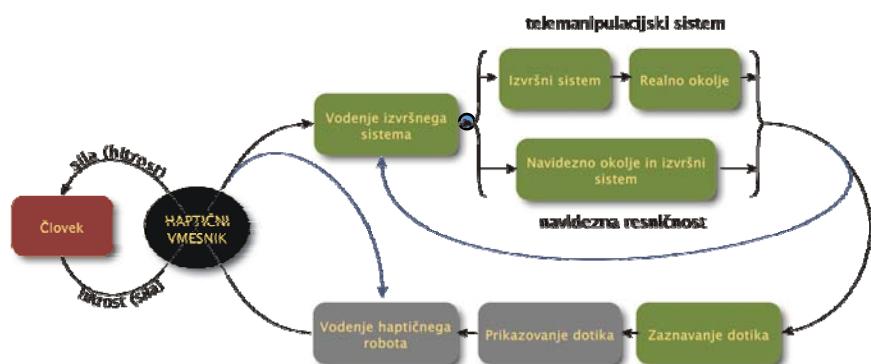


# Detekcija trkov

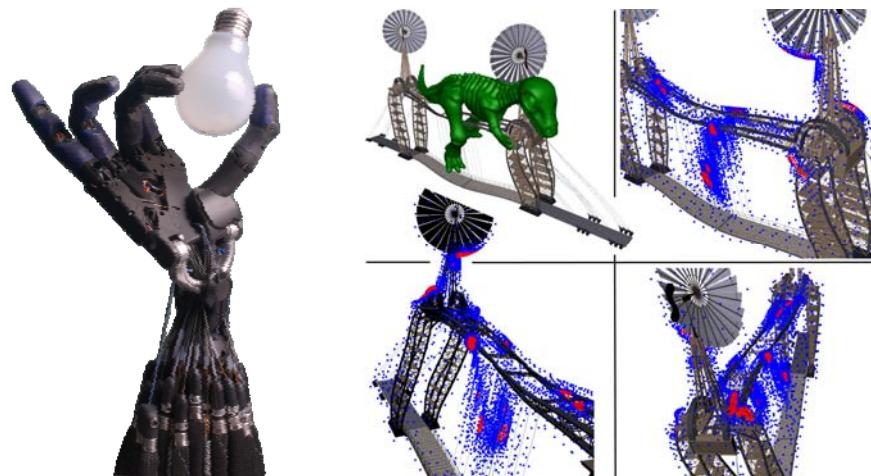
Matjaž Mihelj

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matjaz.mihelj@fe.uni-lj.si,  
(01) 4768 373  
[www.robolab.si](http://www.robolab.si), [www.cobotic.si](http://www.cobotic.si)

## Haptični sistem

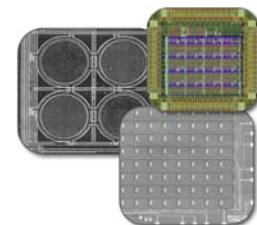
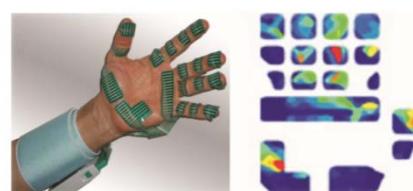


## Realni in navidezni dotik

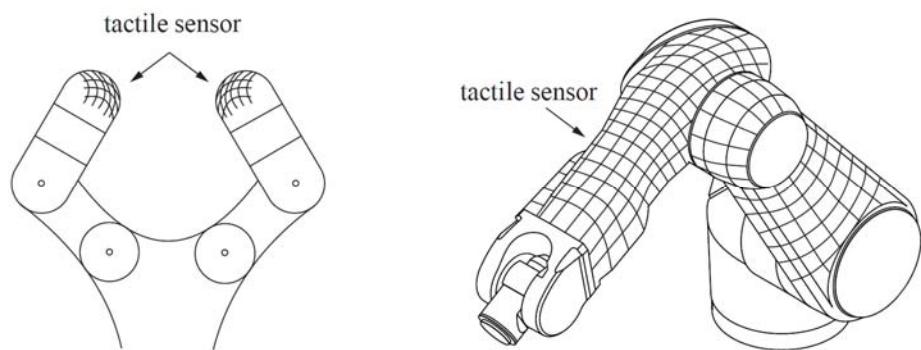


## Merjenje dotika v realnem okolju

- meriti je potrebno silo interakcije med izvršnim sistemom in okoljem
- senzorji sil in momentov
  - robotski senzorji zapestja
- taktilni senzorji
  - senzorji občutljivi na silo (prevodni elastomeri, uporovni lističi, piezoelektrični kristali) merijo predvsem silo dotika
  - senzorji občutljivi na premik (kapacitivni in optoelektrični senzorji) merijo mehansko deformacijo elastičnega ovoja



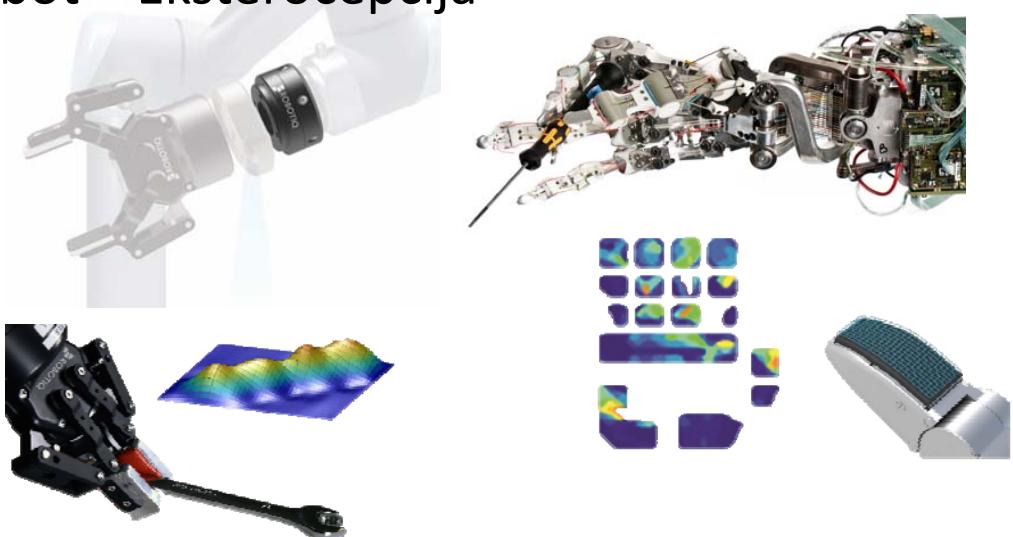
## Taktilni senzorji



## Merjenje dotika v realnem okolju



## Robot – Eksterocepcija

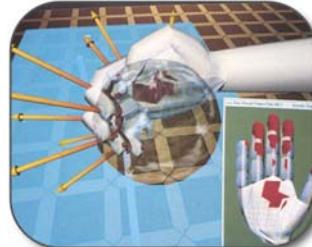
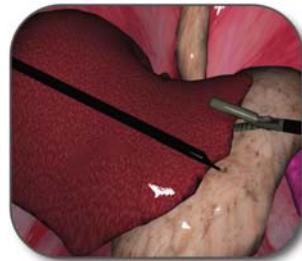


Vir: DLR, Nemčija in Robotia, ZDA

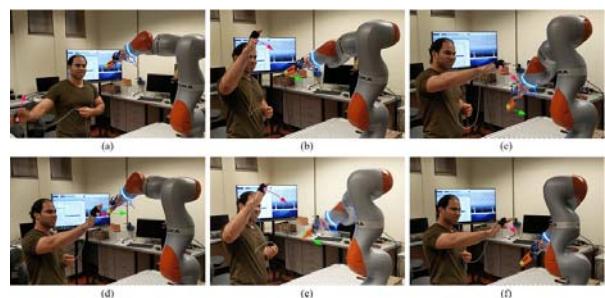
Vir: „This Robotic Hand Can Touch and Feel Just Like a Human Hand“, SynTouch Inc., ZDA

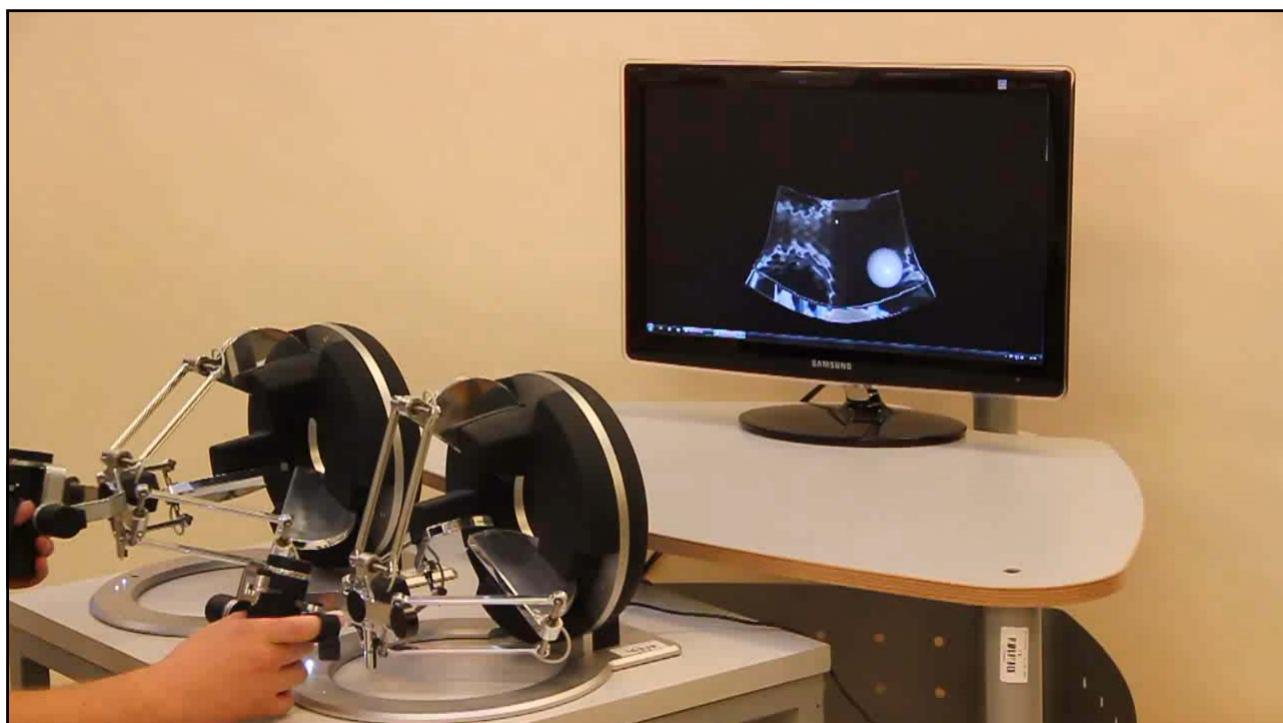
## Zaznavanje dotika v navideznem okolju

- modeliranje navideznih objektov
  - zaznavanje dotika med objekti (kompleksnost izračuna)



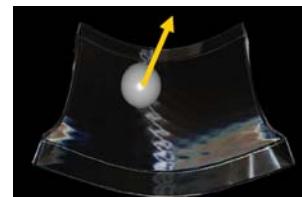
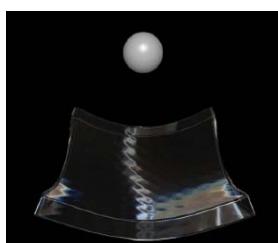
# Izogibanje trkom



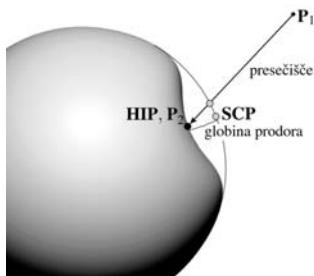


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## Zaznavanje dotika v navideznem okolju



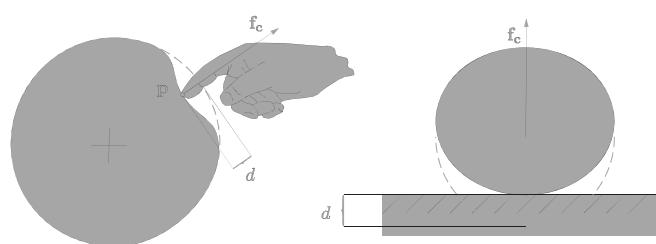
## Dotik v navideznem okolju



- točka haptične interakcije **HIP**
- točka dotika na površini objekta **SCP**
- globina prodora - razdalja med **HIP** in **SCP**

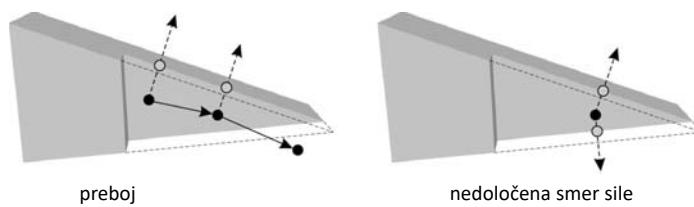


## Sila trka

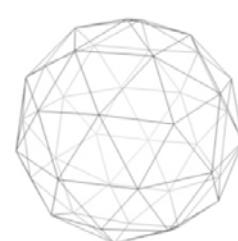
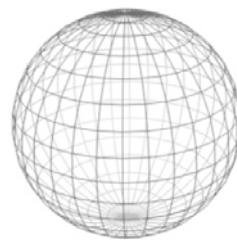
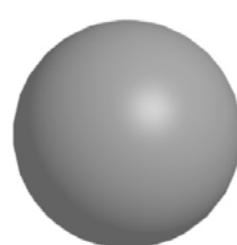


$$\mathbf{f}_c = k d \mathbf{n}$$

## Problem določanja HIP



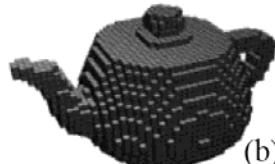
## Načini opisovanja (modeliranja) objektov



## Različne predstavitev objekta



Zvezni model

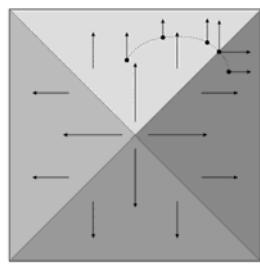
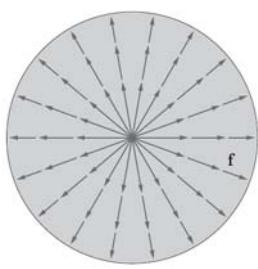


Vokseli



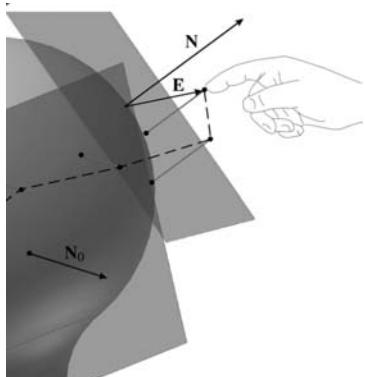
Lupina točk

## Modeliranje - volumetrična metoda



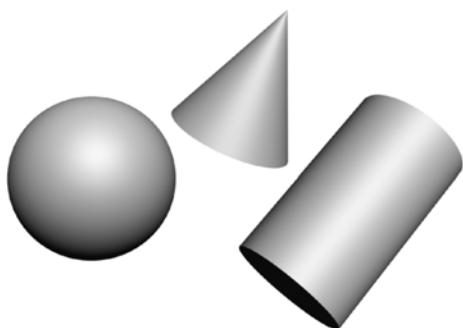
- vektorsko polje
- razdelitev na področja
  - skupna smer sile
  - dolžina vektorja proporcionalna razdalji do površine
- značilnosti metode
  - za kompleksne objekte ni trivialna
  - nezveznosti na mejah
  - problem debeline objektov

## Modeliranje - metoda vmesne ploskve



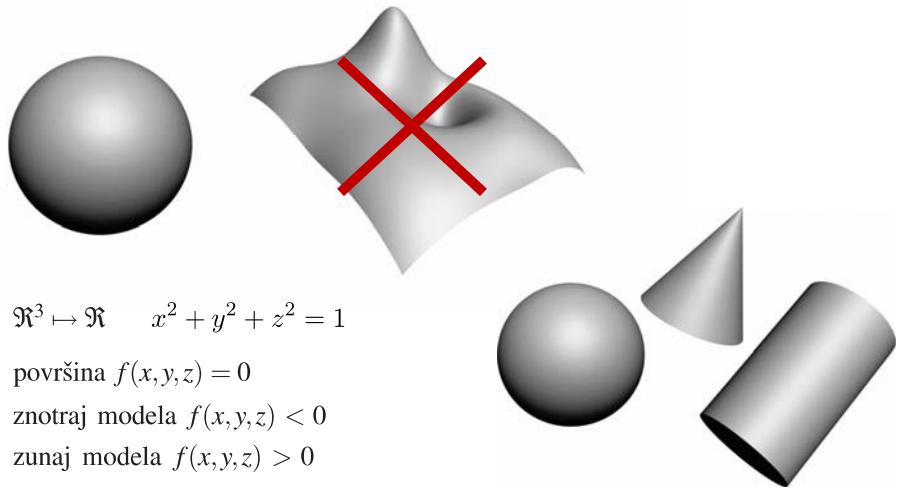
- nižja frekvenca osveževanja ploskve
- razdalja med ploskvijo in sondijo
  - $d=EN$
  - N - enotska normala na vmesno ravnino
  - E - razdalja med vrhom sonde ter središčno točko vmesne ravnine

## Modeliranje - implicitna površina

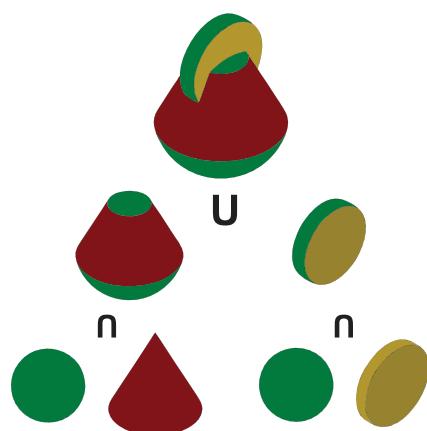


- preslikava:  $f : \mathbb{R}^3 \mapsto \mathbb{R}$
- površina določena s točkami (izvorno zaprta površina)  
$$f(x, y, z) = 0$$
- notranjost modela:  
$$f(x, y, z) < 0$$

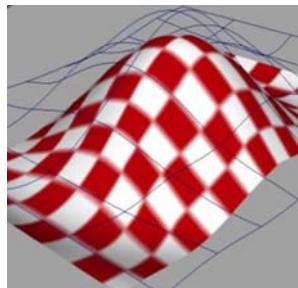
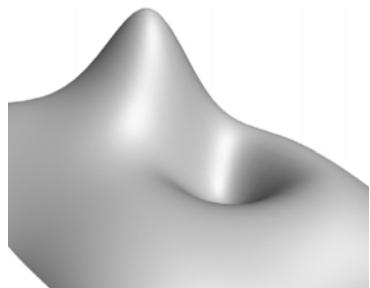
## Modeliranje - implicitna površina



## Konstruktivna toga geometrija

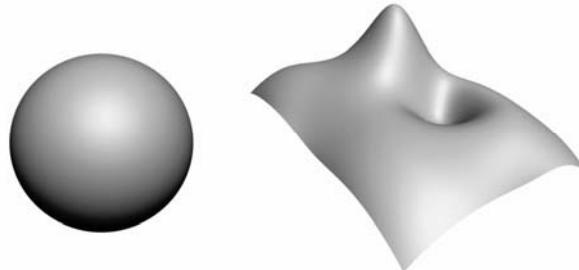


## Modeliranje - parametrična površina



- preslikava:  $f : \mathbb{R}^2 \mapsto \mathbb{R}^3$
- izvorno odprtega tipa
- NURBS (Non-Uniform Rational B-Spline) - odsekoma zvezne polinomske funkcije dvoparametrskih vektorskih vrednosti

## Parametrični opis in zlepki



$$x(u, v) = r \cos(u) \cos(v)$$

$$y(u, v) = r \cos(u) \sin(v)$$

$$z(u, v) = r \sin(u)$$

$r$  polmer krogle

$u$  teče od  $-\pi/2$  do  $\pi/2$

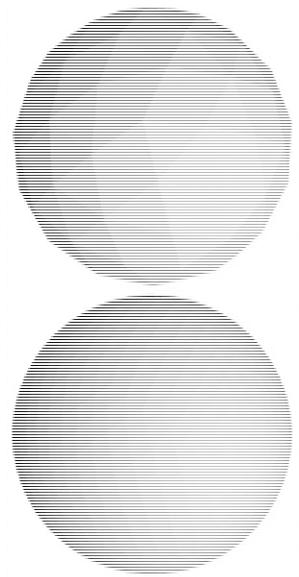
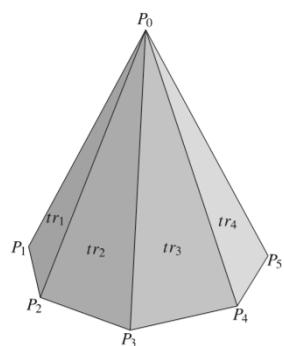
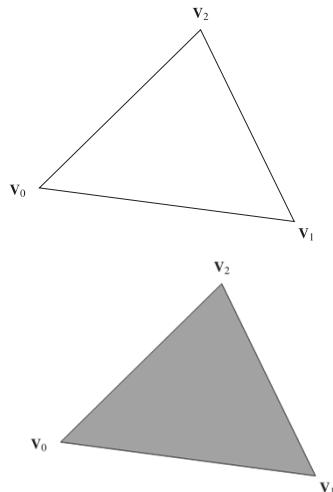
$v$  teče od 0 do  $2\pi$

$$y = \begin{cases} f(x) & \Leftarrow x < 0 \\ g(x) & \Leftarrow 0 \leq x < 1 \\ h(x) & \Leftarrow x \geq 1 \end{cases}$$

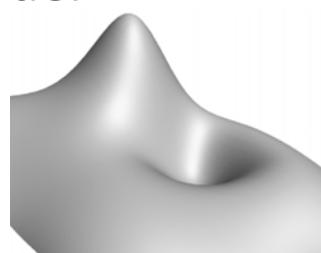
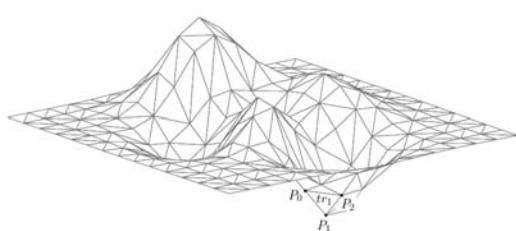
$$f(0) = g(0), \quad g(1) = h(1)$$

$$f'(0) = g'(0), \quad g'(1) = h'(1)$$

## Modeliranje - poligonski model



## Modeliranje - poligonski model

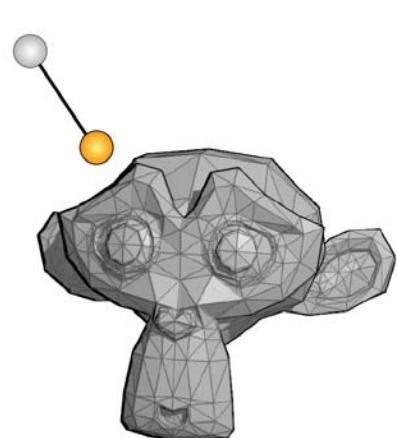


- uporaba na področju računalniške grafike
- predstavitev ploskve s

$$tr_1 = \triangle P_0 P_1 P_2$$

- nezveznosti na prehodih poligonov

## Detekcija trka v poligonskih modelih

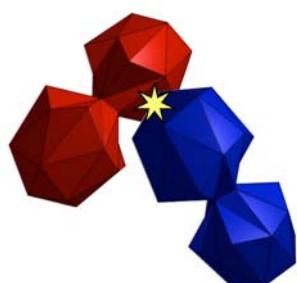


segment-mreža

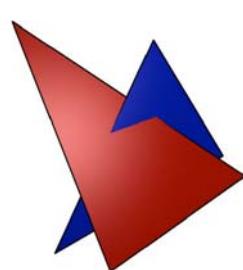


mreža-mreža

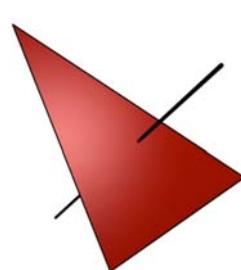
## Detekcija trka v poligonskih modelih



Globalno opazovanje

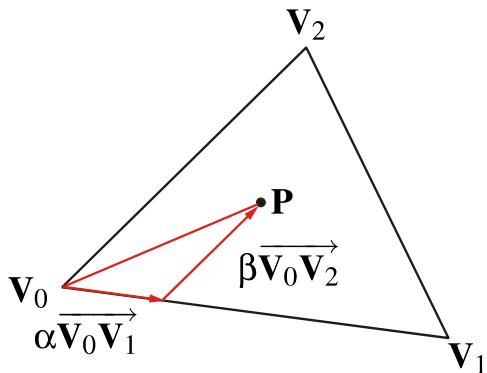


Lokalno opazovanje



Detajlno opazovanje

## Zaznavanje dotika v poligonskih modelih

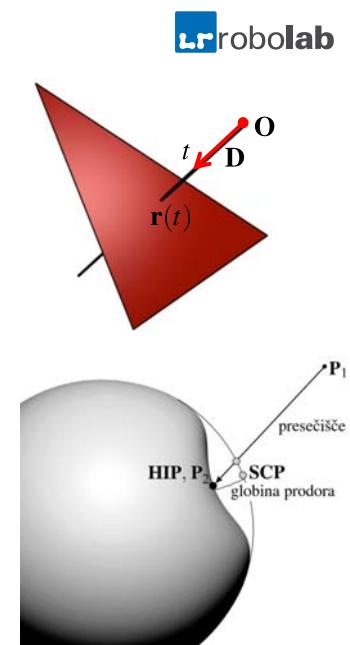


- normala na ravnino  
 $\mathbf{N} = \overrightarrow{\mathbf{V}_0\mathbf{V}_1} \times \overrightarrow{\mathbf{V}_0\mathbf{V}_2}$
- za točko  $\mathbf{P}$  na ravnini velja  
 $(\mathbf{P} - \mathbf{V}_0) \cdot \mathbf{N} = 0$
- vektorska enačba ravnine  
 $\mathbf{N} \cdot \mathbf{P} + d = 0$

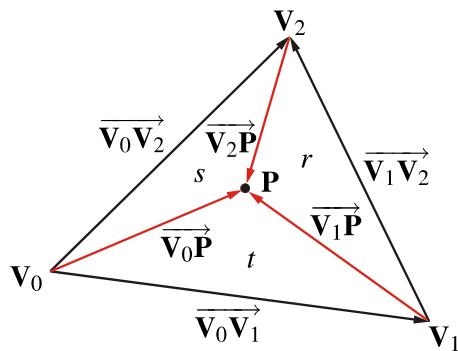
## Presečišče žarka in ravnine

- parametrična vektorska enačba žarka  
 $\mathbf{r}(t) = \mathbf{O} + \mathbf{D}t$
- enačba ravnine  
 $\mathbf{N} \cdot \mathbf{P} + d = 0$
- parameter  $t$  v presečišču žarka in poligona  

$$\mathbf{r}(t) = \mathbf{P} \quad \Rightarrow \quad t = -\frac{d + \mathbf{N} \cdot \mathbf{O}}{\mathbf{N} \cdot \mathbf{D}}$$



## Površinske koordinate trikotnika



- površine pod-trikotnikov

$$A_{\triangle PV_1V_2} = rA_{\triangle V_0V_1V_2}$$

$$A_{\triangle V_0PV_2} = sA_{\triangle V_0V_1V_2}$$

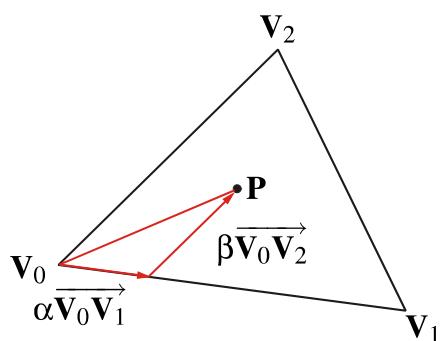
$$A_{\triangle V_0V_1P} = tA_{\triangle V_0V_1V_2}$$

- točka  $\mathbf{P}$  leži znotraj trikotnika

$$0 \leq \{r, s, t\} \leq 1$$

$$r + s + t = 1$$

## Pogoj za $\mathbf{P} \in \triangle V_0V_1V_2$



- parametrična enačba ravnine  

$$\mathbf{P} = \mathbf{V}_0 + \alpha(\mathbf{V}_1 - \mathbf{V}_0) + \beta(\mathbf{V}_2 - \mathbf{V}_0)$$

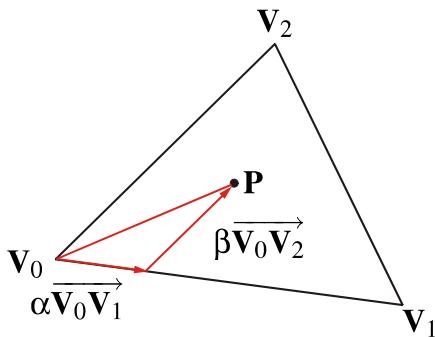
- definiramo

$$\alpha = s \quad \beta = t \quad 1 - \alpha - \beta = r$$

- enačba ravnine s površinskimi koordinatami

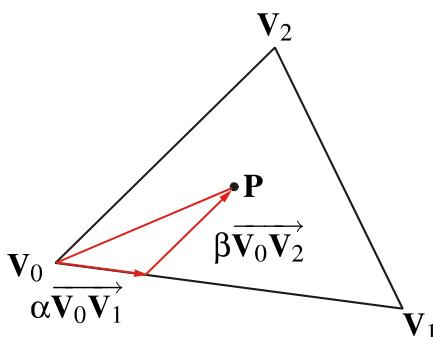
$$\mathbf{P} = r\mathbf{V}_0 + s\mathbf{V}_1 + t\mathbf{V}_2$$

## Pogoj za $\mathbf{P} \in \triangle \mathbf{V}_0 \mathbf{V}_1 \mathbf{V}_2$



- ugotovili smo  
 $0 \leq \{r, s, t\} \leq 1$   
 $r + s + t = 1$
- in  
 $\alpha = s \quad \beta = t \quad 1 - \alpha - \beta = r$
- sledi pogoj za  $\mathbf{P} \in \triangle \mathbf{V}_0 \mathbf{V}_1 \mathbf{V}_2$   
 $\alpha \geq 0, \beta \geq 0 \quad \text{in} \quad \alpha + \beta \leq 1$

## Izračun parametričnih koordinat $(\alpha, \beta)$



- parametrična enačba ravnine  
 $\mathbf{P} = \mathbf{V}_0 + \alpha(\mathbf{V}_1 - \mathbf{V}_0) + \beta(\mathbf{V}_2 - \mathbf{V}_0)$
- v komponentni obliki  

$$\begin{cases} x_P - x_0 = \alpha(x_1 - x_0) + \beta(x_2 - x_0) \\ y_P - y_0 = \alpha(y_1 - y_0) + \beta(y_2 - y_0) \\ z_P - z_0 = \alpha(z_1 - z_0) + \beta(z_2 - z_0) \end{cases}$$
- ker  $\mathbf{P}$  leži na ravnini določeni s točkami  $\mathbf{V}_0, \mathbf{V}_1$  in  $\mathbf{V}_2$ , obstaja enolična rešitev za  $(\alpha, \beta)$

## Preslikava $\triangle V_0V_1V_2$ na osnovno ravnino

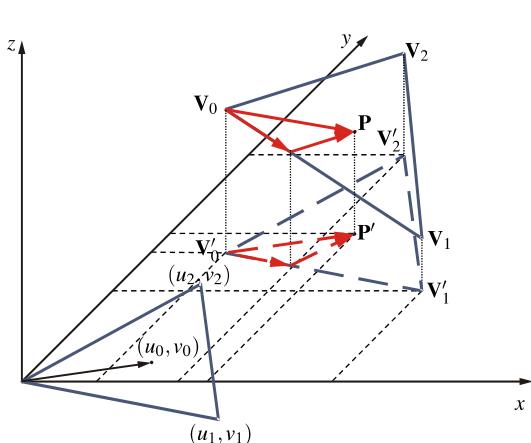
- dominantna os vektorja normale na poligon

$$i_0 = \begin{cases} 0 & \Leftarrow |\mathbf{N}_x| = \max(|\mathbf{N}_x|, |\mathbf{N}_y|, |\mathbf{N}_z|) \\ 1 & \Leftarrow |\mathbf{N}_y| = \max(|\mathbf{N}_x|, |\mathbf{N}_y|, |\mathbf{N}_z|) \\ 2 & \Leftarrow |\mathbf{N}_z| = \max(|\mathbf{N}_x|, |\mathbf{N}_y|, |\mathbf{N}_z|) \end{cases}$$

- projiciramo na ravnino pravokotno na dominantno os
- definiramo indeksa  $i_1$  ter  $i_2$  različna od  $i_0$ ;

$$(i_1 \text{ in } i_2 \in \{0, 1, 2\}, i_1 \neq i_2)$$

## Preslikava $\triangle V_0V_1V_2$ na osnovno ravnino



- koordinate preslikanega trikotnika

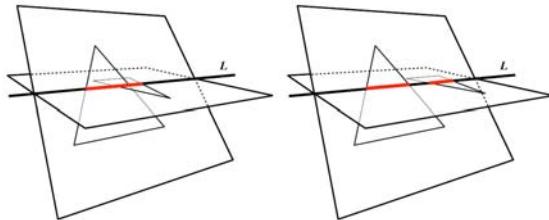
$$\begin{aligned} u_0 &= P_{i_1} - V_{0,i_1} & u_1 &= V_{1,i_1} - V_{0,i_1} & u_2 &= V_{2,i_1} - V_{0,i_1} \\ v_0 &= P_{i_2} - V_{0,i_2} & v_1 &= V_{1,i_2} - V_{0,i_2} & v_2 &= V_{2,i_2} - V_{0,i_2} \end{aligned}$$

$$\begin{cases} x_P - x_0 = \alpha(x_1 - x_0) + \beta(x_2 - x_0) \\ y_P - y_0 = \alpha(y_1 - y_0) + \beta(y_2 - y_0) \\ z_P - z_0 = \alpha(z_1 - z_0) + \beta(z_2 - z_0) \end{cases}$$

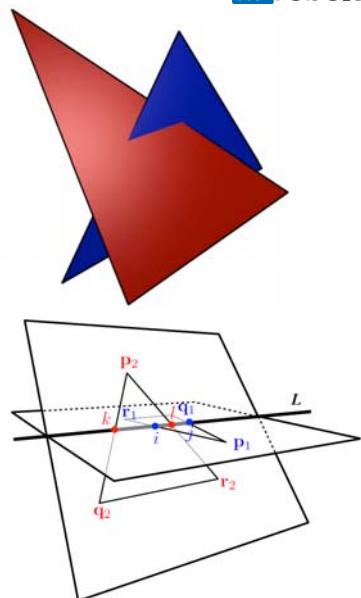
- parametrična enačba preslikane točke  $P$

$$\begin{cases} u_0 = \alpha u_1 + \beta u_2 \\ v_0 = \alpha v_1 + \beta v_2 \end{cases}$$

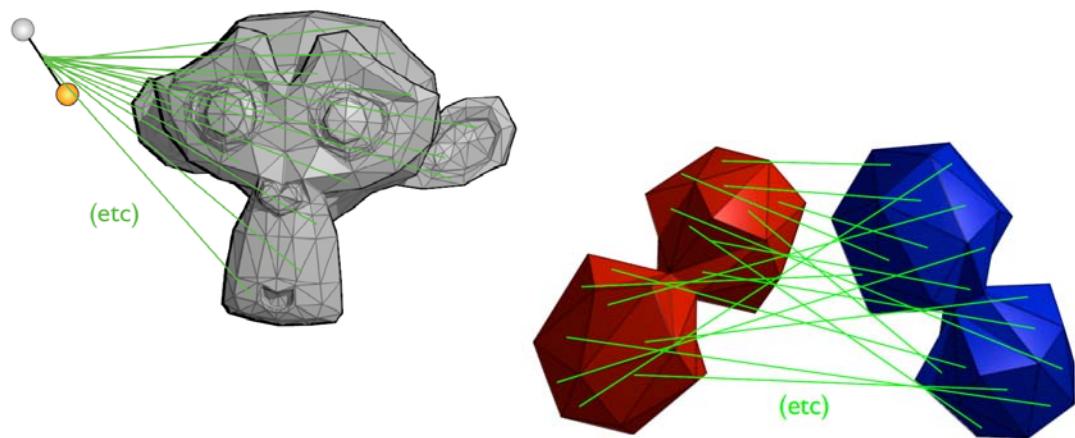
## Presečišče trikotnikov



- Trikotnika A in B se lahko sekata, če se medsebojno sekata njuni ravnini.
- Preverimo oglisca trikotnika A glede na ravnino trikotnika B in obratno za hitro izločanje.
- Če trikotnika sekata presečišče njunih ravnin, preverimo interval prekrivanja glede na os sekanja ravnin.

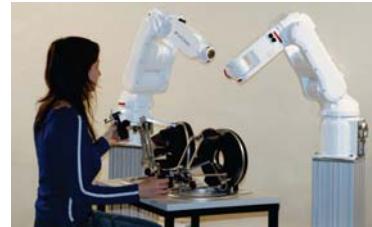


## Analiza trkov

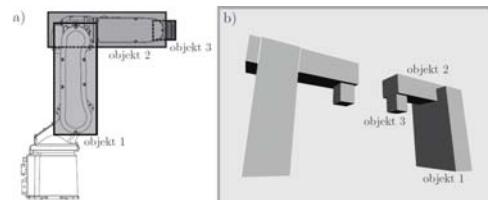
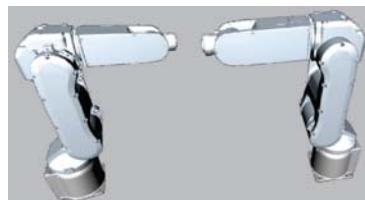
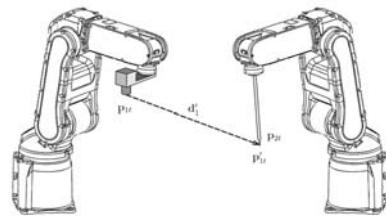


Analiza trkov „vsak z vsakim“

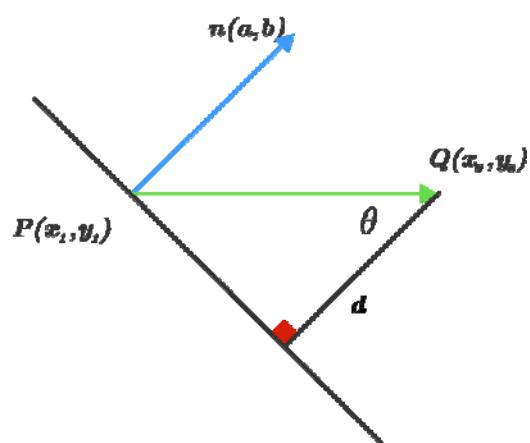
## Analiza trkov



ur robolab



## Minimalna razdalja točke od premice

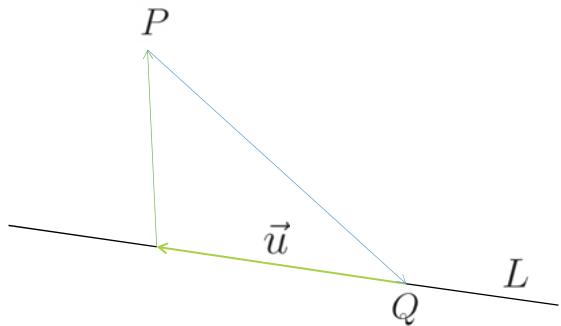


- Točka  $(x_0, y_0)$
- Premica  $ax + by + c = 0$
- Minimalna razdalja

$$d = \frac{|ax_0 + by_0 + c|}{\sqrt{a^2 + b^2}}$$



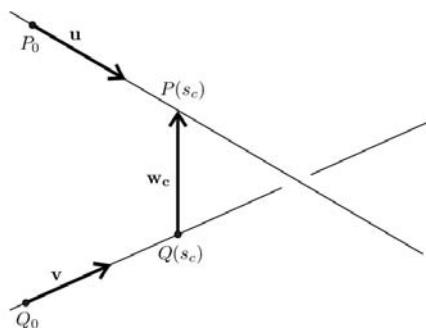
## Minimalna razdalja točke od premice



$$\vec{r}(t) = Q + t\vec{u}$$

$$d(P, L) = \frac{|(\vec{PQ}) \times \vec{u}|}{|\vec{u}|}$$

## Minimalna razdalja med premicama



$$\mathbf{L}_1 : P(s) = P_0 + s(P_1 - P_0) = P_0 + s\mathbf{u}$$

$$\mathbf{L}_2 : Q(t) = Q_0 + t(Q_1 - Q_0) = Q_0 + t\mathbf{v}$$

$$\mathbf{u} \cdot \mathbf{w}_c = 0$$

$$\mathbf{v} \cdot \mathbf{w}_c = 0$$

$$\mathbf{w}_c = P(s_c) - Q(t_c) = P_0 - Q_0 + s_c\mathbf{u} - t_c\mathbf{v}$$

$$a = \mathbf{u} \cdot \mathbf{u}, b = \mathbf{u} \cdot \mathbf{v}, c = \mathbf{v} \cdot \mathbf{v}$$

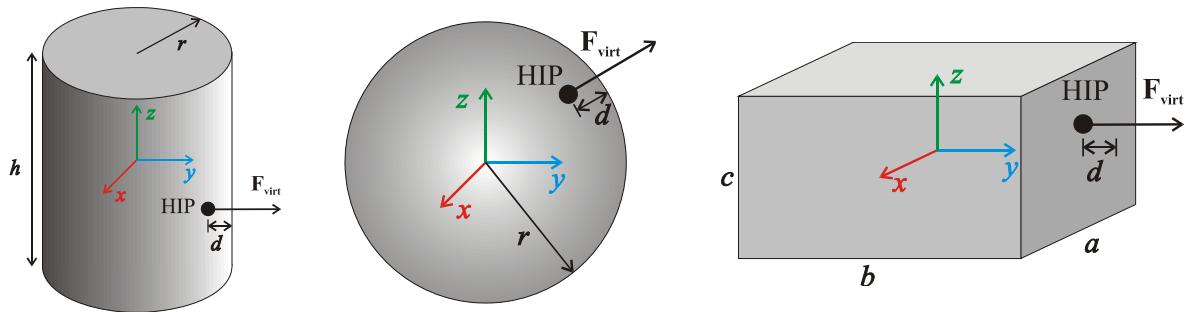
$$d = \mathbf{u} \cdot (\mathbf{P}_0 - \mathbf{Q}_0), e = \mathbf{v} \cdot (\mathbf{P}_0 - \mathbf{Q}_0)$$

$$d(\mathbf{L}_1, \mathbf{L}_2) = \|\mathbf{w}_c\| = \|P(s_c) - Q(t_c)\|$$

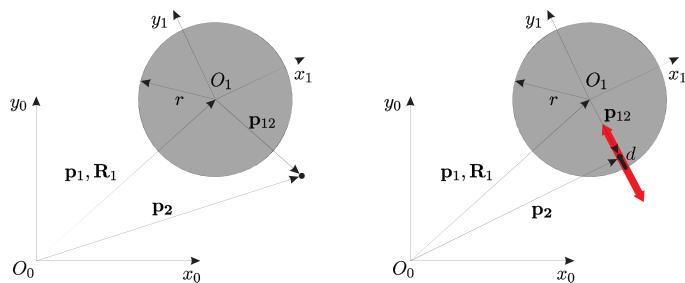


$$d(\mathbf{L}_1, \mathbf{L}_2) = \left\| P_0 - Q_0 + \frac{(be - cd)\mathbf{u} - (ae - bd)\mathbf{v}}{ac - b^2} \right\|$$

## Detekcija trka s kroglo, kvadrom in valjem

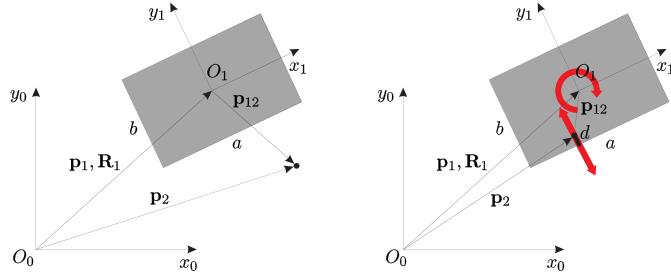


## Trk krogle in delca



$$d = \begin{cases} 0 & \text{za } \|\mathbf{p}_{12}\| > r \\ r - \|\mathbf{p}_{12}\| & \text{za } \|\mathbf{p}_{12}\| < r \end{cases}$$

## Trk kvadra in delca

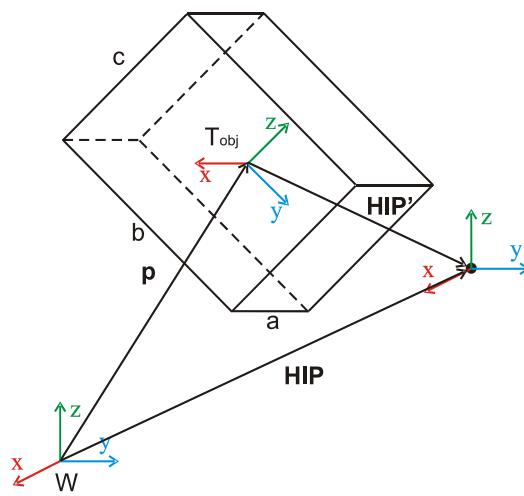


$$\mathbf{p}_{12}^1 = \mathbf{R}_1^T \mathbf{p}_{12}$$

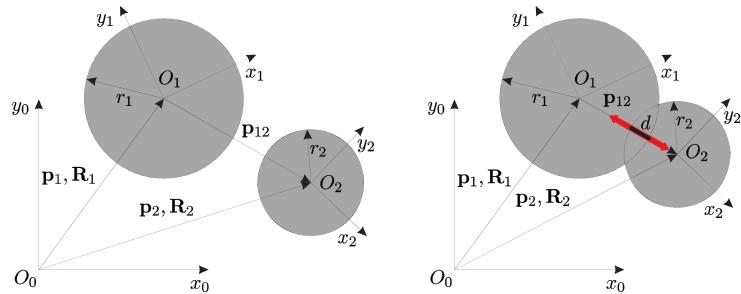
$$|p_{12_x}^1| < \frac{a}{2} \quad \wedge \quad |p_{12_y}^1| < \frac{b}{2}$$

$$d = \frac{a}{2} - |p_{12_x}^1| \quad \vee \quad d = \frac{b}{2} - |p_{12_y}^1|$$

## Trk kvadra in delca

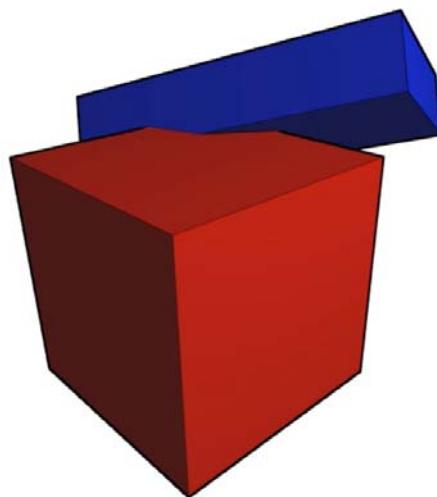


## Trk dveh krogel

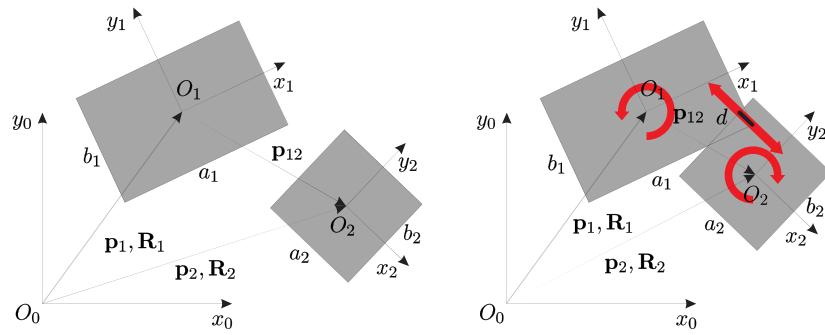


$$d = \begin{cases} 0 & \text{za } \|\mathbf{p}_{12}\| < r_1 + r_2 \\ r_1 + r_2 - \|\mathbf{p}_{12}\| & \text{za } \|\mathbf{p}_{12}\| > r_1 + r_2 \end{cases}$$

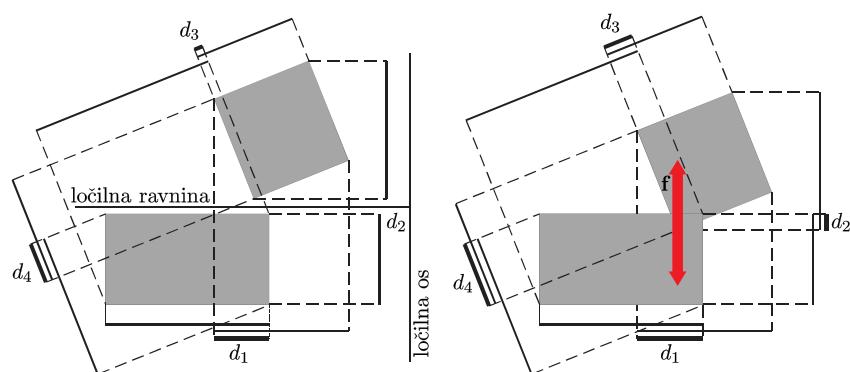
## Trk dveh kvadrov



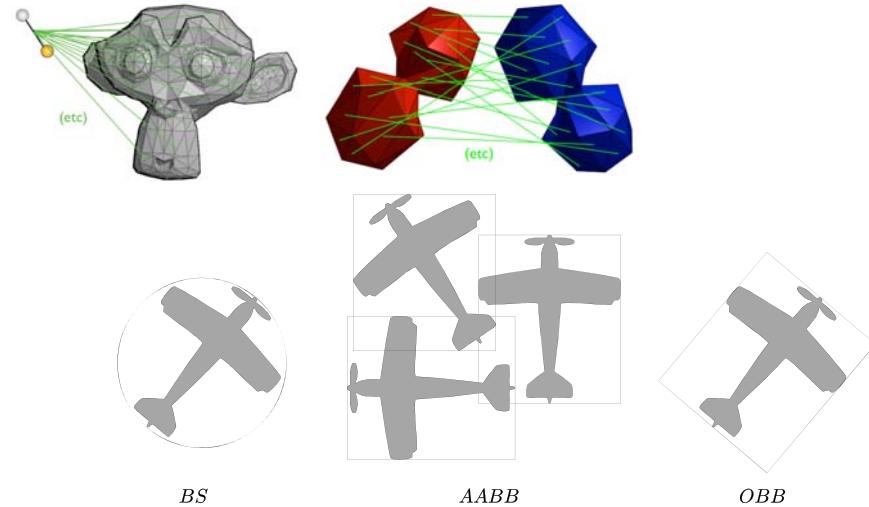
## Trk dveh kvadrov



## Ločilna ravnina



## Omejitveni volumni

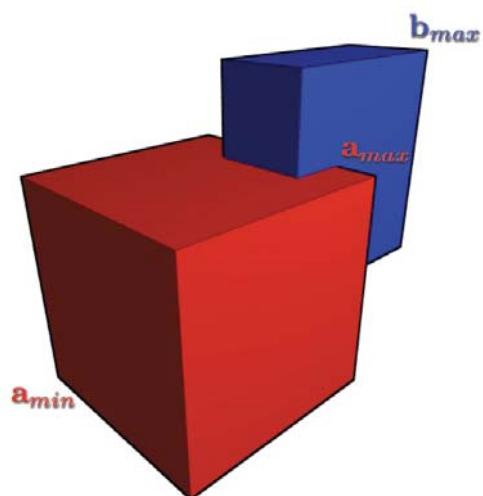


## AABB

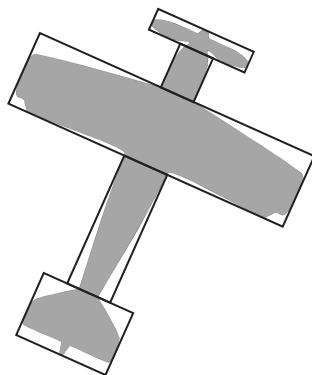
- pogoj za prekrivanje

$$\mathbf{a}_{min} < \mathbf{b}_{max}$$

$$\mathbf{b}_{min} < \mathbf{a}_{max}$$

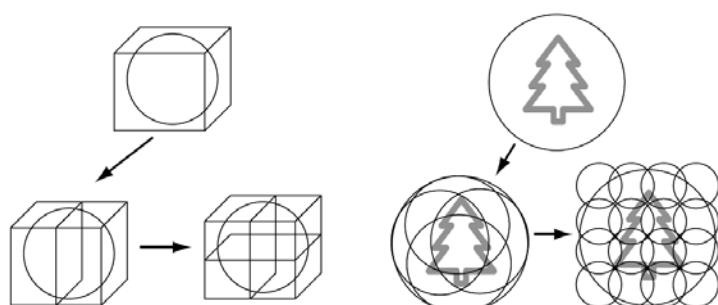


## Omejitveni volumen

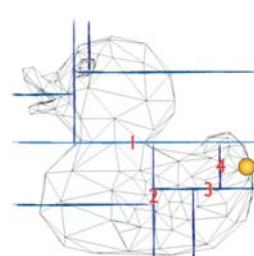
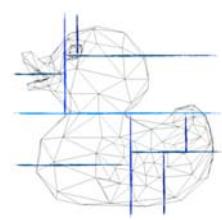
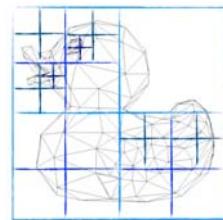


OBB

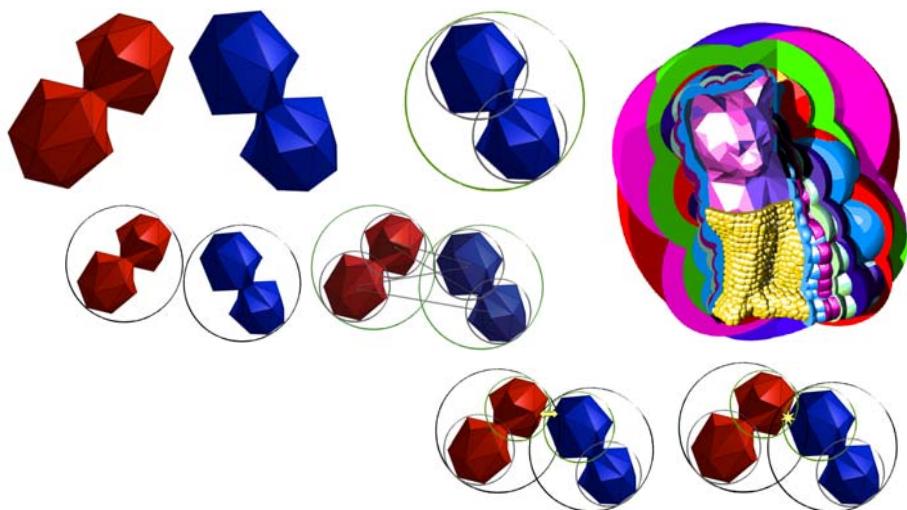
## Generiranje AABB in krogelnih dreves



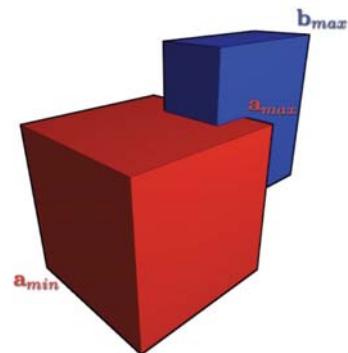
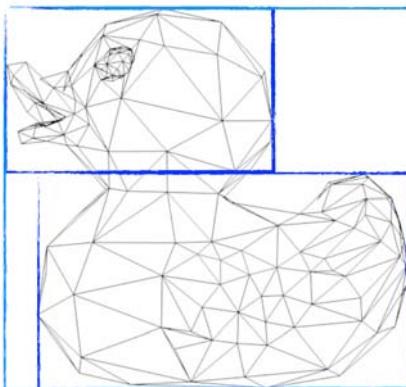
## Različne segmentacije objekta



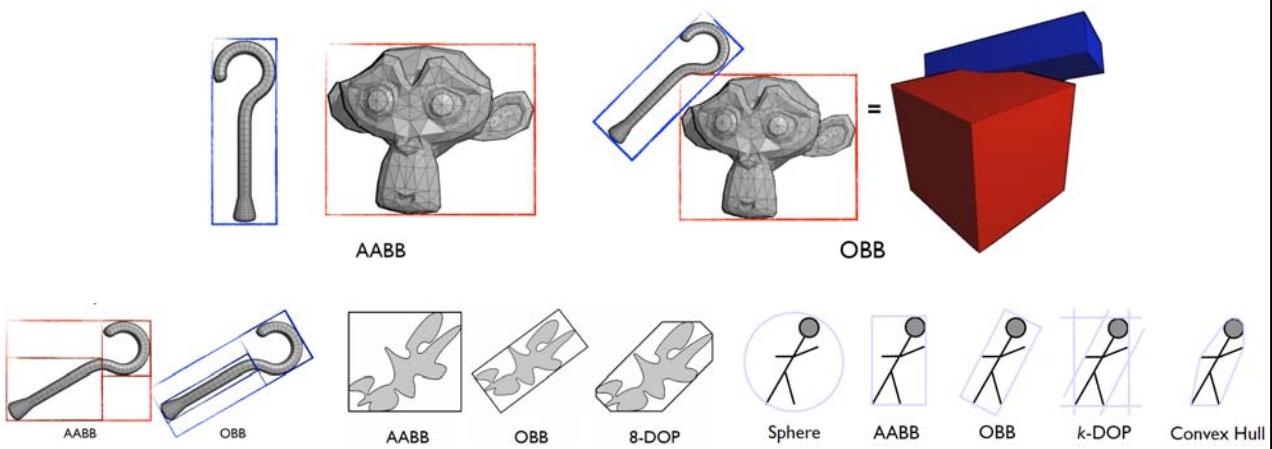
## Trki med kompleksnimi objekti – BS



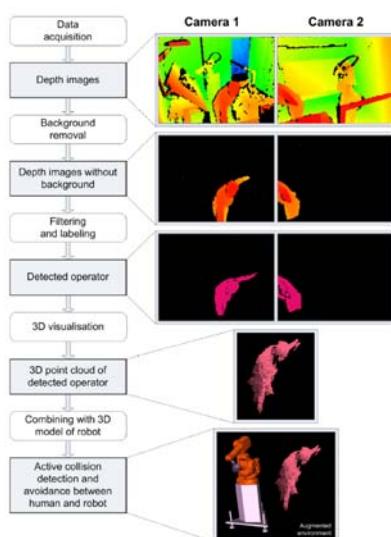
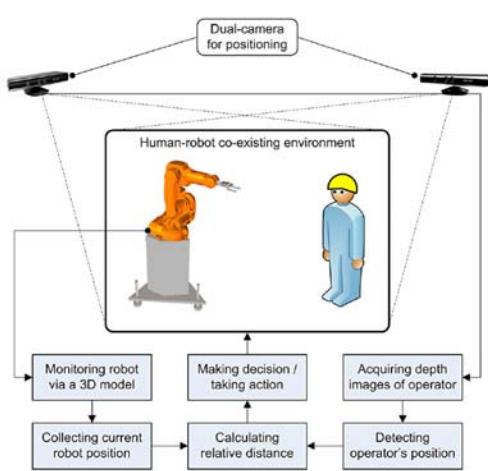
## Trki med kompleksnimi objekti – AABB



## AABB vs. OBB



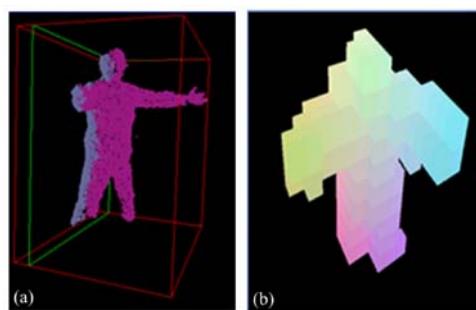
## Primer detekcije trka med človekom in robotom



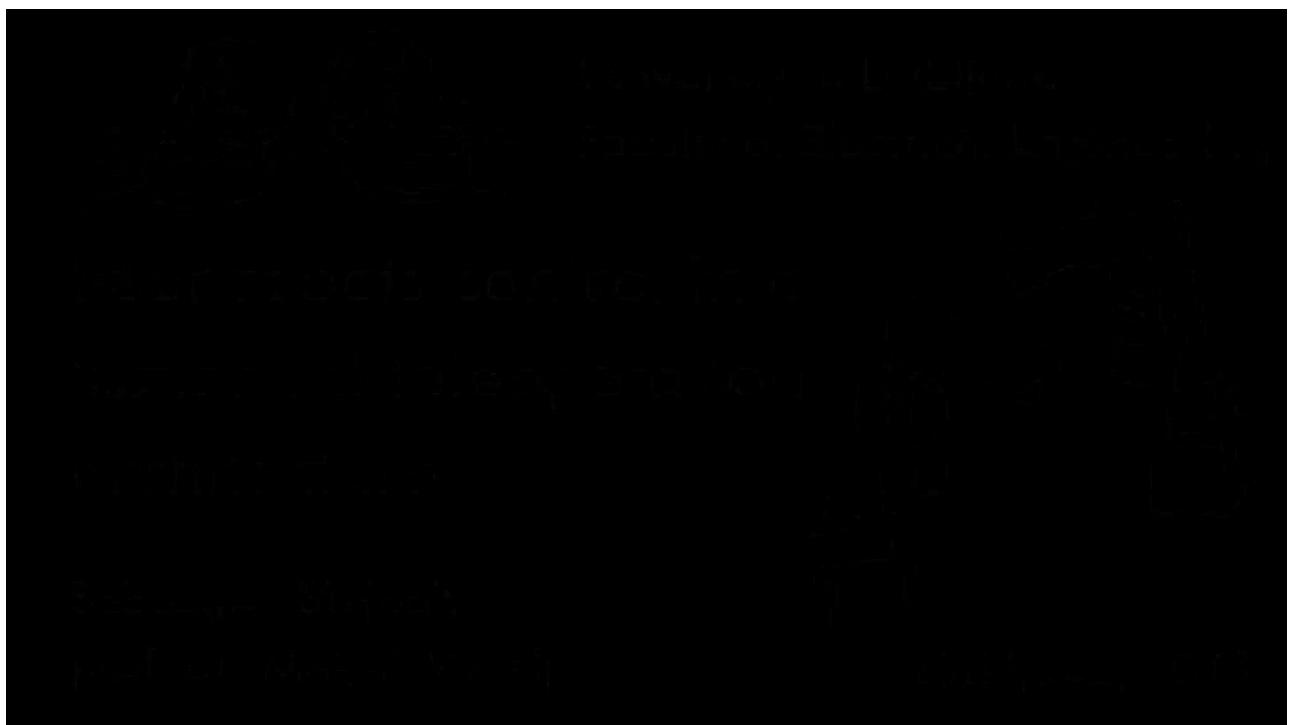
B. Schmidta, L. Wang, „Depth camera based collision avoidance via active robot control“, Journal of Manufacturing Systems, Volume 33, 2014, 711-718.

## Primer detekcije trka med človekom in robotom

- Zajem globinske slike,
- odstranitev točk ozadja in točk, ki pripadajo modelu okolja iz senzornega oblaka točk,
- vključitev 3D modela robota,
- izračun minimalne razdalje
  - pretvorba oblaka točk v AABB omejitvene volumne (AABB določen z minimalno in maksimalno vrednostjo koordinat točk v določenem območju),
  - okrog AABB očrtamo kroglo BS za hitrejši izračun,
  - omejitveni volumni BS tudi za segmente robota,
  - izračun razdalj med dvema kroglama.



B. Schmidta, L. Wang, „Depth camera based collision avoidance via active robot control“, Journal of Manufacturing Systems, Volume 33, 2014, 711-718.



# Časovno-kritična detekcija trkov v deformnih modelih

Povzeto po:

Jernej Barbič, University of Southern California (Carnegie Mellon University)  
Doug L. James, Cornell University



## Različne predstavitev objekta



Zvezni model

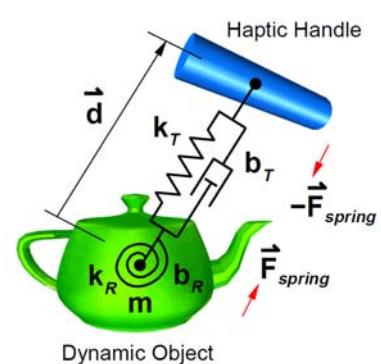
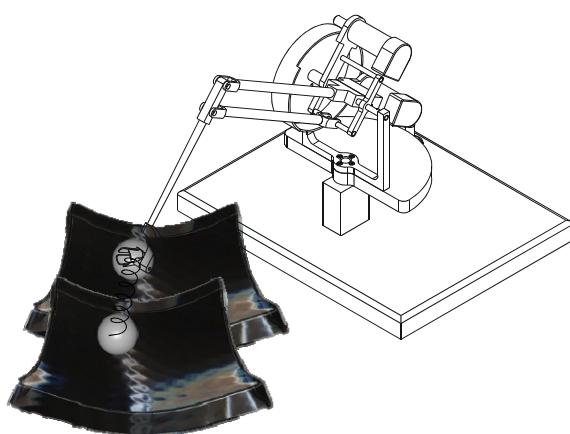


Voksli

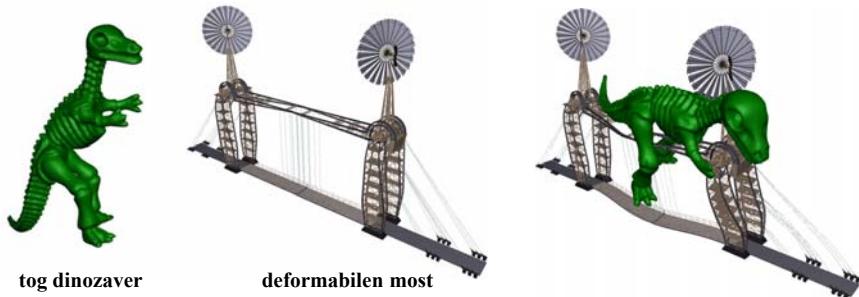


Lupina točk

## Navidezna sklopitev



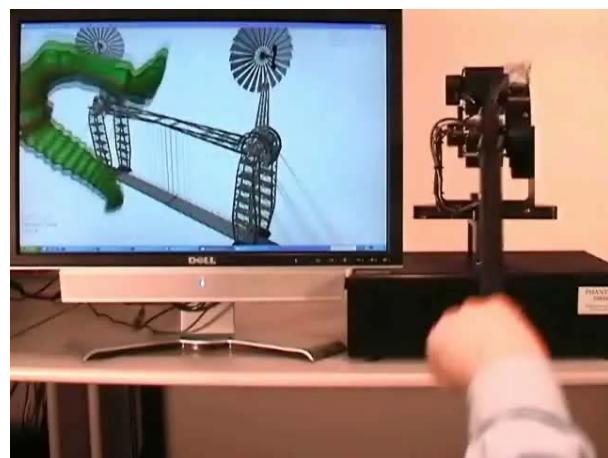
## Dotik objektov s kompleksno geometrijo



- En tog in en deformabilen objekt
- Oba objekta s kompleksno geometrijo

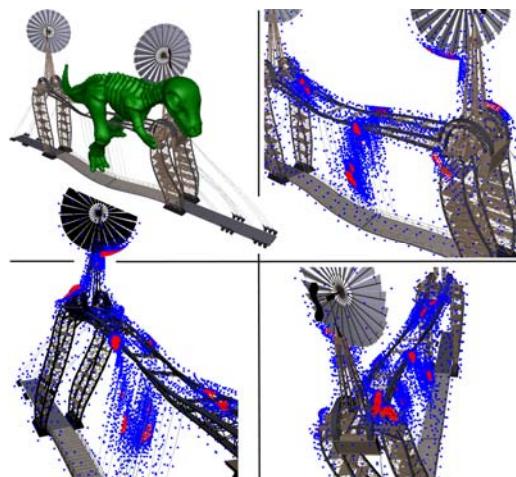
## Haptična interakcija

- Uporabnik zaznava sile interakcije
- Zahtevana visoka vzorčna frekvenca (1000 Hz)



## Porazdeljen dotik

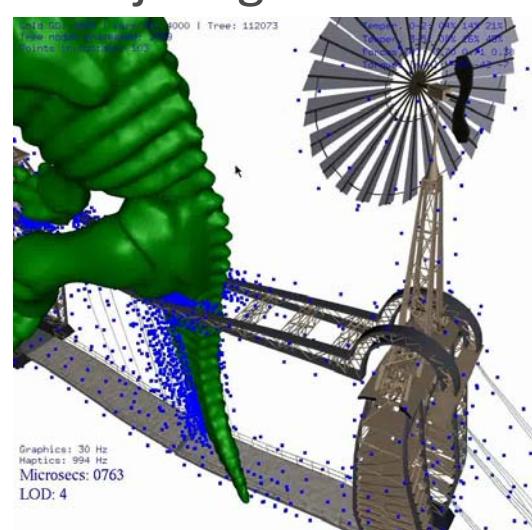
Več sočasnih dotikov, vsak porazdeljen po površini različni od nič.



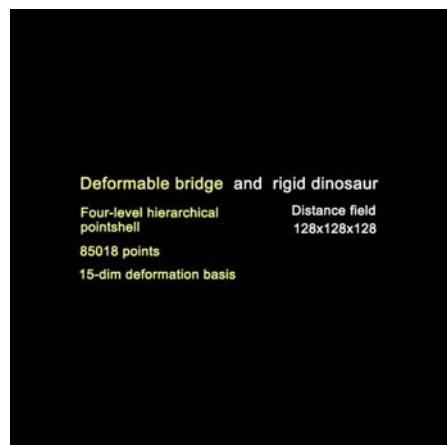
Dvanajst dotikov (rdeče)

## Haptično prikazovanje porazdeljenega dotika

- Zakaj je zahtevno?
  - visoka vzorčna frekvenca
  - dinamika deformacij
  - detekcija trka
  - izračun reakcijskih sil.



## Tog in deformabilen dotik

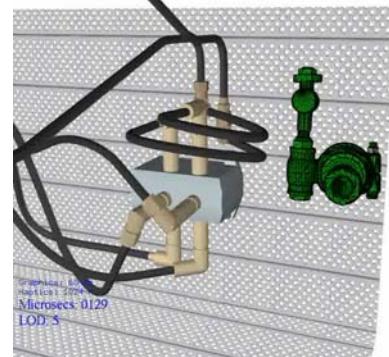


Deformable bridge and rigid dinosaur  
Four-level hierarchical pointshell      Distance field 128x128x128  
85018 points  
15-dim deformation basis



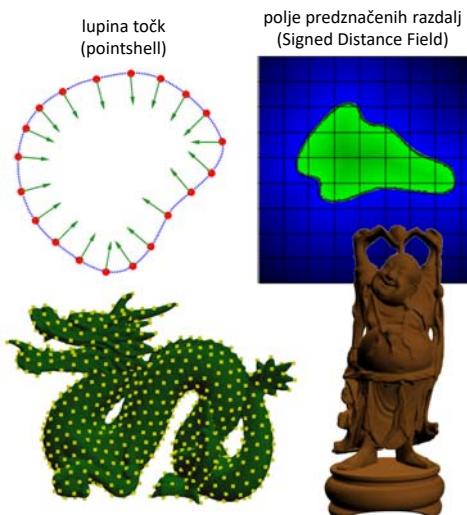
Cold: 60; 17%; Warm: 60; 2000; Tree: 109121  
Tree nodes processed: 0003  
Points in contact: 0

Temper: 0-2; 045 085 095  
Temper, 3-5; 035 055 075  
Forces [N]: 0.00 0.00 0.00  
Torques [Nm]: 0 0 0



Operater zaznava sile in navore dotika.

## Model dotika



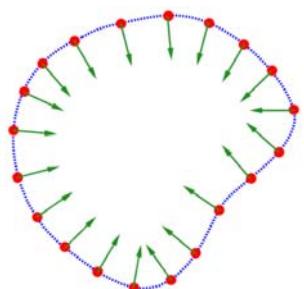
### • Polje predznačenih razdalj

- vzorčena mreža točk, ki določajo najmanjšo razdaljo do površine objekta
- negativne vrednosti razdalj zunanj objekta
- pozitivne vrednosti razdalj zunaj objekta
- uporaba
  - računalniška grafika,
  - detekcija trka,
  - deformabilni objekti,
  - načrtovanje trajektorij,
  - dinamika več teles (multi-body dynamics).

2	2	2	2	2	2	2
2	1	1	1	1	1	2
2	1	0	0	1	2	
2	1	0	1	1	2	
2	1	1	1	1	2	2
2	2	2	2	2	2	3

For each distance value in the field, is the value <= 0? if yes, draw the pixel if no, ignore it.

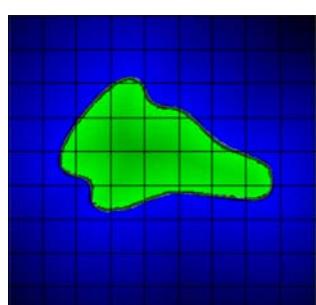
## Lupina točk



[McNeely et al. 1999]

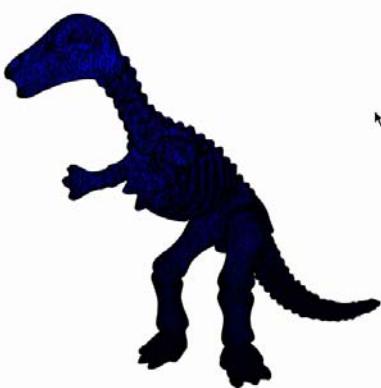


## Polje predznačenih razdalj

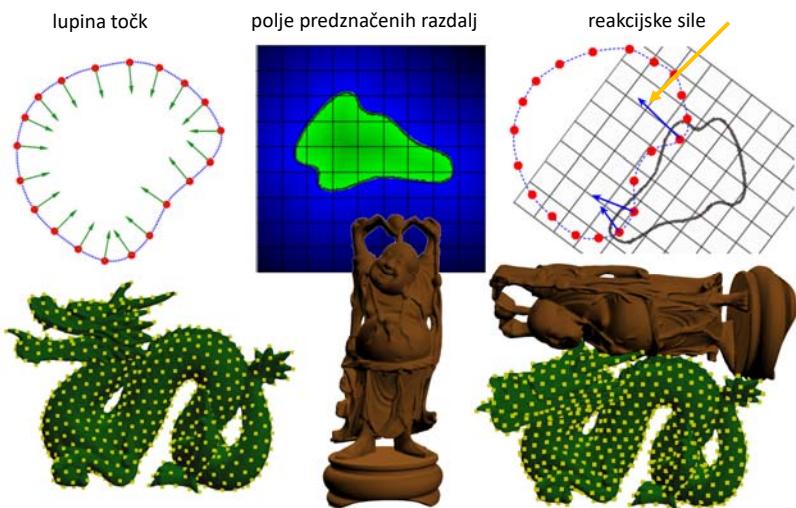


notranjost / zunanjost

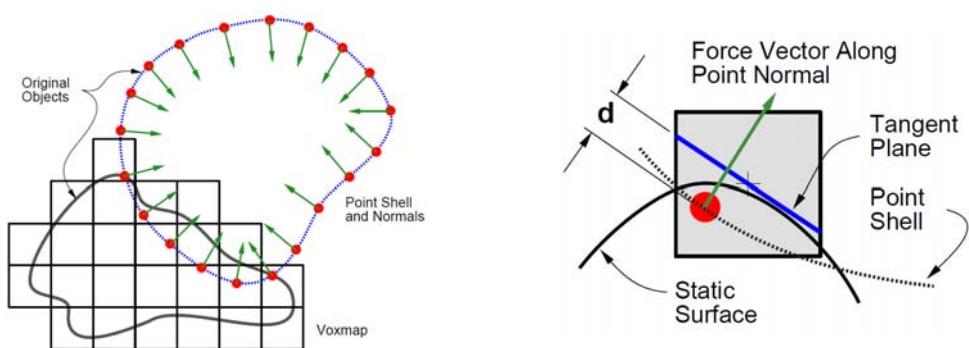
Prikazana ločljivost  
128 x 128 x 128



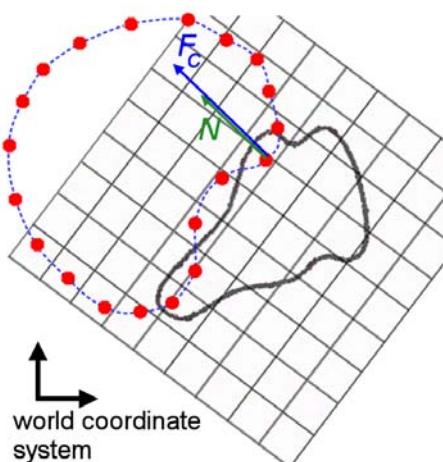
## Sile dotika



## Trk luzione točk in množice voksalov



## Sila dotika



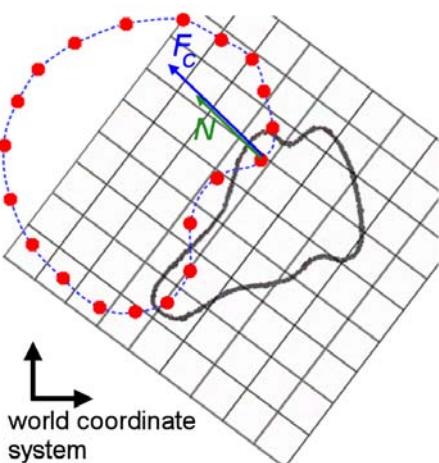
$$F_C = -k_C d N$$

navznoter usmerjena normala  
vrednost polja predznačenih razdalj ( $d < 0$  v dotiku)

togost

- Vsota preko vseh točk.
- Navor =  $r \times F_C$

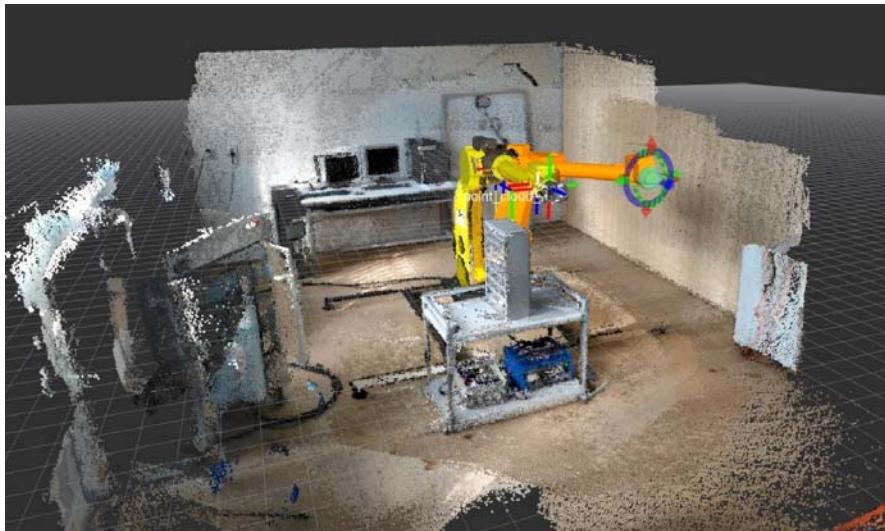
## Zakaj tak model dotika?



$$F_C = -k_C d N$$

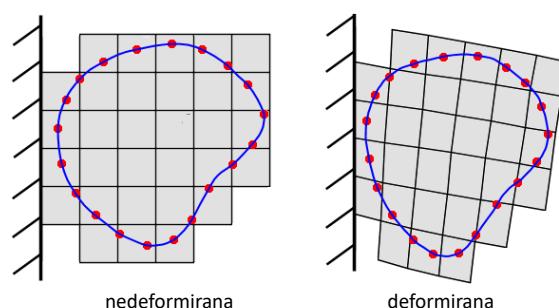
- Hiter: „Lookup“ polje razdalj (vrednost polja predznačenih razdalj).
- Robusten: Sila dotika je zvezna.

## Voksli in oblak točk



## Deformabilna lupina točk

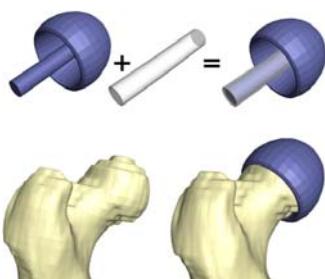
Lupina točk vgrajena v FEM  
(metoda končnih elementov) mrežo.



Splošni FEM modeli se ne izračunavajo s hapticimi vzorčnimi frekvencami za kompleksno geometrijo.

## Princip metode končnih elementov

**Geometrijski model**



Razdelitev na elemente

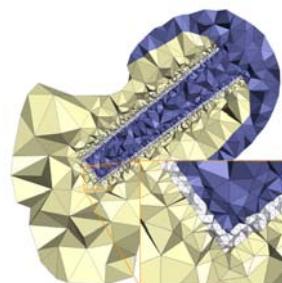
Materialne lastnosti

Lastnosti elementov

Robni pogoji

Obremenitve

**Numerični model**

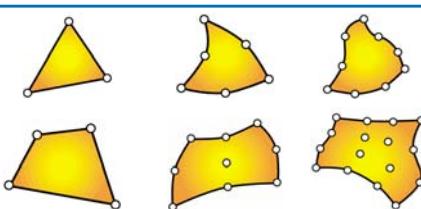


$$[K] \cdot \{u\} = \{F\}$$

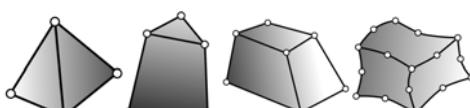
## Metoda končnih elementov - dimenzijske razlike



Vrednost odvisna od ene spremenljivke (porazdelitev potenciala med ploščama kondenzatorja, kjer je med ploščama nelinearni dielektrik). Po ostalih dveh dimenzijah se konfiguracija ne spreminja do neskončnosti.



Vrednost odvisna od dveh spremenljivk (prečni prerezi rotacijskih strojev). Po tretji dimenzijski - običajno z - se konfiguracija ne spreminja do neskončnosti.



Vrednost odvisna od treh spremenljivk. Vsi problemi so dejansko takšni, ker se konfiguracija spreminja po vseh dimenzijah, vendar jih zaradi intenzivnosti računanja poskušamo reševati kot 2D probleme

## Statični problem

Osnovni ravnotežni sistem enačb

$$[K] \cdot \{u\} = \{F\}$$

$[K]$  – globalna togostna matrika,

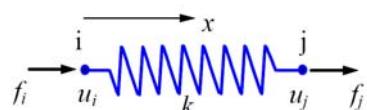
$\{u\}$  – vektor prostostnih stopenj vozlišč,

$\{F\}$  – vektor točkovnih sil v vozliščih.

Iščemo neznane pomike vozlišč  $\{u\}$

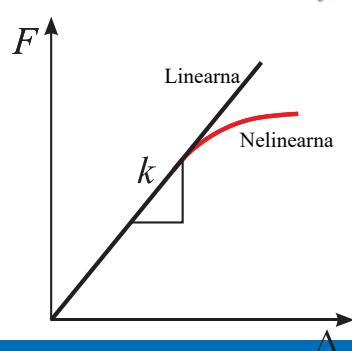
$$\{u\} = [K]^{-1} \cdot \{F\}$$

## Primer vzmeti



$$F = k\Delta \quad \text{kjer je} \quad \Delta = u_j - u_i$$

Dve vozlišči:	$i, j$
Premiki vozlišč:	$u_i, u_j$
Vozliščne sile:	$f_i, f_j$
Konstanta vzmeti (tugost):	$k$



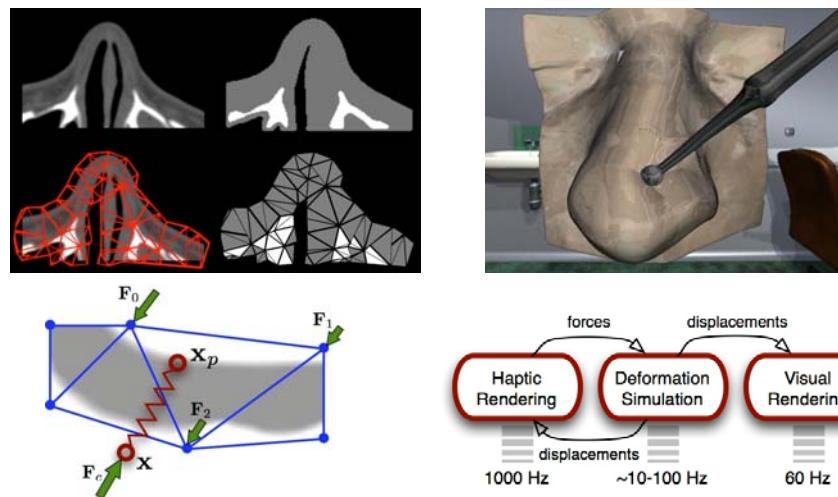
$$f_i = -F = -k(u_j - u_i) = ku_i - ku_j$$

$$f_j = F = k(u_j - u_i) = -ku_i + ku_j$$

$$\begin{bmatrix} k & -k \\ -k & k \end{bmatrix} \begin{bmatrix} u_i \\ u_j \end{bmatrix} = \begin{bmatrix} f_i \\ f_j \end{bmatrix}$$

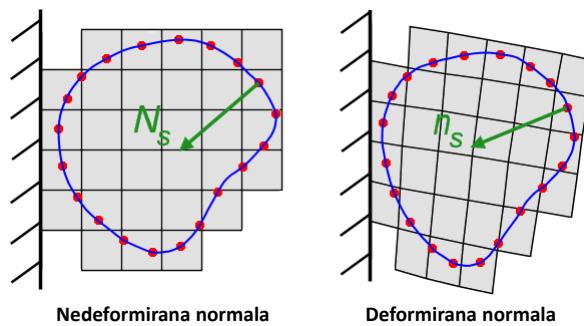
$$[K] \cdot \{u\} = \{F\}$$

## Deformni FEM modeli

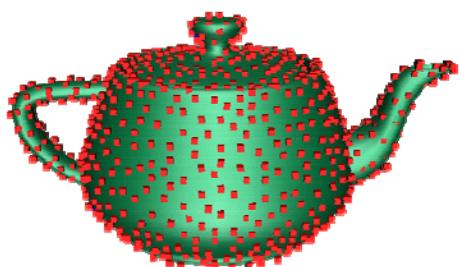


## Izračun deformiranih normal

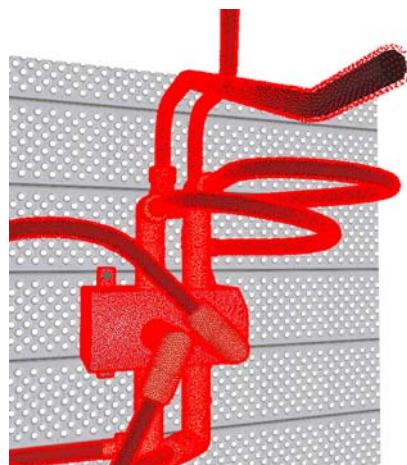
- za točke v dotiku
- s haptično vzorčno frekvenco



## Kako simulirati velike lupine točk?

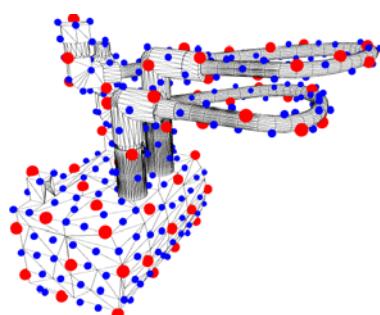


V 1 ms je mogoče procesirati omejeno število točk.

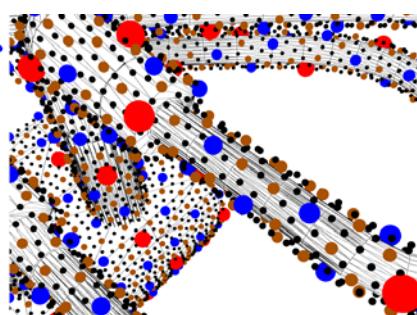


80,000 točk

## Večločljivostna lupina točk



Nivoja 1 in 2.

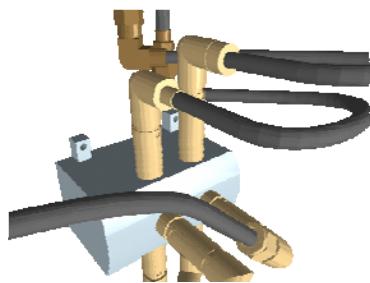


Detajlno: Nivoji 1, 2, 3 in 4.

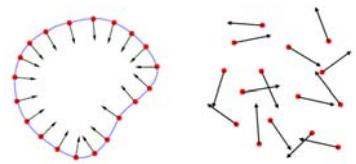
Uporabno za toge in deformne lupine točk.

## Generiranje lupine točk

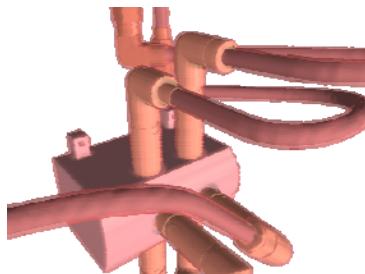
Točke postavimo na površine, ki popolnoma zapirajo volumen (manifold surface).



**Geometrija "Polygon soup"**  
Množica neorganiziranih trikotnikov brez kakršnekoli relacije med njimi (Maya, Blender).

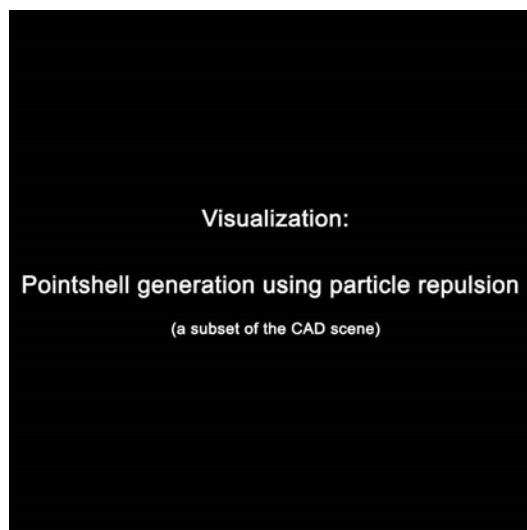


dobra lupina točk      slaba lupina točk



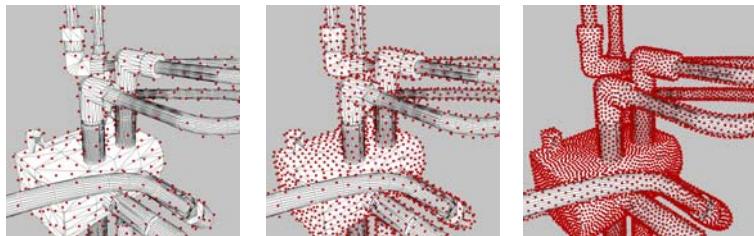
Odmaknjena površina

## Generiranje lupine točk

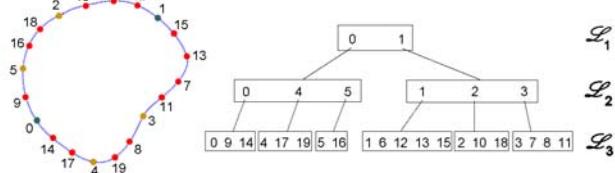


[Turk 1992, 2001, Witkin and Heckbert 1994]

## Gnezdeno drevo točk



Pri ostalih implementacijah odvisno od podrobnosti modela

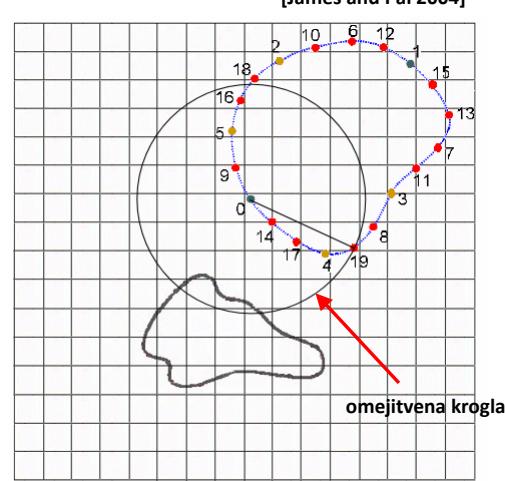
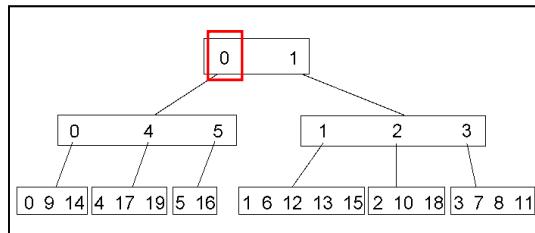


Vsek nivo povzroči površino z višjo ločljivostjo

[Mendoza and O'Sullivan 2006, Hubbard 1995]

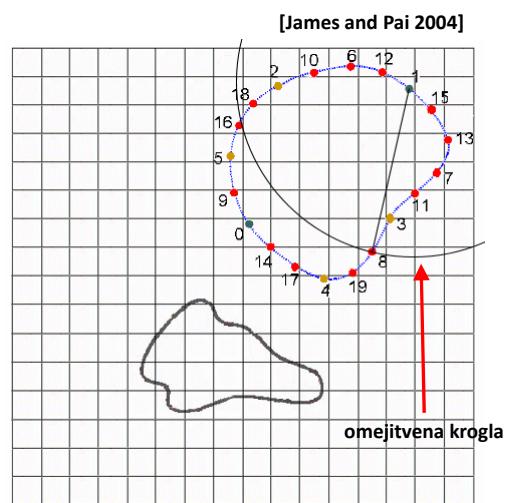
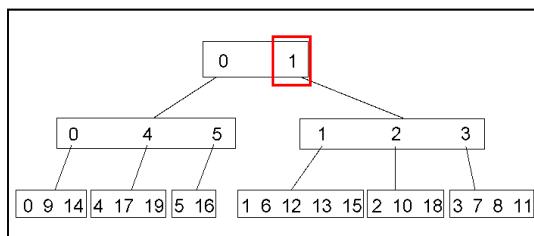
## Deformna sferična hierarhija

- Obsegajo vse točke na lupini
- Postavimo izhodišče krogla v točko (vozlišče) na lupini
- Krogla objema vse točke drevesa pod vozliščem



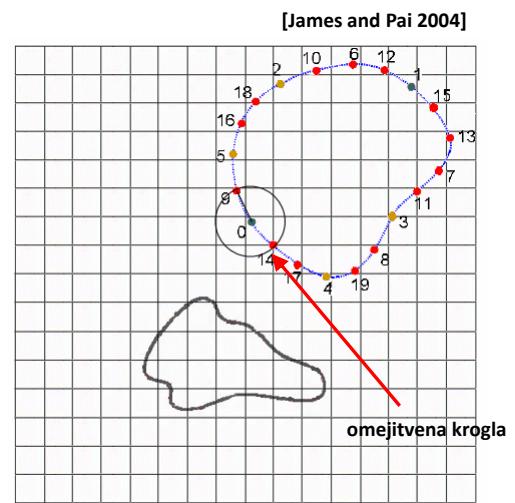
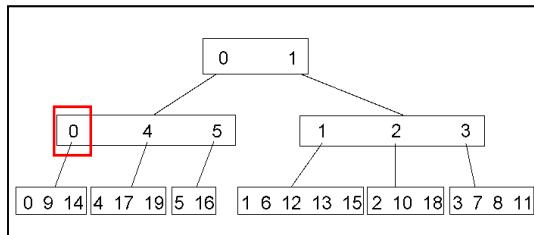
## Deformna sferična hierarhija

- Obsega vse točke na lupini
- Postavimo izhodišče krogle v točko (vozlišče) na lupini
- Kroga objema vse točke drevesa pod vozliščem



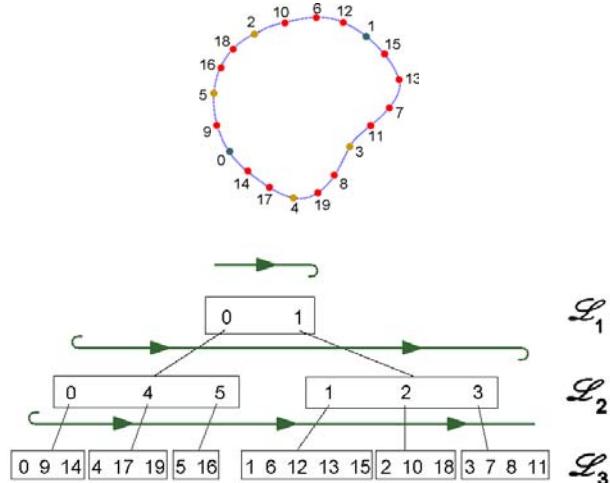
## Deformna sferična hierarhija

- Obsega vse točke na lupini
- Postavimo izhodišče krogle v točko (vozlišče) na lupini
- Kroga objema vse točke drevesa pod vozliščem



## Prečenje najprej po širini

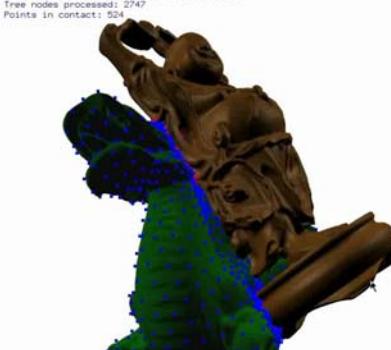
- izbira pod-dreves na podlagi sferične hierarhije
- linearna operacija
- večločljivostna sestava sile dotika
- mogoče prekiniti v kateremkoli trenutku
- izračun samo za prečene točke
  - Položaj točke
  - Radij omejitvene krogle
  - Vrednost polja razdalj
- izračun samo za točke v dotiku
  - normala
  - „delna“ sila dotika



## Kompleksni dotiki

- Prepotovati je potrebno velik del drevesne strukture
- Točk na lupini je preveč, da bi prečili vse
- Kako „kvalitetno“ poslabšati simulacijo?

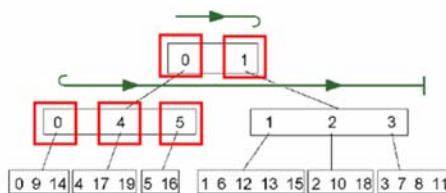
Cold GD: 4000 | Warm GD: 5000 | Tree: 341001  
Tree nodes processed: 2747  
Points in contact: 5249



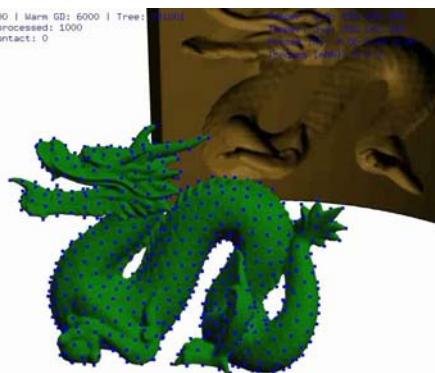
v dotiku / preverjeno

## Kako „kvalitetno“ poslabšati simulacijo?

- Določiti število vozlišč, ki jih je mogoče procesirati v enem haptičnem ciklu
- Prečenje najprej po širini, dokler ni dosežena kvota vozlišč



Cold GB: 4800 | Warm GB: 6000 | Tree: 1000  
Tree nodes processed: 1000  
Points in contact: 0

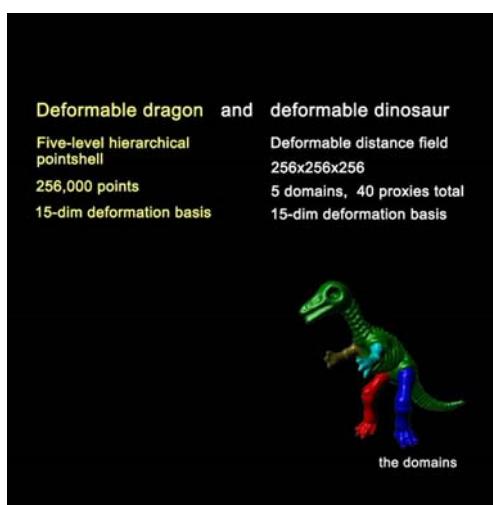


Graphics: 20 Hz  
Haptics: 1024 Hz  
Microsecs: 0239  
LOD: 5

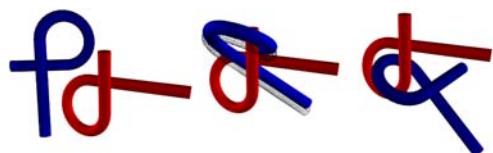
[v dotiku / preverjeno](#)

## Deformabilen vs. deformabilen dotik

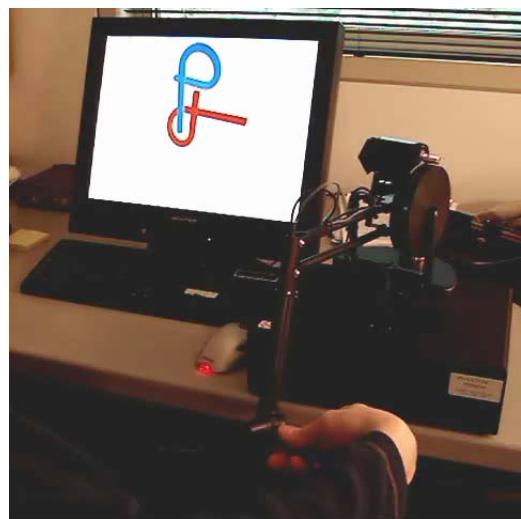
deformabilno polje oddaljenosti  
&  
deformabilna lupina točk



## Primer – načrtovanje trajektorije



fiksen / manipuliran



## Zaključek

- Časovno-kritično haptično zaznavanje deformabilnih modelov mogoče tudi s haptičnimi frekvencami
- Gnezdeno drevo točk za časovno-kritične operacije
- Celotna simulacija se poenostavi zaradi zmanjšanja kompleksnosti



Boeing 777  
pristajalni mehanizem 2 milijona trikotnikov

