A Hybrid Deformation Model for Virtual Cutting

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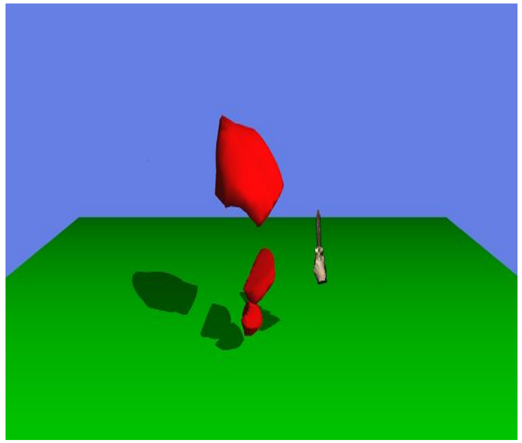
Outline

- Motivation
- Related work
- The hybrid deformation model
- The cutting procedure
- Results
- Conclusion and future work

Motivation

- A valid deformation model to simulate large deformations and non-linear behaviors of soft tissues in virtual surgery
- Cutting the soft tissues realistically and robustly with the reconstructed scalpel



Motivation

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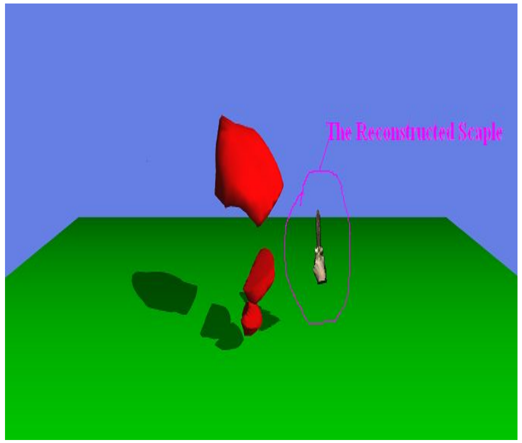
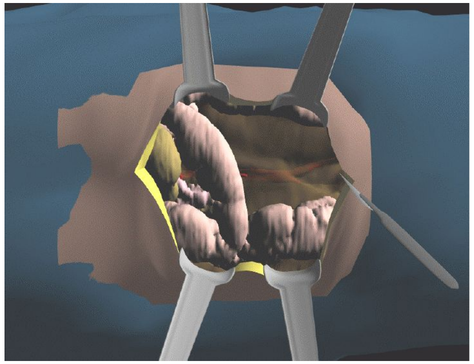
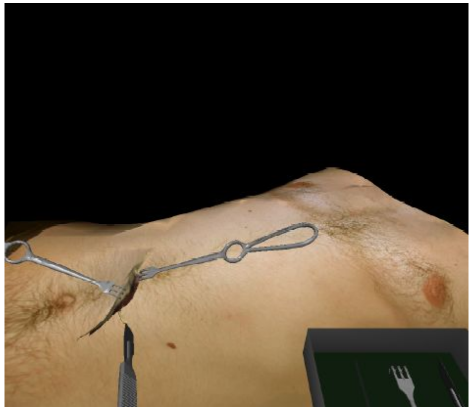
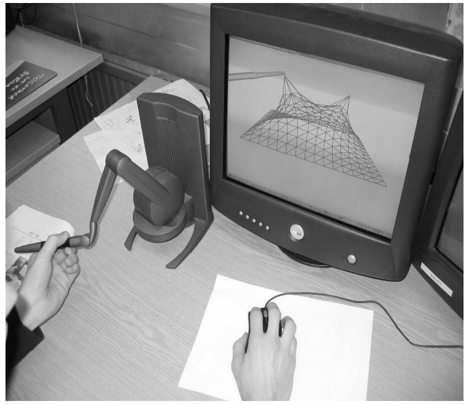


Related Work

- Virtual surgery system
  - The HT Abdominal Trauma Simulator(Bro-Nielsen et al,1998)
  - PC-based suturing simulator for open wounds(Webster et al,2001)
  - Open Surgery Simulator(Bielser et al,2002)
  - Hernia repair system(Paul Gasson et al,2004)

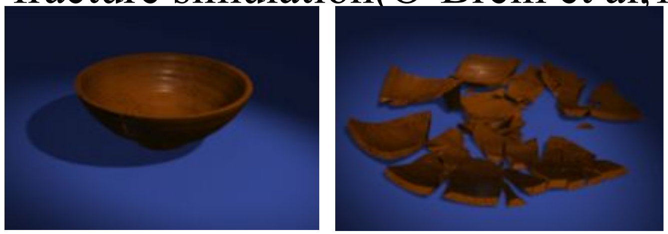




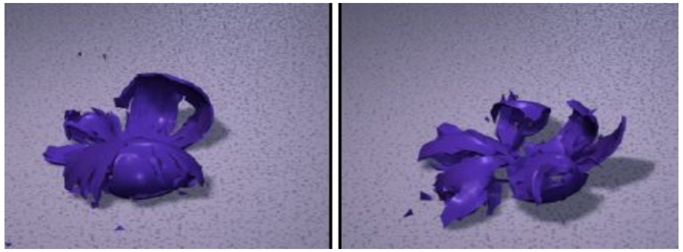


Related Work

- Deformation simulation based on FEM
  - Brittle fracture simulation(O'Brein et al,1999)



  - Ductile fracture simulation(O'Brein et al,2002)



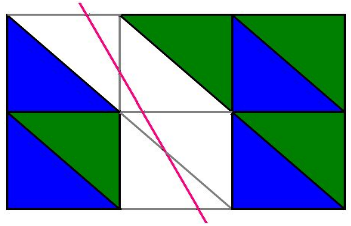
Limitation: Time-consuming

  - Total lagrangian explicit dynamics FEM(K.Miller et al,2007)

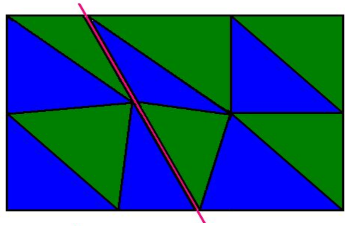
    need not to assemble global stiffness matirx; easy to cut;could be accelerated by GPU

Related Work

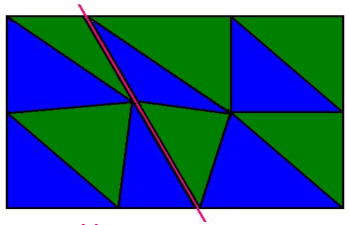
- Cutting methods for FEM
  - Removing cutting method(D.C.Popescu,et al,2005)



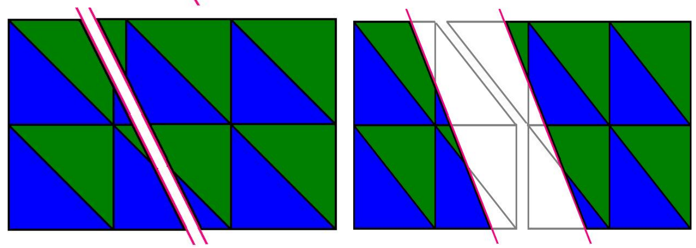
  - Snapping cutting method(H.W.Nienhuys,et al,2000)



  - Decomposition cutting method(D.Bielser,et al,1999; F.Ganovelli,et al,2000)



  - The virtual node method(N.Molino,et al,200)



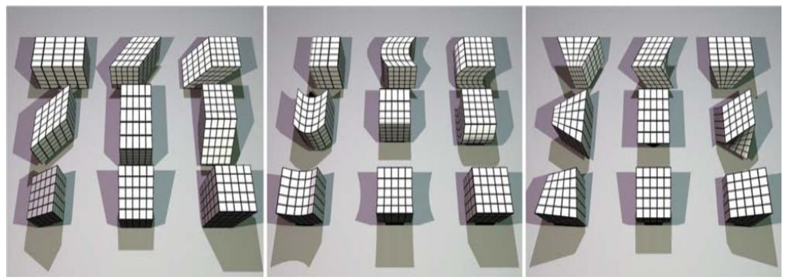
Related Work

- Meshless deformation method
  - Meshless,continuum mechanics based model(M.Muller, et al,2004)
  - Meshless animation of fracturing solids(M.Pauly, et al,2005)

    Limitation: costly to compute in real time

  - Meshless shape matching deformation model(M.Muller, et al,2004)

    pure geometry constrained; large deformations; high efficiency

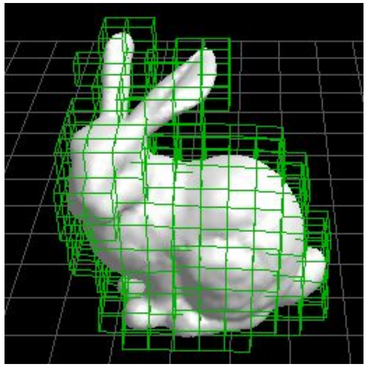


Related Work

- Acceleration scheme
  - Multi-resolution models

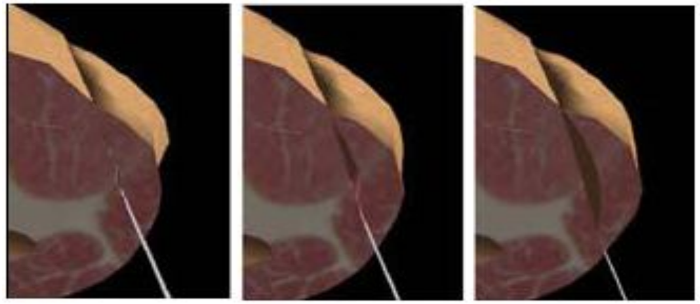
    lattice-based FEM(S.Capell,et al, 2002)

    fast lattice shape matching(A.R.Rivers,et al, 2007)



  - Hybrid model

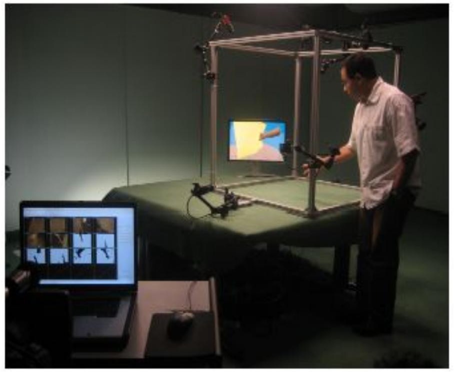
    hybrid condensed FEM model(W.Wen,et al, 2005): partitioning the soft tissue into operational and non-operational regions

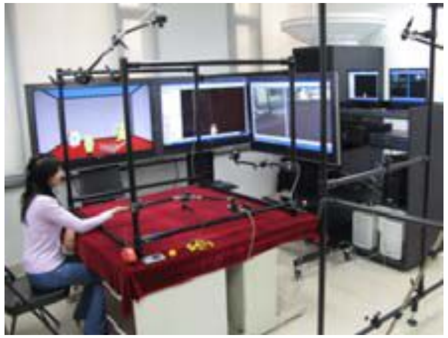


  - GPU acceleration

Related Work

- Interaction platforms
  - Grimage developed by INRIA (J.Allard, et al, 2007)
  - Ours Dream World(Shujun Zhang, et al, 2009)
  - Tele-immersive framework(G.Kurillo,et al, 2009)





Related Work

- Our contributions
  - propose a novel hybrid deformation model which partitions a soft tissue into operational and nonoperational regions. The operational regions is simulatied by TLED model, and the nonoperational region is simulated by FLSM model
  - develop the reconstructed scalpel driven immersive virtual cutting

The hybrid deformation model

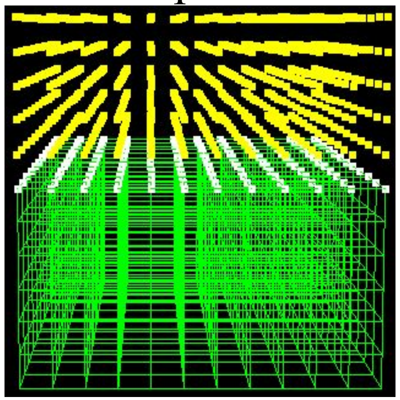
- Pre-computation

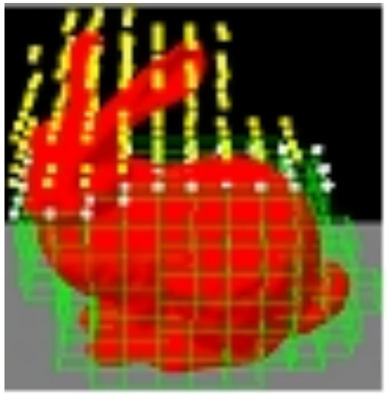
The input is the triangle mesh of the object, then use kd-tree constructed on GPU to accelerate the calculation of distance scalar field;

Sample the volume of the objects according to the distance scalar field;

Calculate pre-computed data for different regions , the operational region is simulated by TLED model and the non-operational region is simulated by FLSM model;

load this information into the texture memory on the GPU, Initialize the nodal variables for the fist time step.





The hybrid deformation model

- Implementation
  - Calculation of displacements of FLSM nodes
    - For each region R_i of FLSM model,we find the optimal rotation matrix R_r and the translation vectors C_r^t and C_r^0 by minimizing equation(1)

$$\sum_{i \in R_i} w_i \left(R_r \left(x_i^0 - C_r^0 \right) + C_r^t - x_i^t \right) \qquad (1)$$

the optimal translation vectors turn out to be the center of mass of the initial shape C_r^0 and the center of the actual shape C_r^t

$$C_r^0 = \frac{\sum_{i \in R_i} w_i x_i^0}{\sum_{i \in R_i} w_i} \qquad C_r^t = \frac{\sum_{i \in R_i} w_i x_i^t}{\sum_{i \in R_i} w_i} \qquad (2)$$

estimate the least squares rotation R_r for particles in region R_i using the rotational part of A_r

$$A_r = \sum_{i \in R_i} \tilde{m}_i \left(x_i^t - C_r^t \right) \left(x_i^0 - C_r^0 \right)^T \qquad (3)$$

$$A_r = R_r U \qquad (4)$$

$$T_r = R_r \left(C_r^t - R_r C_r^0 \right) \qquad (5)$$

The hybrid deformation model

- Each node's goal position g_i can be restated as the transformation of the rest position x_i^0 by the average rigid transformation over the regions the node belongs to.

$$g_i = \frac{1}{|\Re_i|} \sum_{r \in \Re_i} T_r x_i^0 \qquad (6)$$

as for each interfacial node, we define an external force exerted on it according to the goal position.

$$F_i' = \beta(g_i(t) - x_i(t)) \qquad (7)$$

- Finally, as for the FLSM nodes, the positions x_i and velocities v_i are updated using the goal positions g_i.

$$v_i(t+h) = v_i(t) + \partial \frac{g_i(t) - x_i(t)}{h} + h \frac{f_{ext}(t)}{w_i} \qquad (8)$$

$$x_i(t+h) = x_i(t) + h v_i(t+h) \qquad (9)$$

The hybrid deformation model

- Calculation of displacements of the interfacial and TLED nodes
  - For each finite element, we first compute the deformation gradient ${}_0^tX$.

$$ {}_0^t X_{ij} = \frac{\partial\, {}^t x_i}{\partial\, {}^0 x_j} \qquad (10) $$

  - Then the strain-displacement matrix at time t is computed by transforming a stationary matrix using the deformation gradient.

$$ {}_0^t B_{\mathbf{L}}^{(a)} = {}_0 B_{\mathbf{L}0}^{(a)}\, {}_0^t X^{\mathbf{T}} \qquad (11) $$

  - Compute second Piola-Kirchoff stress at integration points.

$$ S_{ij} = \mu\left(\delta_{ij} - {}_0^t C_{ij}^{-1}\right) + \lambda\, {}^t J\left({}^t J - 1\right) {}_0^t C_{ij}^{-1} \qquad (12) $$

  - Compute element nodal reaction forces using Gaussian quadrature .

$$ {}^t F = \int_{{}^0V} {}_0^t B_L^T\, {}_0^t \hat{S}\, d\, {}^0V \qquad (13) $$

  - Finally, for TLED and interfacial nodes,obtain net nodal reaction forces at time *t,* and explicitly compute displacements using central difference formula.

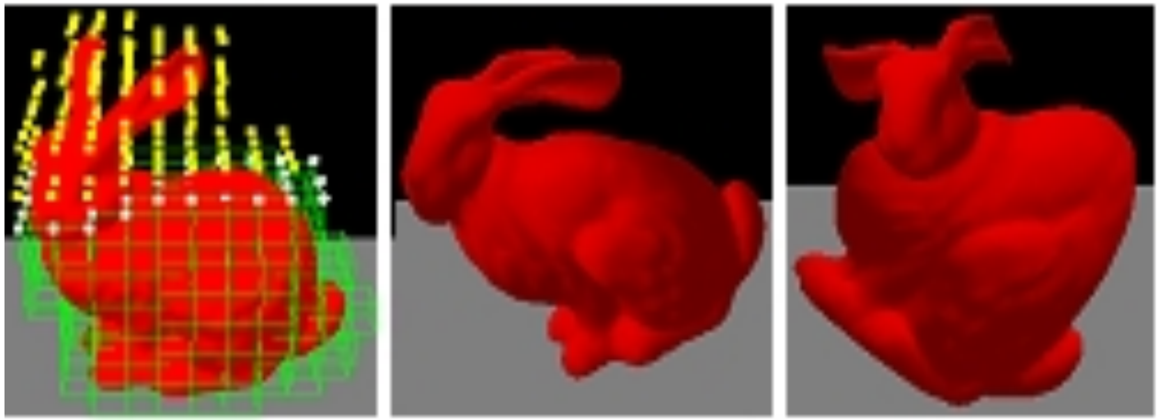
$$ {}^{t+\Delta t} u_i^{(k)} = \frac{\Delta t^2}{M_k}\left({}^t R_i - {}^t F_i^{(k)}\right) + 2\, {}^t u_i^{(k)} - {}^{t-\Delta t} u_i^{(k)} \qquad (14) $$

The hybrid deformation model

- Interpolatory Calculation of Embedded Object Displacements

  the hybrid deformation model embeds the complex geometry of objects into the deformable lattices. For each vertex, the displacement can be computed via interpolatory calculation from the value of the lattice's nodes.

- Deformation results

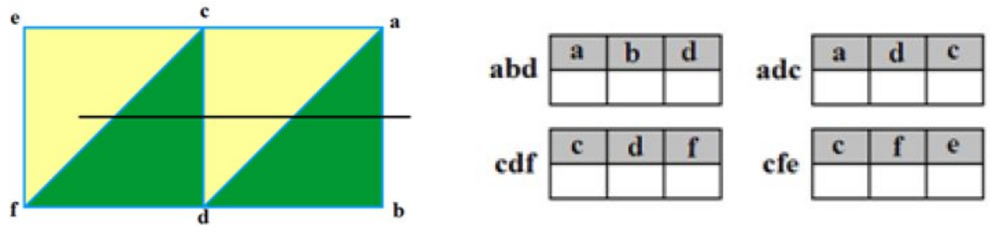


BH VRLAB

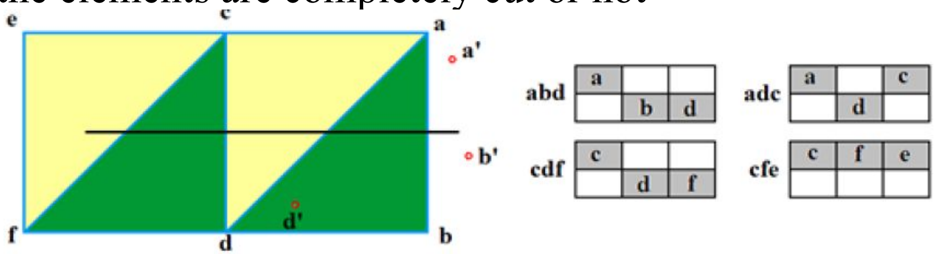
Virtual Cutting

- We combine the hybrid deformation model with the virtual node algorithm to support the cutting interaction. The reconstructed scalpel cuts the operational region of soft objects simulated by the TLED.
- The cutting procedure:
  - Collision detection

    find the elements intersecting with the cutting plane swept by the reconstructed scalpel. We adopted the spatial hashing algorithm (M.Teschner, et al, 2003) to accelerate this step.

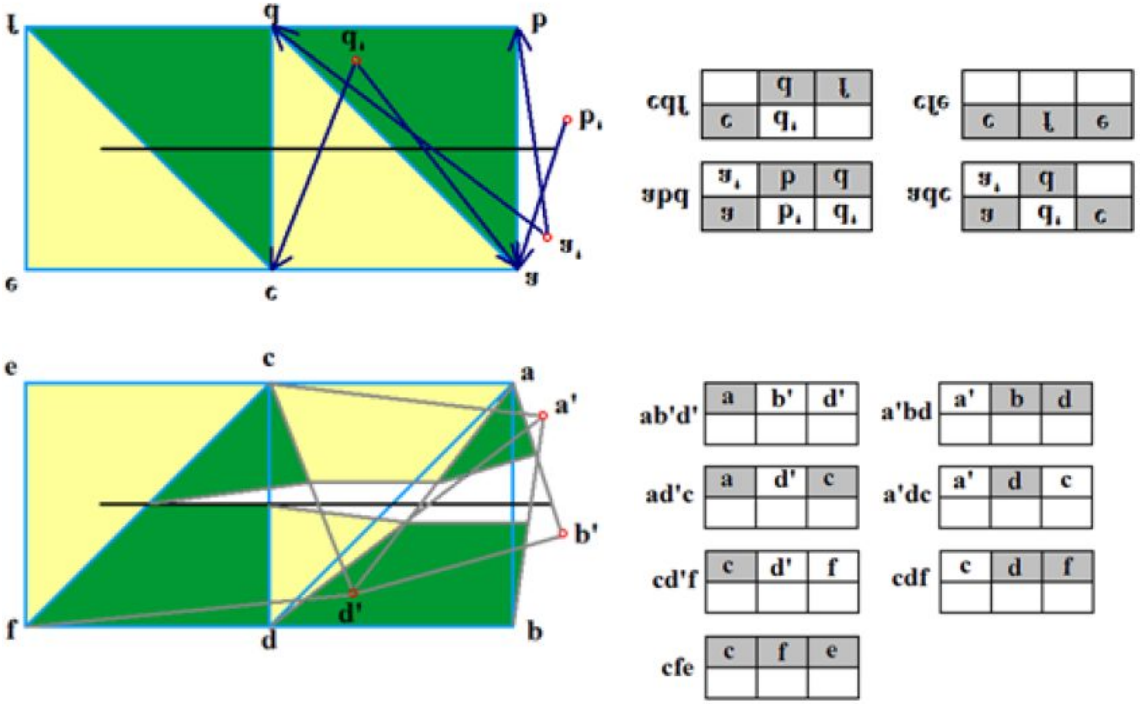


  - Check if the elements are completely cut or not



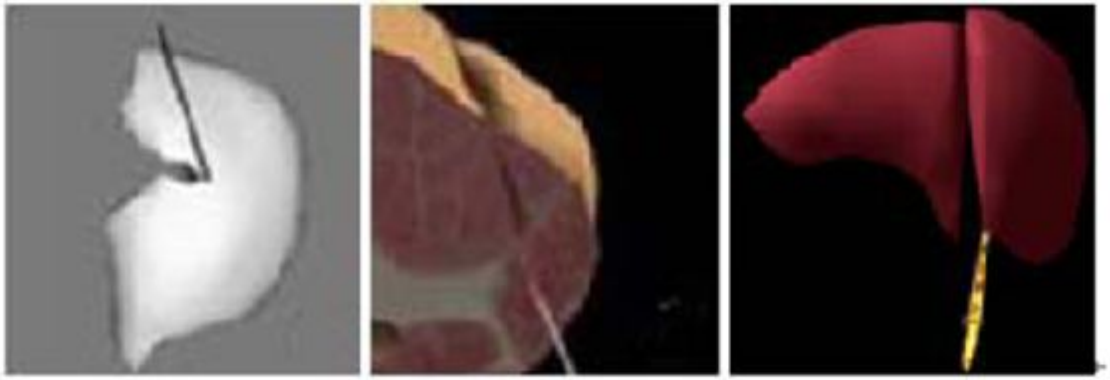
Virtual Cutting

- Use the virtual node algorithm to change the mesh topology



Virtual Cutting

- Cutting visual feedback comparison



(a) (b) (c)

The cutting visual feedback comparison: (a) removing method (b) decomposition method (c) our method

Experiments Results

- Execution time of deformation

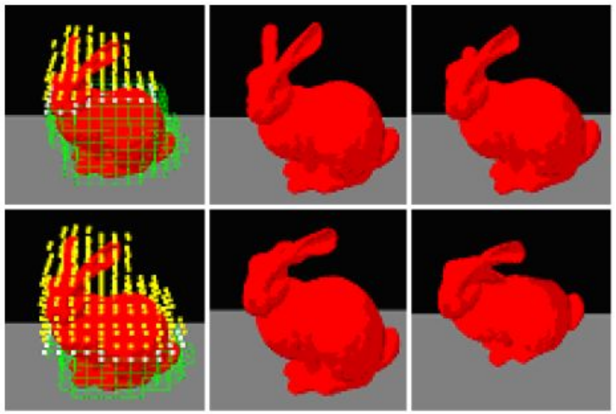
Model	*Number of nodes*	*Ratio*	*Total cost(ms)*
Bunny	2250	0.4	13.5
Apple	2250	0.6	16.2
Liver	2886	0.4	20.4
Kidney	2886	0.6	24.6

- Deformation results with different parameters's value

The new hybrid deformation model cansimulate deformable objects of different stiffness byadjusting parameters Lame constants λ and μ in (1) and ∂ in (11)

-

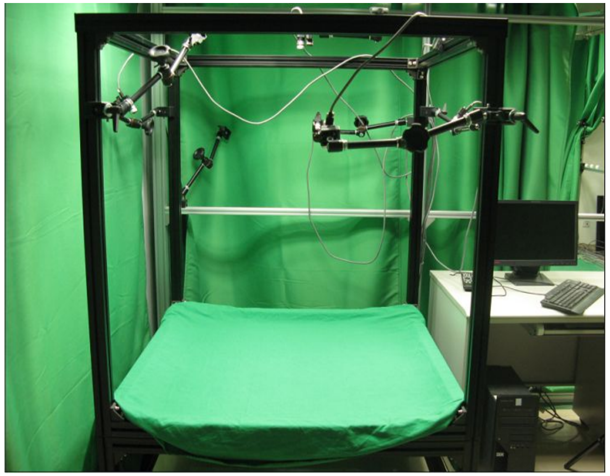
∂
∂

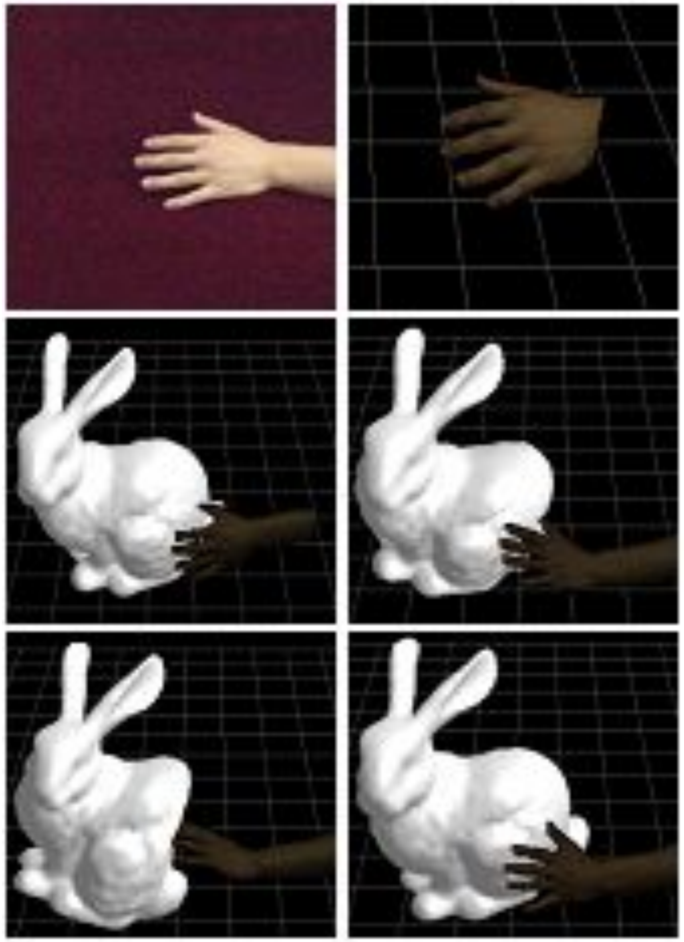


The ratio for thefirst row is 70%, the second row 30%; for the second column, λ =200000.0, μ =200000.0, =0.8; for the third column, λ =20000.0, μ =20000.0, =0.5.

Experiments Results

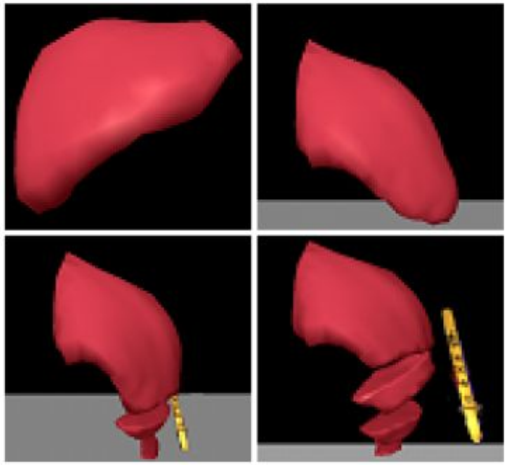
- The reconstructed hand interaction with the deformable bunny





Experiments Results

- The cutting results
  - Cutting the virtual liver simulated by our hybrid model



  - Cutting the bunny shell

Conclusion and future work

- We proposed a novel hybrid deformation model which partitions soft tissue into operational and non-operational regions, and couples FLSM with TLED to simulate deformation.
- The novel hybrid deformation model can simulate the large deformations and nonlinearity of soft tissues in real time. Integrated with the virtual node algorithm, the hybrid deformation model can support stable and realistic virtual cutting.
- With the help of our multicamera based real-time modeling system Dream World, we design a new type of immersive virtual cutting system. Using the reconstructed scalpel to cut the soft tissues in anyview angle and depth, we can achieve realistic and stable visual feedback of virtual cutting.
- In the future, we will extend the system to be a new type of remote surgical simulator.

Thanks!