# Computational Design of Reconfigurables

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#### reconfigurable | riːkənˈfɪg(ə)rəb(ə)l | noun

an object or collection of objects whose transformation between various states defines its functionality or aesthetic appeal.

### Foldable bicycle is a classic example of a reconfigurable



#### Transforming furniture is also a reconfigurable



https://youtu.be/A3PDiDLiOEI

#### Transforming furniture is also a reconfigurable



https://youtu.be/A3PDiDLiOEI

# Space-saving kitchen is also a reconfigurable









### Problems occur if we design each state in isolation...



state #1

### ...collisions prevent transitioning to other states



state #2

#### ...collisions prevent transitioning to other states



first contact

## We model reconfigurables as a graph of transitions



### We model reconfigurables as a graph of transitions



# Our goal is to help the designer keep all transitions collision free



need UI to **notify** designer of new collisions

need UI to *track* progress of collisions

need modeling tools to **resolve** collisions

### Harmonization of all three enables to rapid and creative editing sessions

need UI to **notify** designer of new collisions

need UI to **track** progress of collisions

need modeling tools to *resolve* collisions

#### Traditional CAD tools have limited collision support



#### offline detection

#### notification via "audible bell"

no automatic resolution

solidworks

### Animation tools detect and respond to collisions for physically-based effects



time is linear and "one-way"

no salient states

overlaps OK if not noticeable

#### Previous computational design tools either:





#### ignore collisions

Tanzari Baginari Makahari Akabari Tanga Manane Mitan Tanahari Manana Manana

Boxelization: Folding 3D Objects into Boxes

Stackabilization

Honghua Li<sup>1,4</sup> Braharan Alhanhin<sup>1</sup> Hao Zhang<sup>1</sup> Arial Shanin<sup>2</sup> Daniel Caharo-Dr<sup>4</sup> Simon Fasser University <sup>\*</sup> "National University of Defense Technology <sup>\*</sup> Interdeciptionary Center <sup>\*</sup>Tel Ariv University

box using a contribution folding sequence. Our modeling the initial, contrast of their fact and the physical physical and search fact a variation of the physical physical and search fact a variation of the physical physical the range theory. This interview there major range, finding variations, finding the true messare that can harm for its sequences. We down and search remains an averant input 31 and also physically divisions some using a 32 patient. CPC Foldament 1313 "Owners Checkled" Concurstants.

Represente: public fielding, fabrication, interactive physics Links: ©DL GPDF

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Stacking objects on up of each other by human. Objects are obtain stackin instance, while shipping or straining th explorering, efforts have been invested without compromising the product's in

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alt: (horgboal, ini?, here) @ dis.es.



Making Burr Puzzles from 3D Models



Design of Twisty Joints and Puzzle

day Sun Changai Zheng

Figure 11 Weity Avandilla, (dpl) A twice passife in the shape of an Attacation tensor and income for any planet damp of the sequelar princ (Dpl) The neutron of non-dipervite monosoficiant and avanded), and accounted has construint planes. The different parts of the model, such that errors and laps, were deformed as these they do not collide with one collar regardless of the configuration of the paralle.

1 Introduc

new facinating, incipaing and emotion mally, several exceptionical methods 1



Represents: Computational design, 2D fabricaria ales, Habits Cales, group theory interlocking Medic: ©18, 2019 SWins O'Unero



leverage a specialized subspace

#### We begin with objects as rigid triangle meshes



# Along each transition an object is a 4D *spacetime* volume





# Collisions correspond to intersections in spacetime





### Collision Intervals form the foundation of our notification and tracking UIs

![](_page_24_Figure_1.jpeg)

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![](_page_25_Figure_1.jpeg)

### Spatial and temporal projections of collision intervals alert the designer

![](_page_26_Figure_1.jpeg)

### First priority: alert designer *when* collision is occurring

![](_page_27_Figure_1.jpeg)

### Next: alert designer *where* collision is occurring

![](_page_28_Picture_1.jpeg)

### Designer's current view may be poor, *hotkey* tumbles to optimized view

![](_page_29_Picture_1.jpeg)

### Designer's current view may be poor, *hotkey* tumbles to optimized view

![](_page_30_Picture_1.jpeg)

![](_page_31_Picture_1.jpeg)

Collision interval not central

п

![](_page_32_Picture_1.jpeg)

![](_page_32_Picture_2.jpeg)

Collision interval not central Collision interval occluded

п

![](_page_33_Picture_1.jpeg)

![](_page_33_Picture_2.jpeg)

![](_page_33_Picture_3.jpeg)

#### Collision interval not central

#### Collision interval occluded

View direction along trajectory

п

![](_page_34_Picture_1.jpeg)

![](_page_34_Picture_2.jpeg)

![](_page_34_Picture_3.jpeg)

#### Collision interval not central

#### Collision interval occluded

View direction along trajectory

#### For two objects, center collision interval along view direction orthogonal to motions...

![](_page_35_Picture_1.jpeg)
#### Generally, two choices left: pick direction with least occlusion



### For degenerate views or multiple objects, we search over all views via *Monte Carlo*



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count "red" pixels using hardware "occlusion queries" (GL SAMPLES PASSED)

#### Picture-in-picture allows rapid editing





















## Stroboscopic ghosting complements interactive collision interval tracking



Stroboscopic ghosting complements interactive collision interval tracking



Stroboscopic ghosting complements interactive collision interval tracking



### Fixing collisions can be tedious and unintuitive, how about a hint?



#### decrease/remove collisions

#### agnostic to direction of time

in terms of UI DOFs

## First contacts between objects produce unreliable, biased directions



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## Global solution should *untangle* spacetime intersection



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# 2D reconfigurables *could* be untangled like 3D cloths





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*I<sub>C</sub>* intersection contour



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argmin  $||I_C||$ V length 3D mesh vertices

update via gradient descent $\mathbf{V} \leftarrow \mathbf{V} - \nabla_{\mathbf{V}} \| I_C \|$ 

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argmin  $||I_C||$ V length 3D mesh vertices

update via gradient descent

$$\mathbf{V} \leftarrow \mathbf{V} - \mathbf{\nabla}_{\mathbf{V}} \| I_C \|$$

[Volino & M-T 2006]

#### Naive extension to 3D objects is problematic



 $\mathcal{A},\mathcal{B}\subset \mathbb{R}^4$ 

#### Naive extension to 3D objects is problematic



 $\partial \mathcal{A}, \partial \mathcal{B} \in \mathcal{S}_{3D}$  $\partial \mathcal{A} \cap \partial \mathcal{B} \in \mathcal{S}_{2D}$ 

Difficult to compute or optimize over

#### Naive extension to 3D objects is problematic



 $\partial \mathcal{A}, \partial \mathcal{B} \in \mathcal{S}_{3D}$  $\partial \mathcal{A} \cap \partial \mathcal{B} \in \mathcal{S}_{2D}$ 

Difficult to compute or optimize over

How to minimize surface area of intersection?

 $\underset{\rm UI}{\rm argmin} |I_S|$ 

Intersections of generic surfaces are non-trivial to parameterize...



Intersections of generic surfaces are non-trivial to parameterize...


... but spacetime surfaces are explicit functions of monotonic time





... but spacetime surfaces are explicit functions of monotonic time



Spacetime intersection surface area reduces to integral of 1D intersection contours

#### $\underset{\rm UI}{\rm argmin} |I_S|$

#### $\mathrm{UI} \leftarrow \mathrm{UI} - \nabla_{\mathrm{UI}} |I_S|$

Spacetime intersection surface area reduces to integral of 1D intersection contours

$$\underset{\mathrm{UI}}{\operatorname{argmin}} \int_{0}^{1} \|I_{C}(t)\| \ dt$$

$$\mathrm{UI} \leftarrow \mathrm{UI} - \int_0^1 \nabla_{\mathrm{UI}} \|I_C(t)\| \ dt$$

$$\underset{\mathrm{UI}}{\mathrm{argmin}} \int_{0}^{1} \|I_{C}(t)\| dt$$

$$UI \leftarrow UI - \int_0^1 \nabla_{UI} \|I_C(t)\| dt$$

$$\underset{\mathrm{UI}}{\operatorname{argmin}} \int_{0}^{1} \|I_{C}(t)\| dt$$

$$\mathrm{UI} \leftarrow \mathrm{UI} - \int_0^1 \left( \nabla_{\mathrm{UI}} \mathbf{V}_t \right) \left( \nabla_{\mathbf{V}_t} \| I_C(t) \| \right) dt$$

$$\underset{\mathrm{UI}}{\operatorname{argmin}} \int_{0}^{1} \|I_{C}(t)\| dt$$

$$\mathrm{UI} \leftarrow \mathrm{UI} - \int_{0}^{1} \left( \nabla_{\mathrm{UI}} \mathbf{V}_{t} \right) \frac{\left( \nabla_{\mathbf{V}_{t}} \| I_{C}(t) \| \right)}{\left[ \mathrm{Volino \ \& \ M-T \ 2006 \right]}} dt$$

$$\underset{\mathrm{UI}}{\operatorname{argmin}} \int_{0}^{1} \|I_{C}(t)\| dt$$

$$\begin{aligned} \text{UI} \leftarrow \text{UI} - \int_{0}^{1} \left( \nabla_{\text{UI}} \mathbf{V}_{t} \right) \left( \nabla_{\mathbf{V}_{t}} \| I_{C}(t) \| \right) \ dt \\ & \text{See paper for details...} \\ & \text{[Harmon et al. 2011]} \\ & \text{[Umetani et al. 2011]} \end{aligned}$$

# Gradient direction with respect to UI immediately helps as hint



# Gradient direction with respect to UI immediately helps as hint



# Gradient direction with respect to UI immediately helps as hint



### Collisions involving many objects can be very tedious to fix...



## Collisions involving many objects can be very tedious to fix...



## ... manually fixing one collision may cause more at another place or time



... manually fixing one collision may cause more at another place or time



### ... instead we may follow gradient descent until all collisions disappear



### ... instead we may follow gradient descent until all collisions disappear



# Sometimes, one part's geometry is less important than another's...



90

# Sometimes, one part's geometry is less important than another's...



# Sometimes, one part's geometry is less important than another's...



See paper for details. Made possible in part by

"Mesh Arrangements for Solid Geometry" [Zhou et al. 2016]

presented on Monday



## Swept volume carving invites creative space-saving solutions



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#### Limitations & Future Work

modeling space extend to full modeling / deformation tools

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modeling space extend to full modeling / deformation tools

data integrate with 3D scanning / model repos

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modeling space extend to full modeling / deformation tools

data integrate with 3D scanning / model repos

**physics** feasibility extends beyond collisions

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