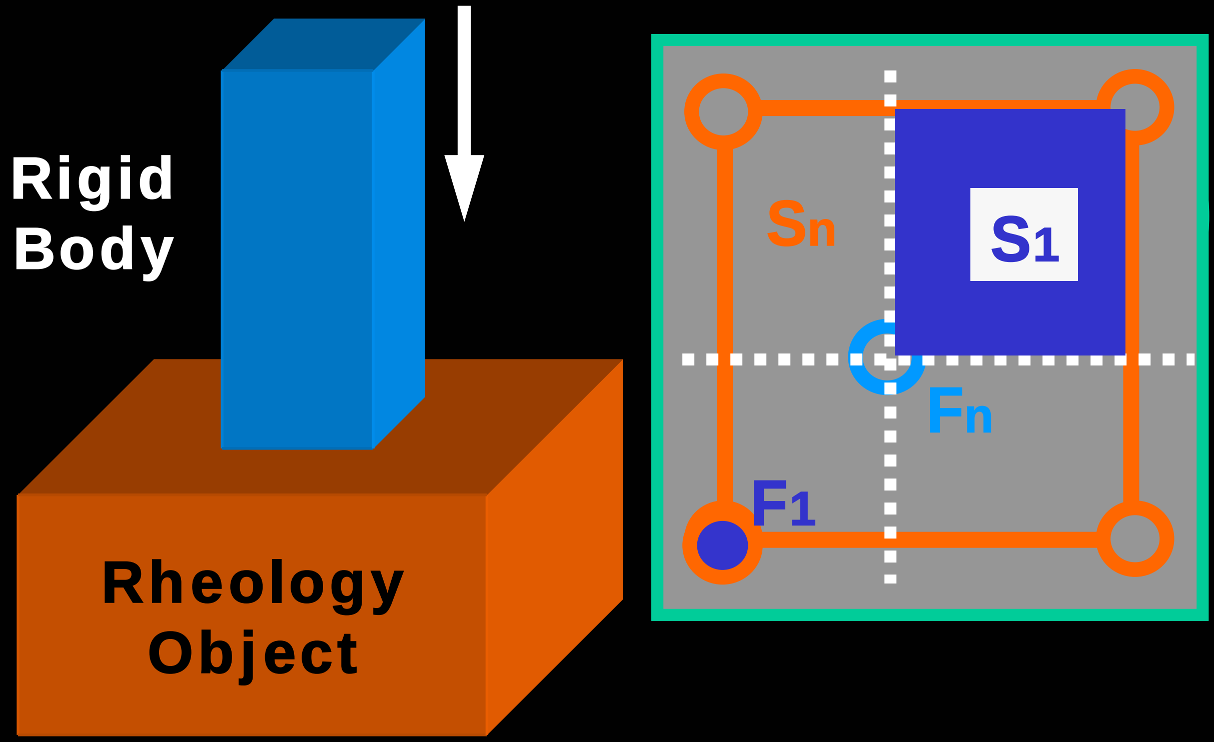
(e.g.,Force differences)



By using **GA**, we determine a set of uncertain parameters so that **S** can be **minimized**.

Digital Force Transmission

- Forces or displacements are exchanged between mass points around encountered rigid and rheology objects.
- The magnitude of force or displacement is proportional to opposite areas.



$$F_1 = F_n(S_1/S_n)$$

HMI
Human Machine Interface Lab

Comparisons

Three models applied by two kinds of combinations (A, B) are **evaluated by their force differences** in order to clarify their characteristics.

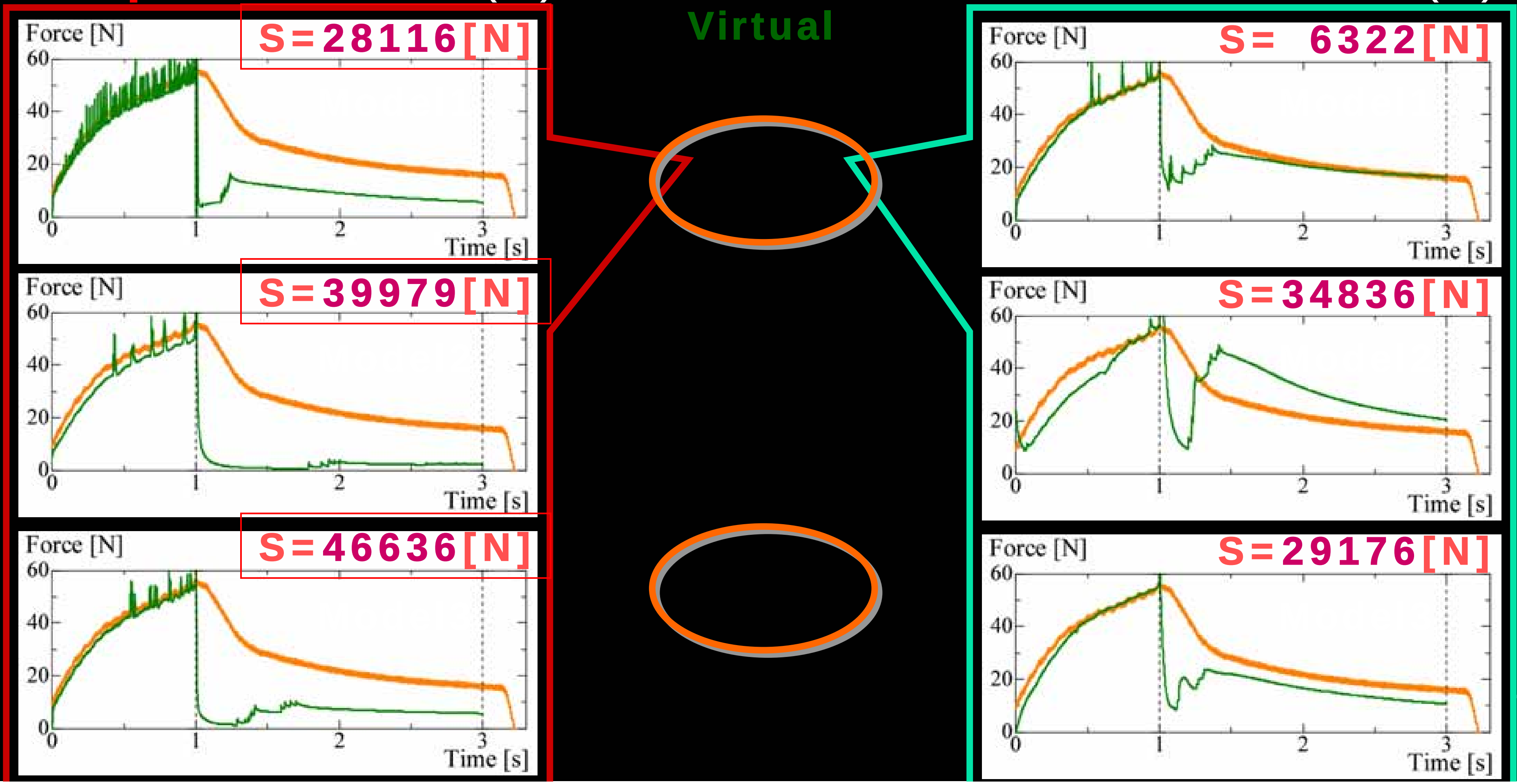
- **Three kinds of models**
  - **Model1** – Our basic model with cell/lattice structure
  - **Model2** – **Model1 with** a Local volume constant condition
  - **Model3** – **Model1 with** a Global volume constant condition
- **Two kinds of combinations**
  - **TYPE-(A)** : Pushing by **displacement** – Calibrating by **shape** – Evaluating by **force**
  - **TYPE-(B)** : Pushing by **force** – Calibrating by **force** – Evaluating by **force**

Experimental results

- **Evaluated** by sum of **Force differences S** :

Calibrated by sum of **Shape difference**(**A**)

Calibrated by sum of **Force difference**(**B**)



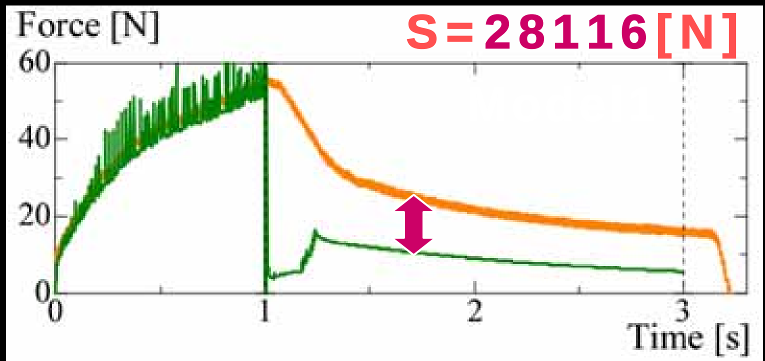
Experimental results

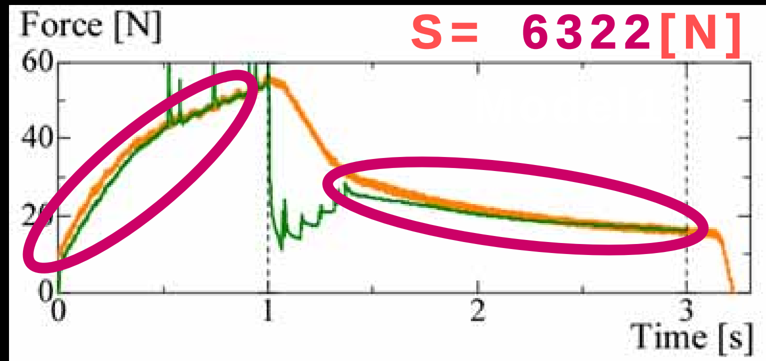
- **Evaluated** by sum of **Force differences S** :

Calibrated by sum of **Shape difference**(**A**)

Real
Virtual

Calibrated by sum of **Force difference**(**B**)





Model1 made by the different two combinations

Model1 made by the combination of pushing & calibrating by force sequences and their difference **shows** high precision of force.

Conclusions

- A modified **MSD** model is proposed for simulating **rheological characteristic**, and also classic pull-off, and friction models are additionally used.
- The model **excluding** volume constant condition (**Model1**) is **more suitable** for obtaining **force precision** because **no ad-hoc force** appears.
- The model made by the combination of pushing and calibrating by force sequences and their difference shows **high precision of force**.