Tune-It: Optimizing Wire Reconfiguration for Sculpture Manufacturing

SIGGRAPH Asia 2024


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BACKGROUND

Wire sculpture art

Wire-wrapped jewelry

Furniture design

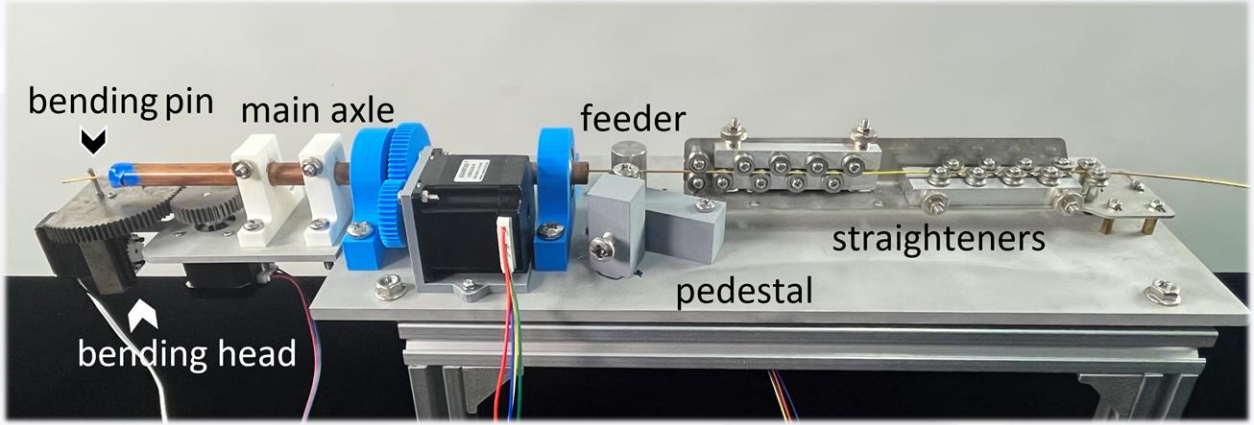
Low-fidelity rapid prototyping

BACKGROUND

Human bending
（Handmade with tool assistance）

Machine bending
（Computer Numerical Control）

BACKGROUND

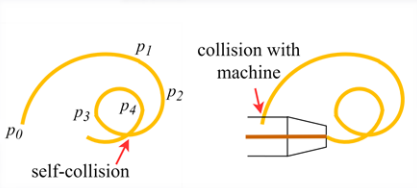


Our DIY bending machine

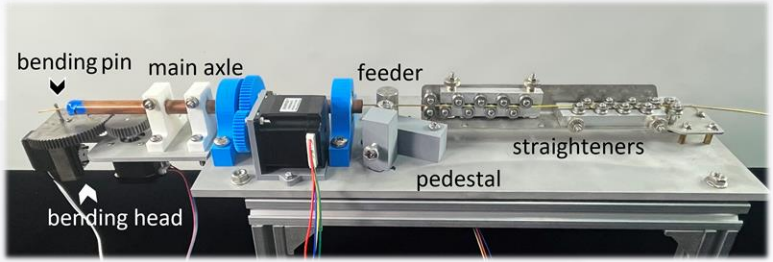
Machine constraint:

Self-**collision** && C**ollision** with the machine

- Collision restrict the geometric complexity of the fabrication wire.



BACKGROUND



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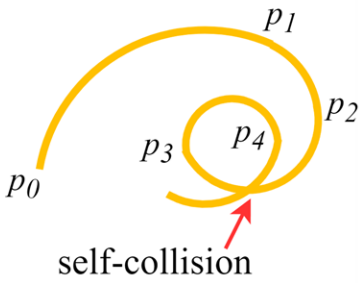
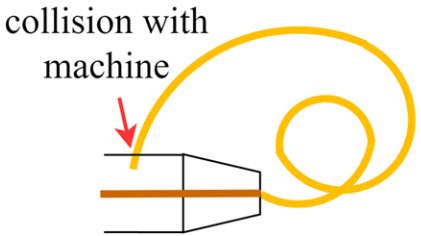
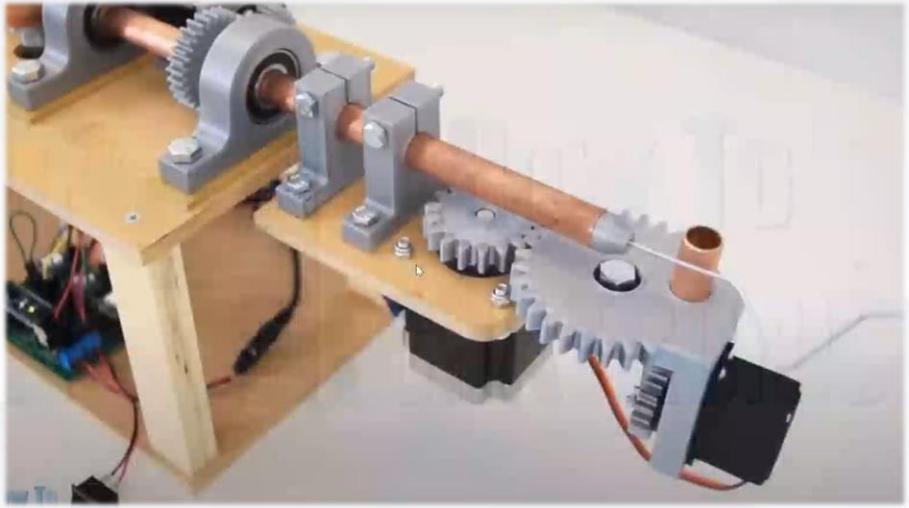




BACKGROUND

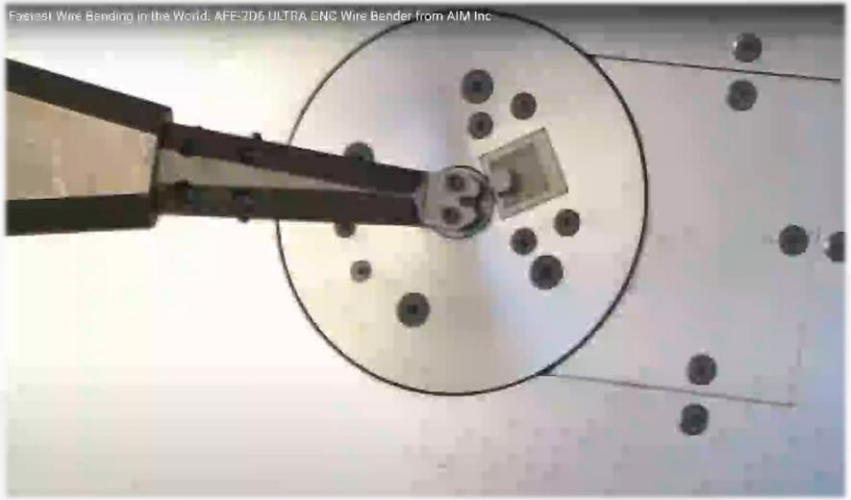
Three bending strategies :

1) Flexion bending strategy: line segment



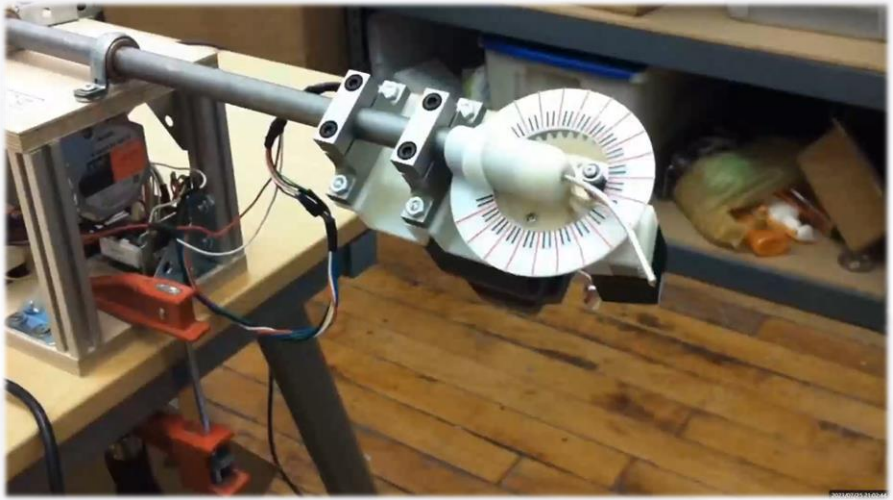
Three bending strategies :

2) Interpolated bending strategy: circular segment



Three bending strategies :

3) Strike bending strategy: circular segment



BACKGROUND

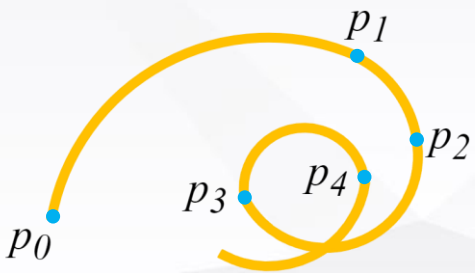
Input

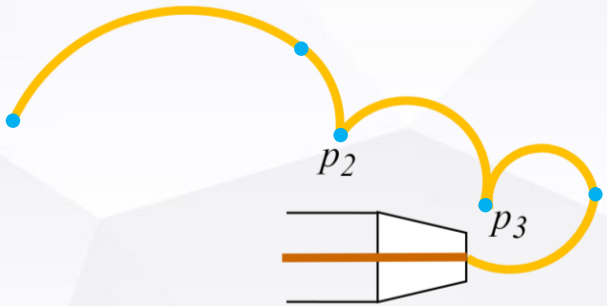
A complex, self-collision 3D curve

Tuning p_i

Output

A manufacturable bending sequence





RELATED WORK

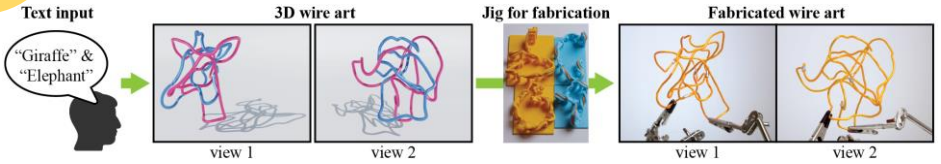
Bending based on human

[Iarussi et al. ACM Trans. Graph. ,

[Torres et al. DIS, 2016]

Too much manual operation

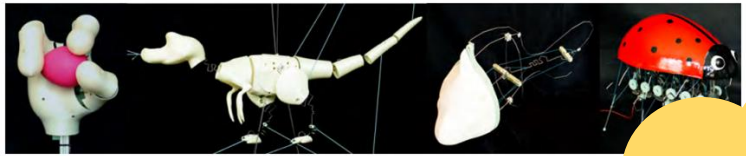
[Wang et al. SIGGRAPH Asia 2019 Posters, 2019]



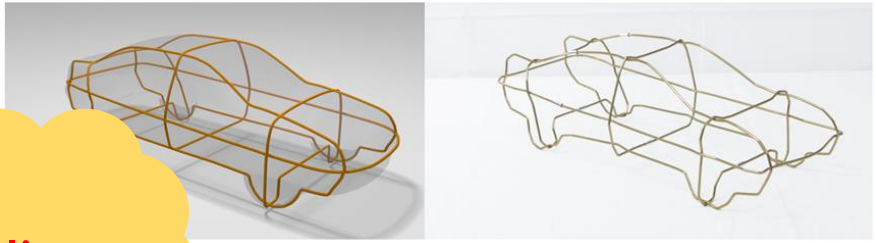
[Tojo et al. SIGGRAPH 2024, 2019]

RELATED WORK

Bending based on machine

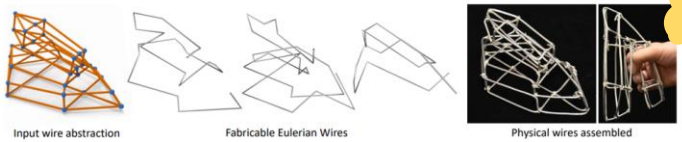


[Xu et al. ACM Trans. Graph. , 2

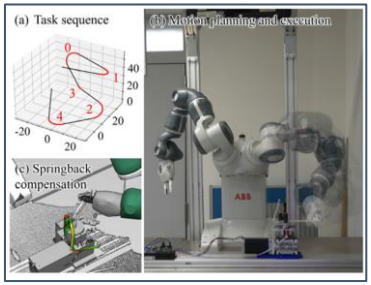


guel et al. ACM Trans. Graph. , 2016]

Multiple lines assembled

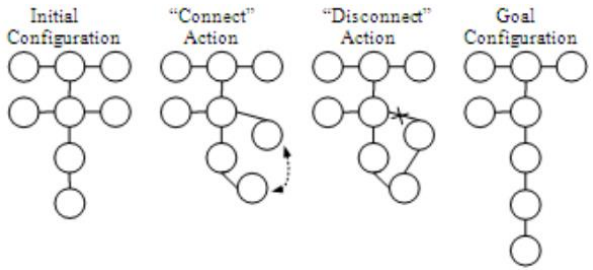


[Lira et al. ACM Trans. Graph. , 2018]

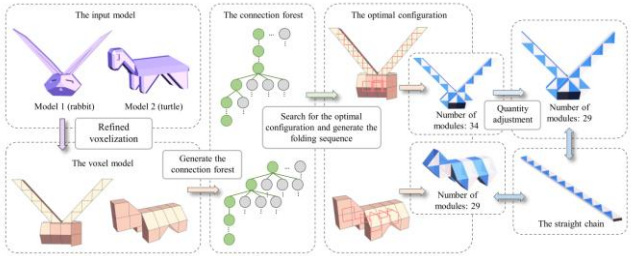


[Liu et al. T-ASE , 2023]

RELATED WORK



[Hou et al. ICRA, 2010]

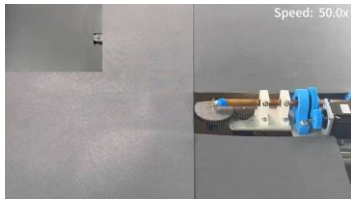


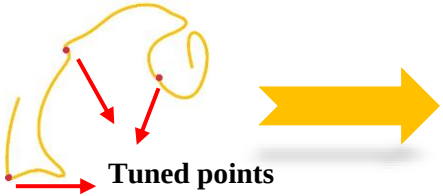
[Zhang et al. SSRN Electronic Journal, 2022]

- Optimal reconfiguration planning (ORP)
- A specific variation ORP, which has been proven to be complete with NP[Hou and Shen 2010]
- Different: Final shape is unknown
- Similar objective

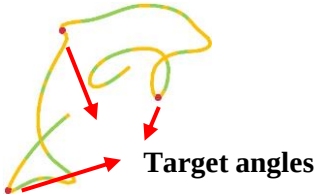
Machine-And-Then-Human-Bending

- **Machine-bending stage**: a tuned version of the input wire to ensure a collision-free CNC bending process.
- **Human-bending stage**: bend tuned wire to the target wire with the help of a human.
- Bending points:
  - Constant points
  - Tuned points
- Goal: Minimize the number of tuned points.





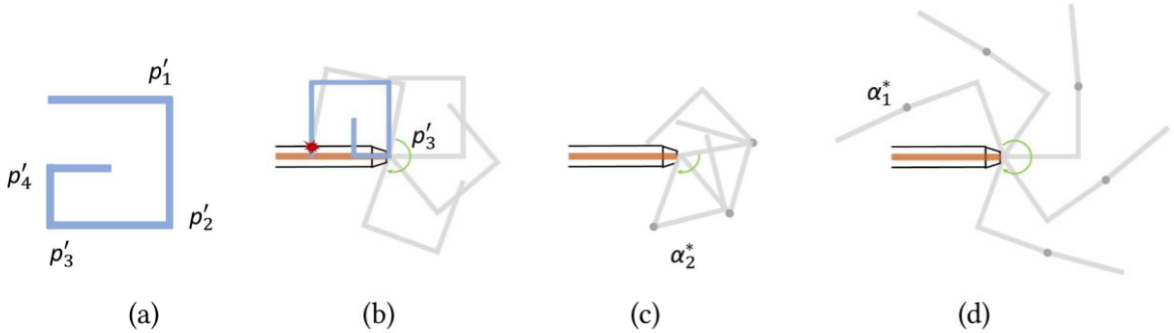
Machine bending stage



Human bending stage

Challenges:

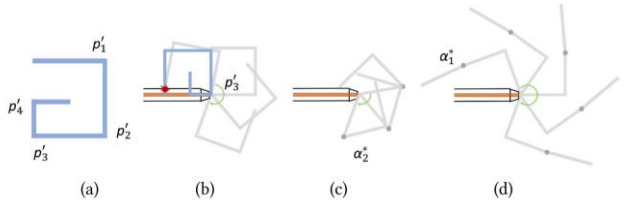
- Collision-free constraints are too hard
- **Couple relationship**



ALGORITHM

Challenges:

- Collision-free constraints are too hard
- **Couple relationship**



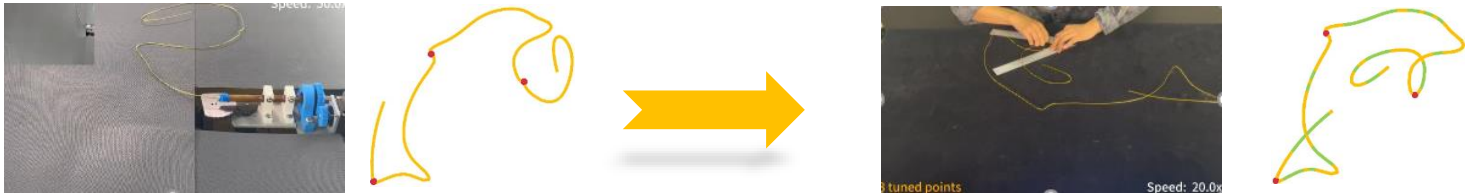
Key idea to solve this problem:

- Decouple the tie of couple relationship by the two level optimization
  - ➢ Outer layer
  - ➢ Inner layer

Innovation

- Shape diversity: Fitting a single curve that consists of arcs and line segments.

- Two-stages-bending: Machine-And-Then-Human-Bending.

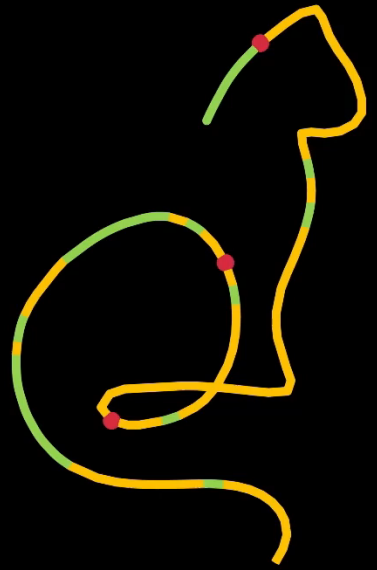


Machine bending stage

Human bending stage

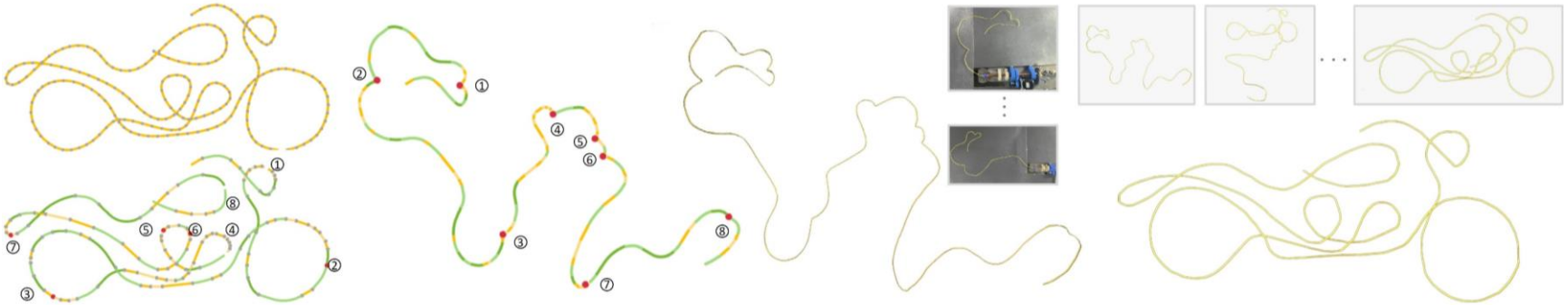
ALGORITHM

Example 1: *Cat* model



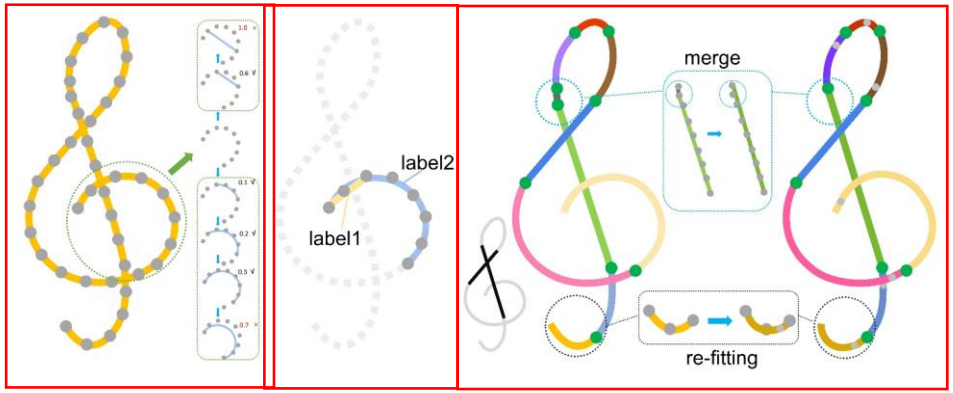
3 tuned points

Overview



(a) Fitting (b) collision-free wire (c) machine-bending (d) human-bending

Fitting



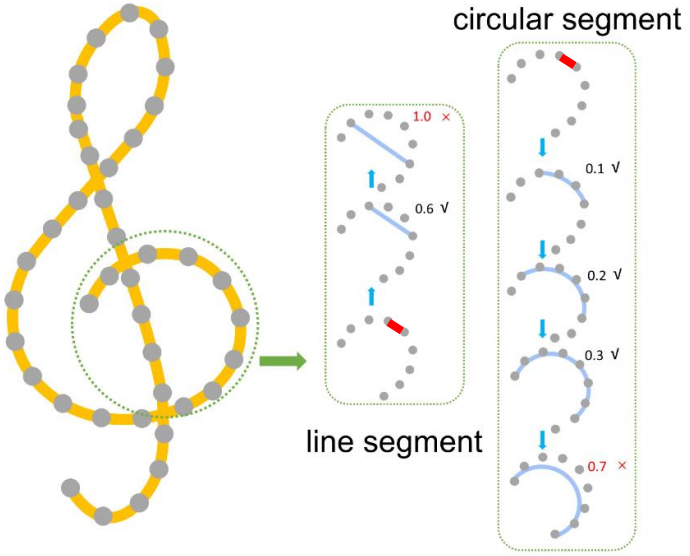
(a) (b) (c) (d)

Example of the fitting

1. Candidate fabricable segments.
2. None-overlapping fabricable segments.
3. Meet the manufacturing constraints.

Fitting: Candidate fabricable segments

- Fit the target shape with continuous **line segments** and **circular segments**.
- Forward-and-backward traverse procedure.



Fitting: None-overlapping fabricable segments

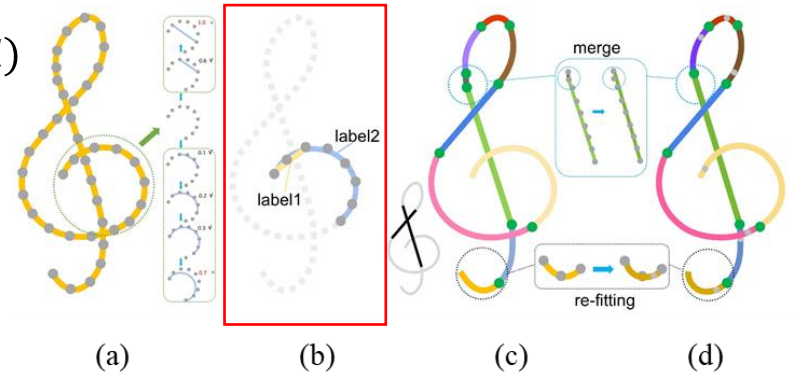
Graph cut

$$\varepsilon = \sum_{s_j \in S_w} D(s_j, l_i) + \sum_{(s_j, s_{j+1}) \in S_w} S(s_j, s_{j+1}, l) + L(l)$$

$$D(s_j, l_i) = \begin{cases} \lambda_1 * d(s_j, l_i), if\ s_j\ in\ \dot{s}_i \\ \infty, otherwise \end{cases}$$

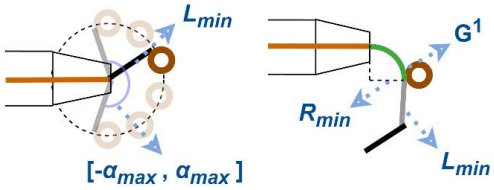
$$S(s_j, s_{j+1}, l) = \begin{cases} 1, if\ l(s_j) \neq l(s_{j+1}) \\ 0, otherwise \end{cases}$$

$$L(l) = \lambda_2 * l(s_j), s_j \in S_w$$

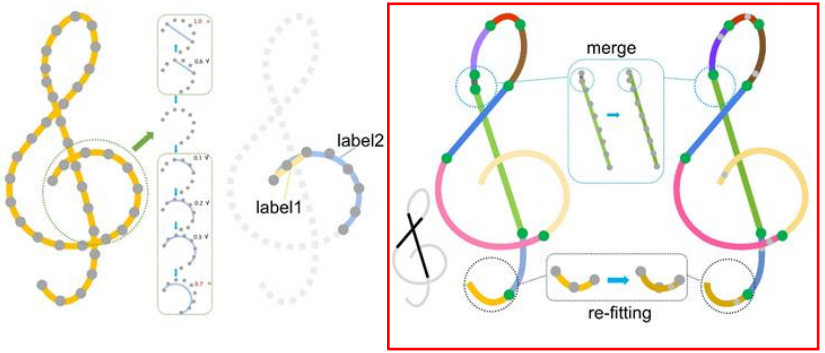


Fitting: Meet the manufacturing constraints

Ensure that each segment adheres to bending fabrication constraints.



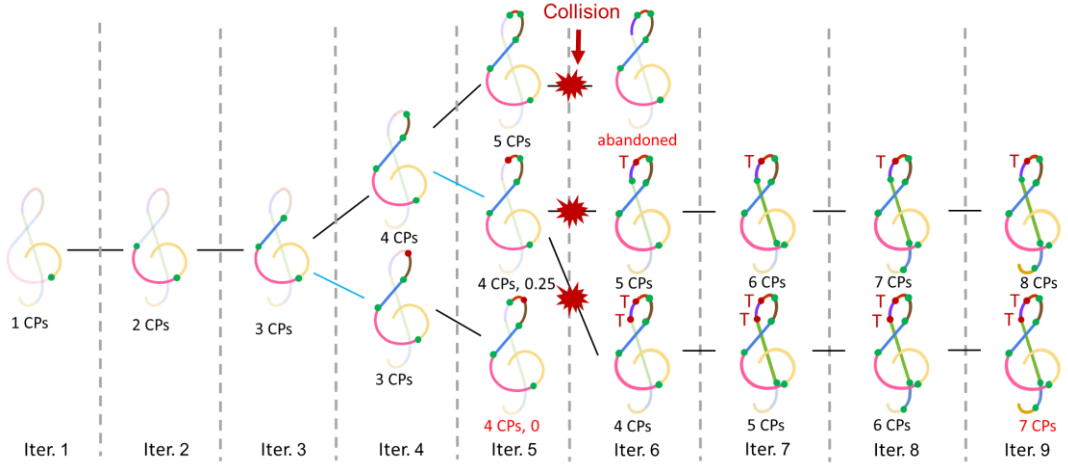
Fabrication constraints



(a) (b) (c) (d)

ALGORITHM

Outer layer—Beam search : Minimize the number of tuned points when selecting them.

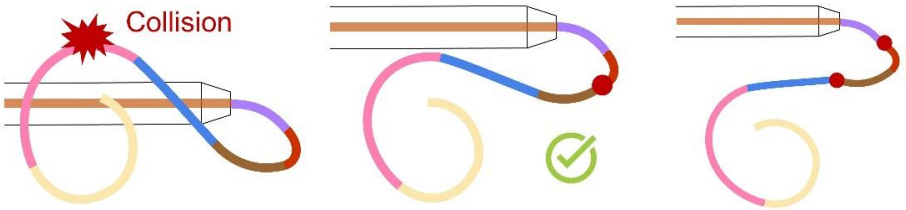


Beam search example

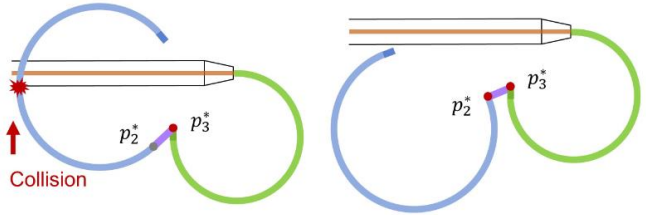
- Candidate nodes generation.
- Candidate nodes scoring.
- Final selection of tuned wire.

Inner layer— CRO: Determining the tuned angles for tuned points.

Collision Resolving Operator, (CRO)



CRO example 1



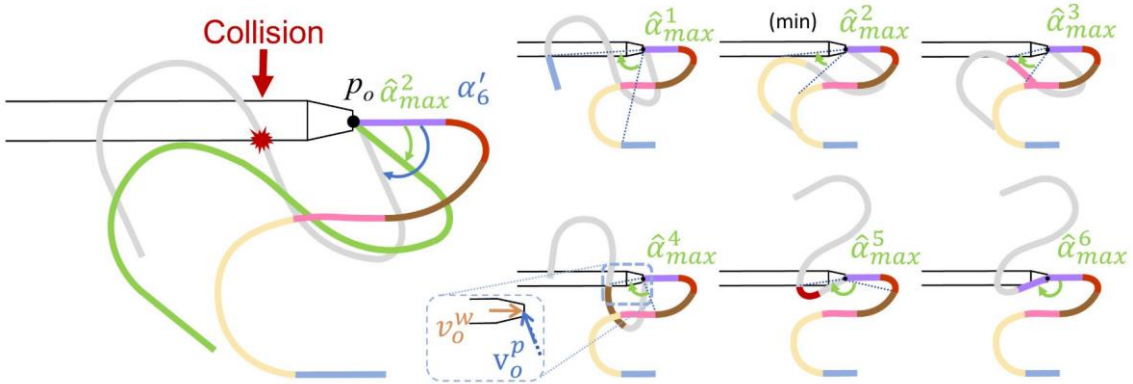
CRO example 2

ALGORITHM

Inner layer— CRO: Determining the tuned angles for tuned points.

Feasible Angle Operator, (FAO)

$$\widehat{\alpha}^{j}_{max} = \min\{\angle(v_o^p, v_o^w) - \arcsin(\frac{0.5d}{\overline{v_o^p}}), p \in s_j^*\}$$

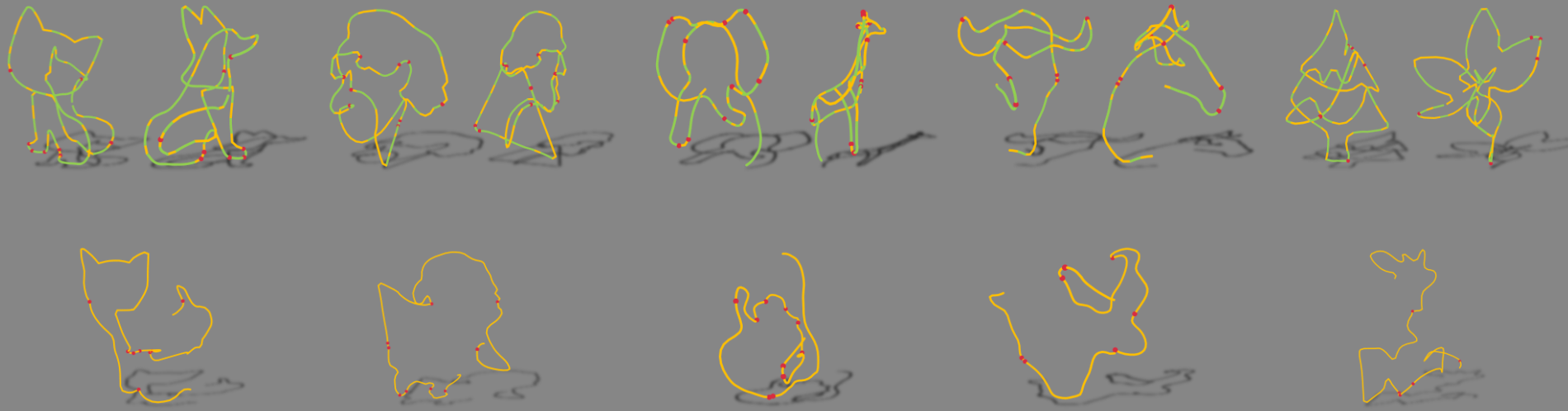


RESULTS

Tuned Results

RESULTS

Tuned Results



Kenji Tojo, Ariel Shamir, Bernd Bickel, and Nobuyuki Umetani. 2024. Fabricable 3D Wire Art. In ACM SIGGRAPH 2024 Conference Proceedings (SIGGRAPH 24).

Fabrication Results

RESULTS

Statistics

					Sec. 4				Sec. 5	
Model	L_t	L_d	$\#N_p$	$\#N_i$	$\#N_s$	$\#N_l$	$\#N_c$	E_{fit}	$\#N_{bs}$	$\#N_{tp}$
Bird	2473.5	710.9	340	5	96	60	36	0.376	362	3
Bull	3307.8	784.4	313	5	107	86	21	0.499	506	7
Cat	2043.5	748.2	314	1	91	75	16	0.326	353	3
Dolphin	2253.5	778.6	339	2	107	82	25	0.249	462	3
Leaf	3429.8	826.0	345	3	126	92	34	0.348	843	9
Ma	3304.2	668.3	157	1	64	48	16	0.322	639	4
Motorbike	4488.8	908.2	384	7	118	72	46	0.648	912	8
Woman	2064.5	791.3	329	5	110	91	19	0.326	646	9

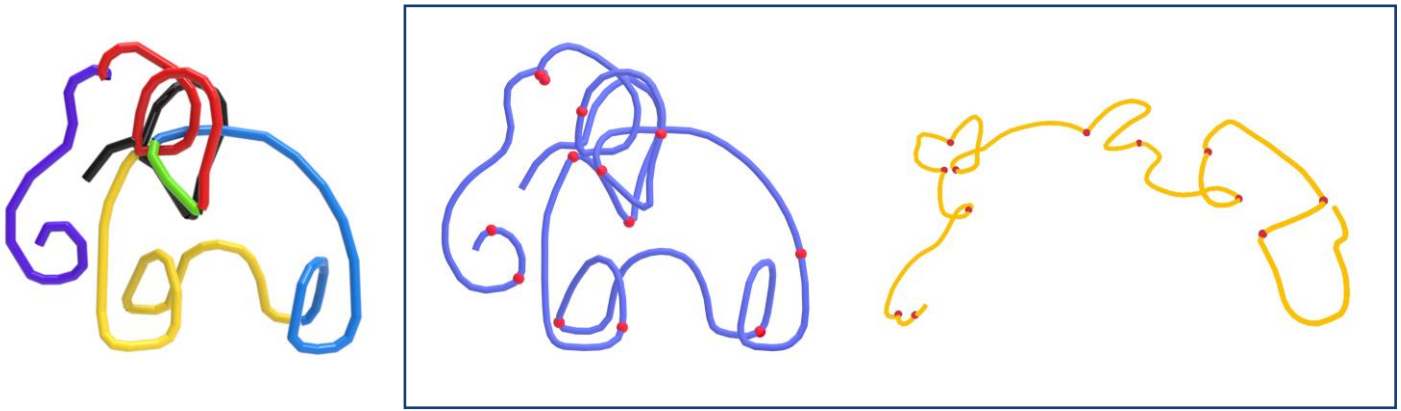
RESULTS

Time Table

	Sec. 4		Sec. 5					Fabrication		
Model	*Fit*	*GR*	*Sc*	*BS*	*CRO*	$\#N_{CRO}$	*Algo*	*Mac*	*Hum*	*Fab*
Bird	5.01	0.32	2.53	0.58	9.52	104	17.96	53.37	2.73	56.10
Bull	2.03	0.24	0.35	0.47	42.92	426	46.01	56.28	5.87	62.15
Cat	3.20	0.25	1.01	0.10	1.63	136	6.19	41.60	2.38	43.98
Dolphin	4.43	0.27	5.46	0.30	4.18	146	14.64	51.30	2.80	54.10
Leaf	3.03	0.24	3.06	1.10	147.99	1346	155.42	66.25	6.20	72.45
Ma	0.95	0.09	2.35	0.17	4.25	134	7.81	34.62	3.42	38.04
Motorbike	2.55	0.29	4.38	3.43	303.36	1656	314.01	71.57	6.13	77.70
Woman	2.83	0.25	0.55	0.16	4.76	566	8.55	49.12	5.48	54.60

RESULTS

Comparison

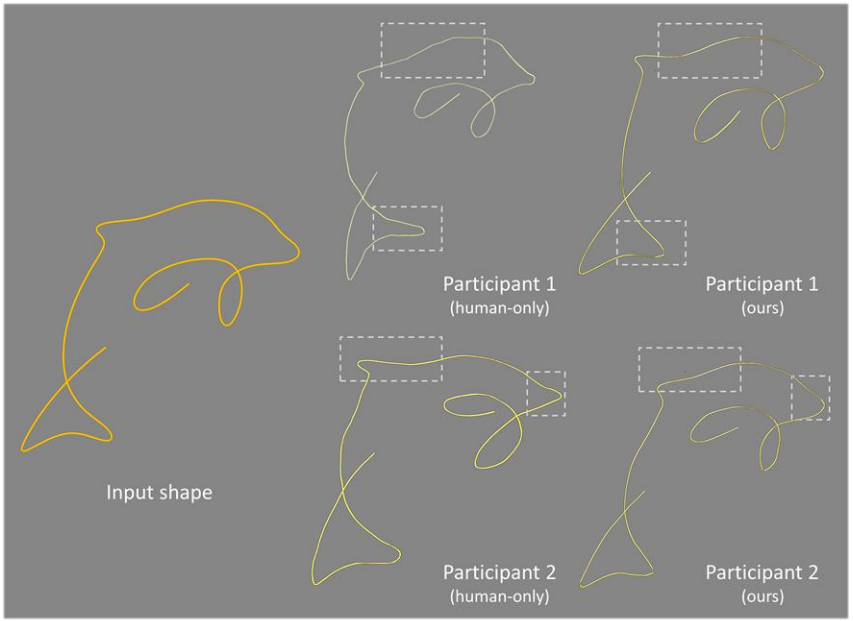


(a) Assembly-based bending

(b) Two-stages-bending (ours)

Wallace Lira, Chi-Wing Fu, and Hao Zhang. 2018. Fabricable eulerian wires for 3D shape abstraction. ACMTransactions on Graphics (TOG) 37, 6 (2018), 1–13.

Comparison



(a) Input shape (b) Human-only (c) Machine-And-Then-Human-Bending (ours)

- The shape produced by our method is more accord with the input shape in angle accuracy, shape smoothness and so on.

LIMITATION

- Not consider physical factors such as gravity, material elasticity, or other functional aspects of actual wire products.
- Not assess wire stability or strength while searching for tuned points to generate a collision-free tuned wire.
- May generate an excessive number of tuned points for certain input wires.

FUTURE WORK

- Incorporating physical simulation into the wire reconfiguration planning process to enhance the accuracy and realism of the wire sculptures.
- Generalizing the proposed two-stages-bending strategy for wire assembly by decomposing complex wire sculptures into multiple tuned wire paths.
- Recognizing the limitation of not considering physical factors suggests promising directions for future work.
- Expanding our solution to the robotics domain.

CONCLUSION

- Presents a computational approach to fabricate wire sculptures with intricate geometric details, which is implemented by the proposed **Machine-And-Then-Human-Bending strategy**.
- The key technique challenge in this paper lies in the generation of **a collison-free fabricable tuned wire** from the input wire, with a minimum number of tuned points.
- The method we develop contains a segment fitting strategy and a bilevel optimization strategy to make the formulation OWR tractable.
- **Physical evaluation** is applied to validate the proposed two-stages-bending strategy with a set of various wire sculptures.

Thank You for Your Criticism and Suggestions

Qibing Wu

https://qibingwu.github.io/

Currently seeking job opportunities.