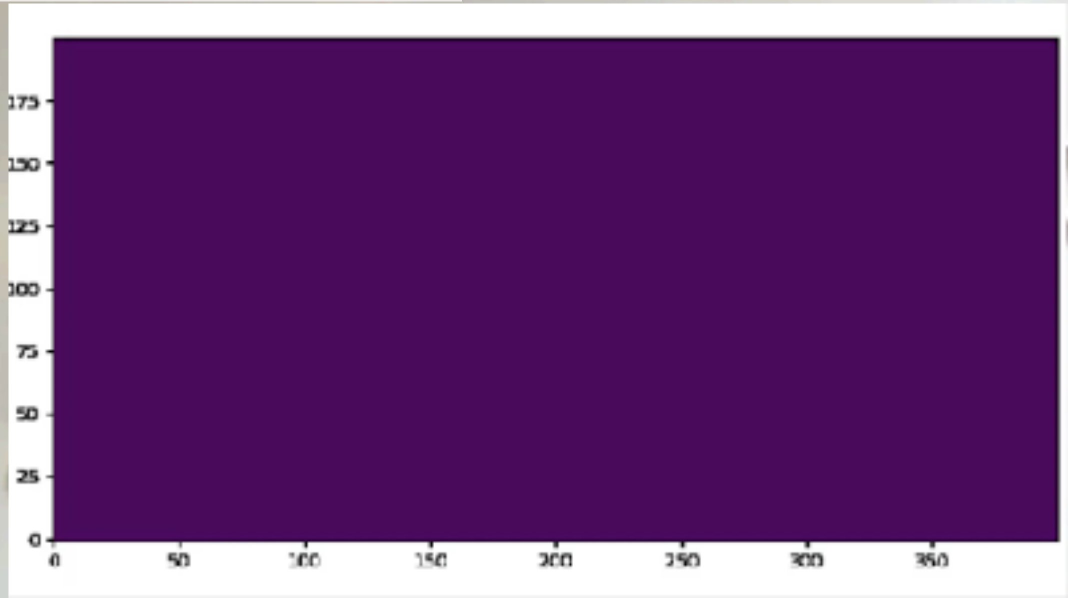
WiSh

a generic solution makes ordinary surfaces shape-aware.

using low-cost, waterproof, lightweight, battery-free RFIDs

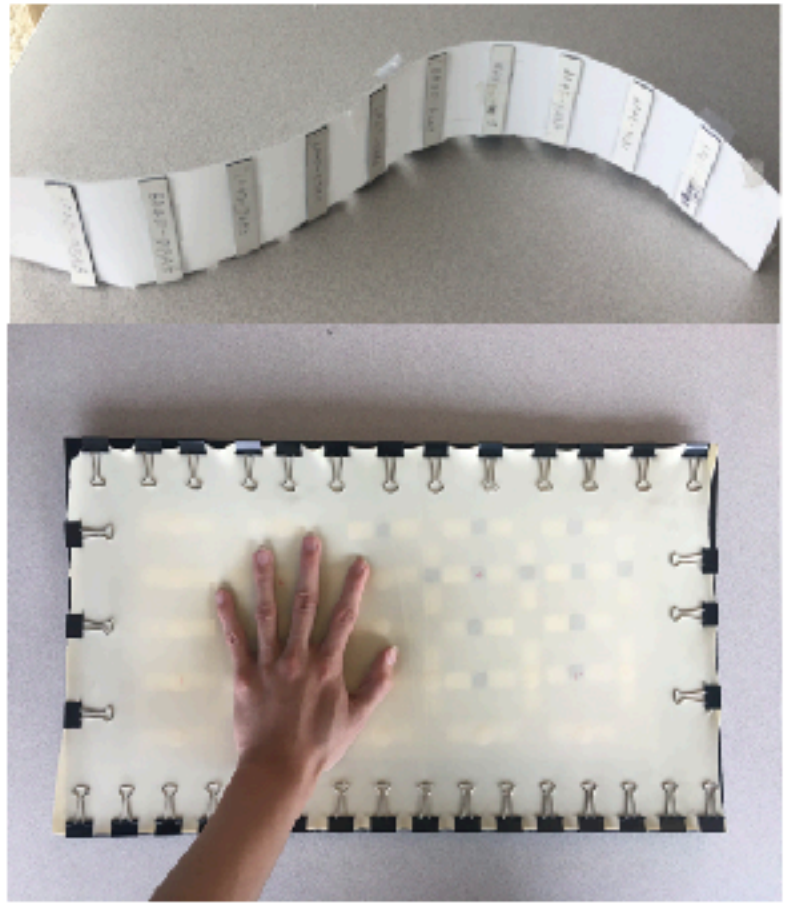


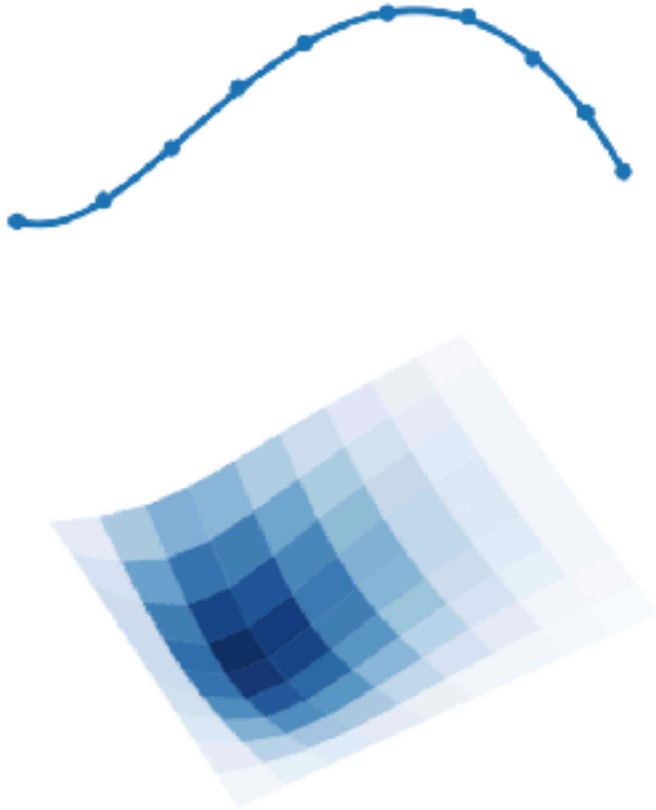
WiSh

Towards a **Wi**reless **Sh**ape-aware World using Passive RFIDs

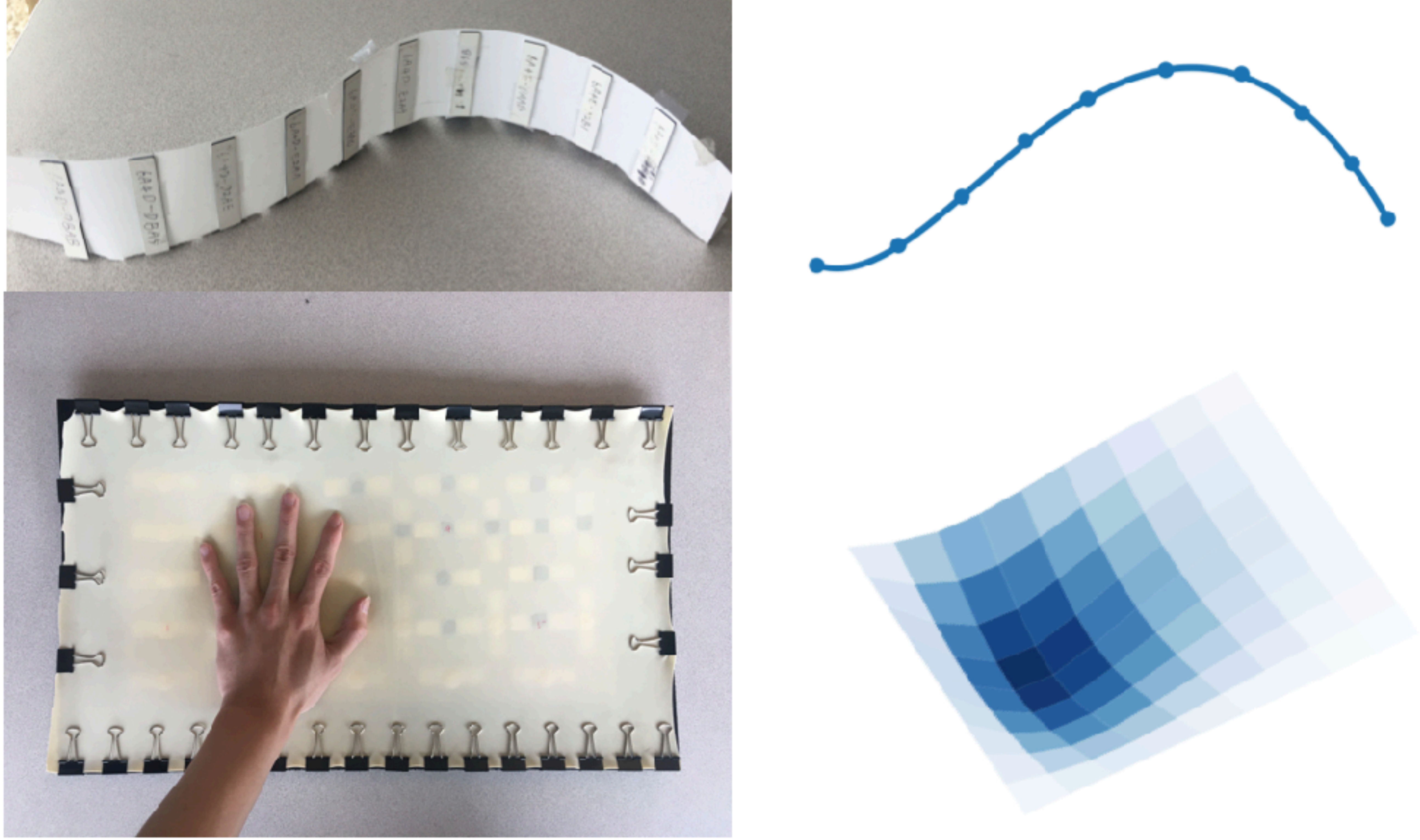
Haojian Jin*
Jingxian Wang*
Zhijian Yang
Swarun Kumar
Jason Hong

Carnegie Mellon University





How can we **design** a **responsive** world?



WiSh makes ordinary surfaces **shape-aware** using **low-cost**, **light weight**, **waterproof**, **battery-free** RFID tags.

Such a system can fundamentally change the way we interact with our daily environment.

Interactive Toys

Smart Carpets

Building Sensing

Such a system can fundamentally change the way we interact with surfaces in our vicinity.

Interactive Toys

Smart Carpets

Building Sensing

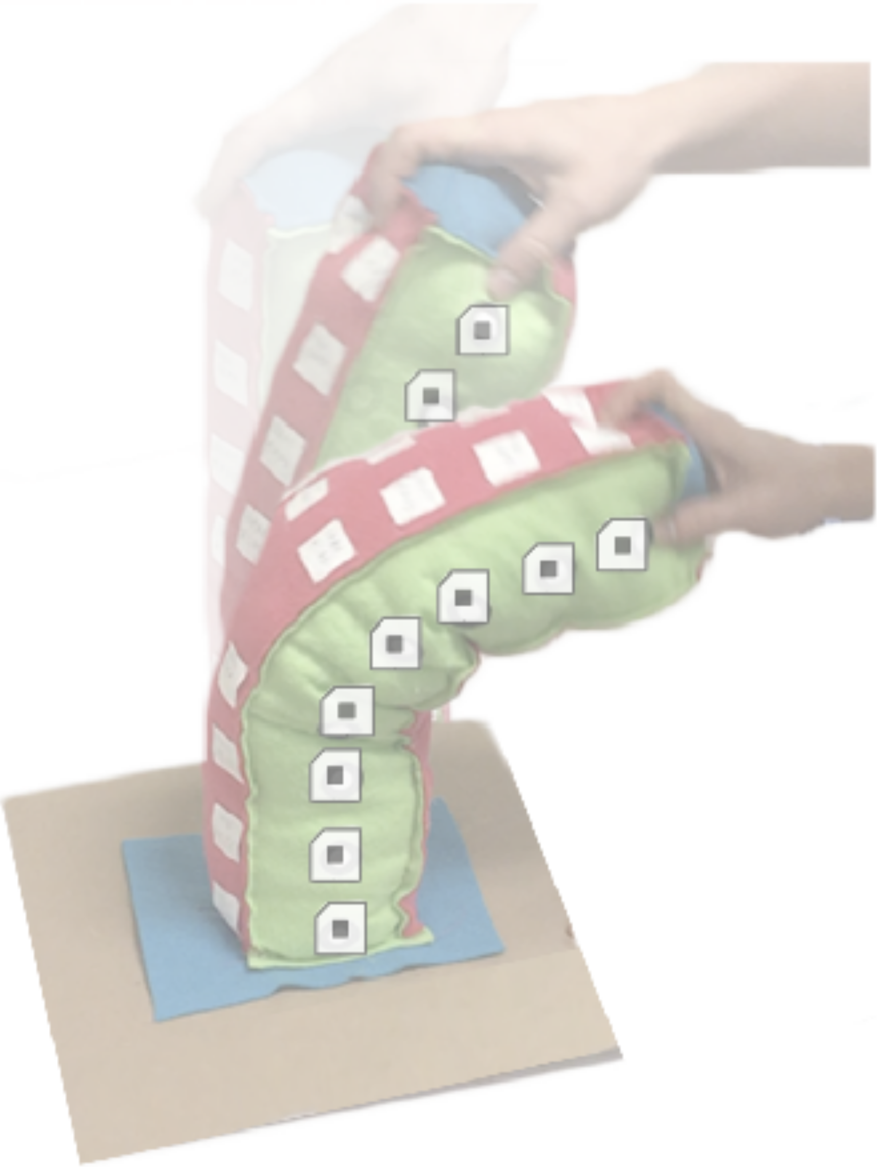
Such a system can fundamentally change the way we interact with surfaces in our vicinity.

Interactive Toys

Smart Carpets

Building Sensing

Such a system can fundamentally change the way we interact with surfaces in our vicinity.



Interactive Toys

Smart Carpets

Building Sensing

Instrument surfaces with RFID tags

Interactive Toys

Smart Carpets

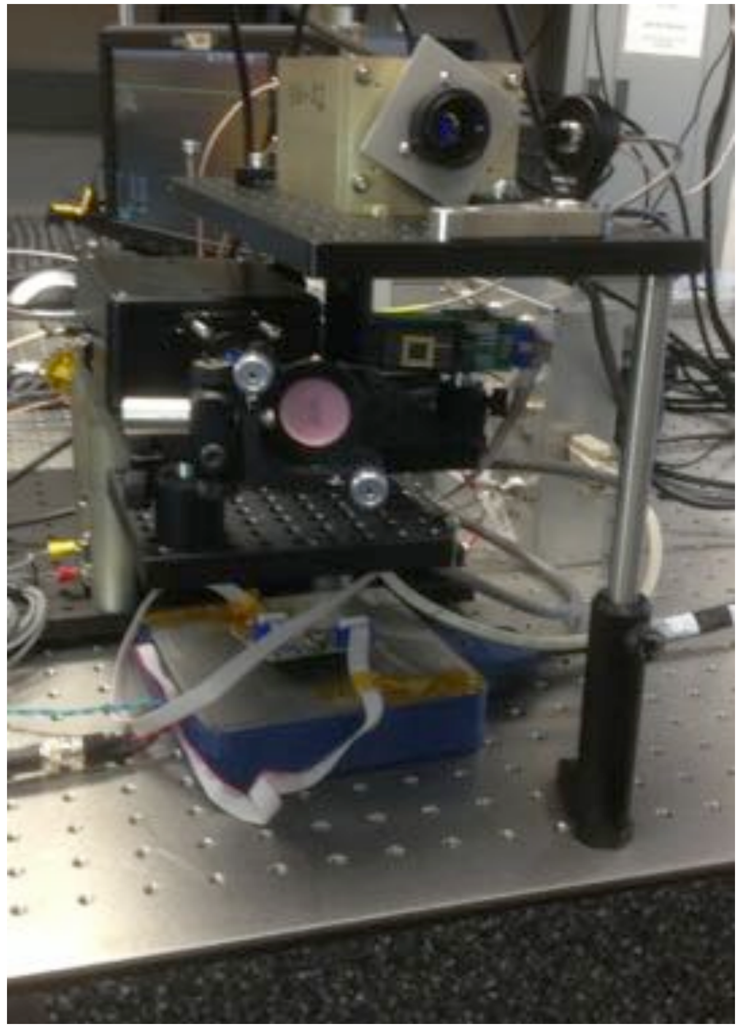
Building Sensing

Knowing the shape can enable
so many applications

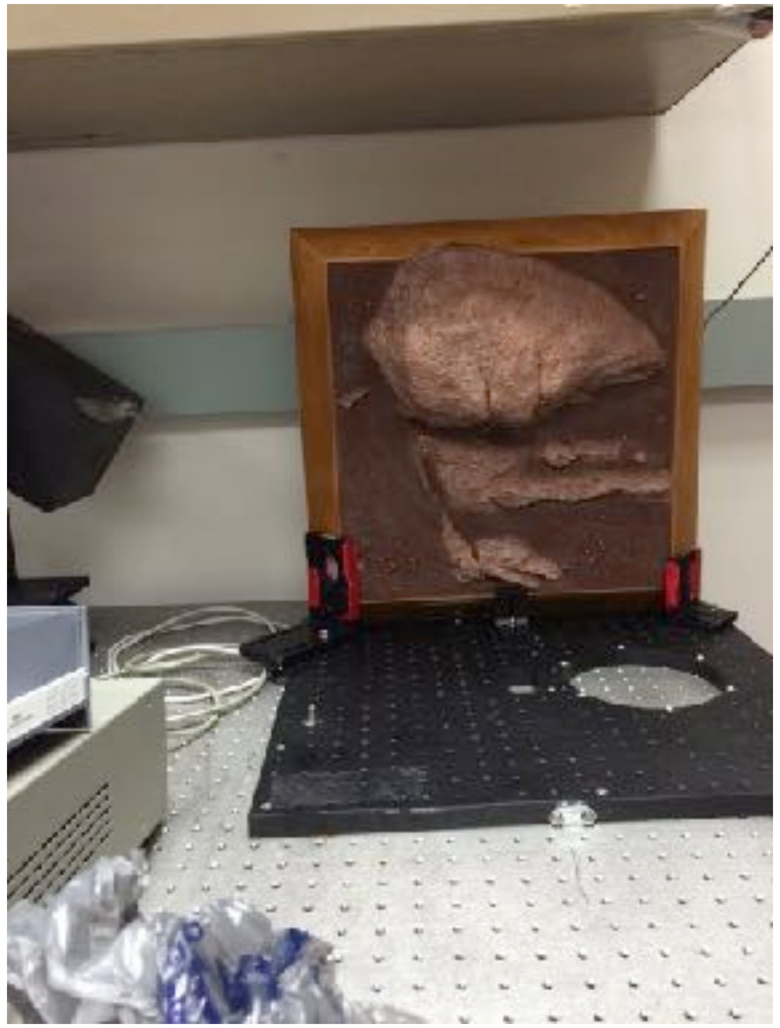
Knowing the shape can enable
so many applications

How can we sense the shape today?

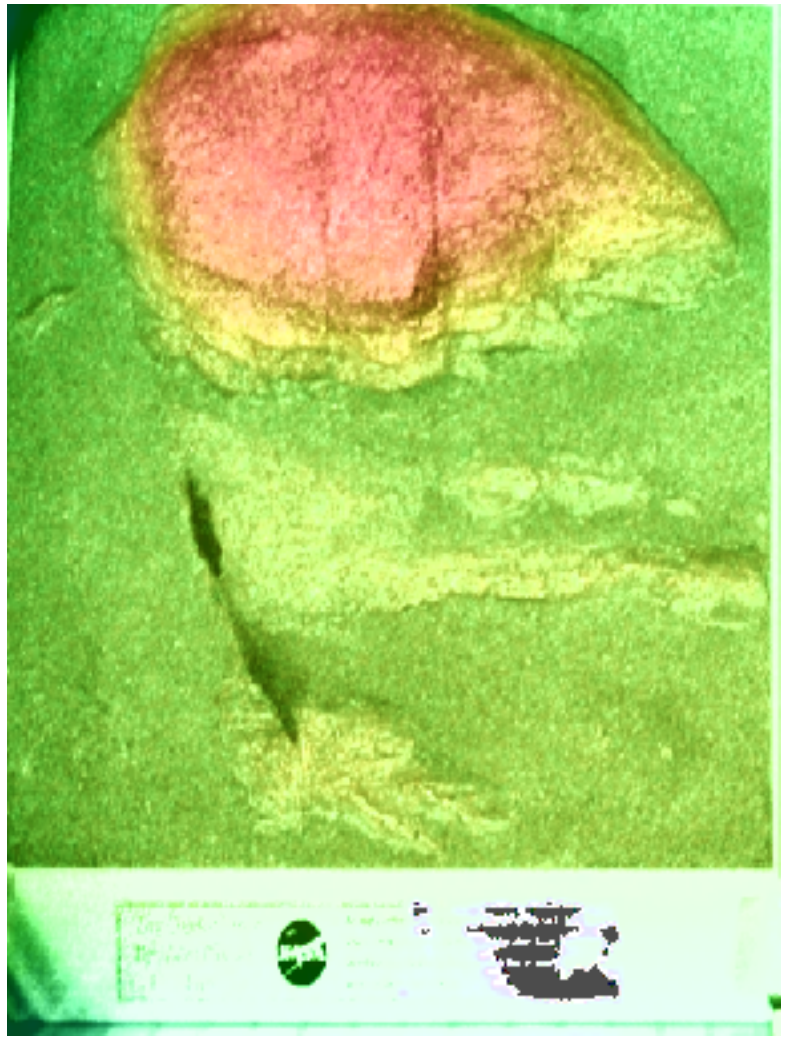
External infrastructure



Lidar



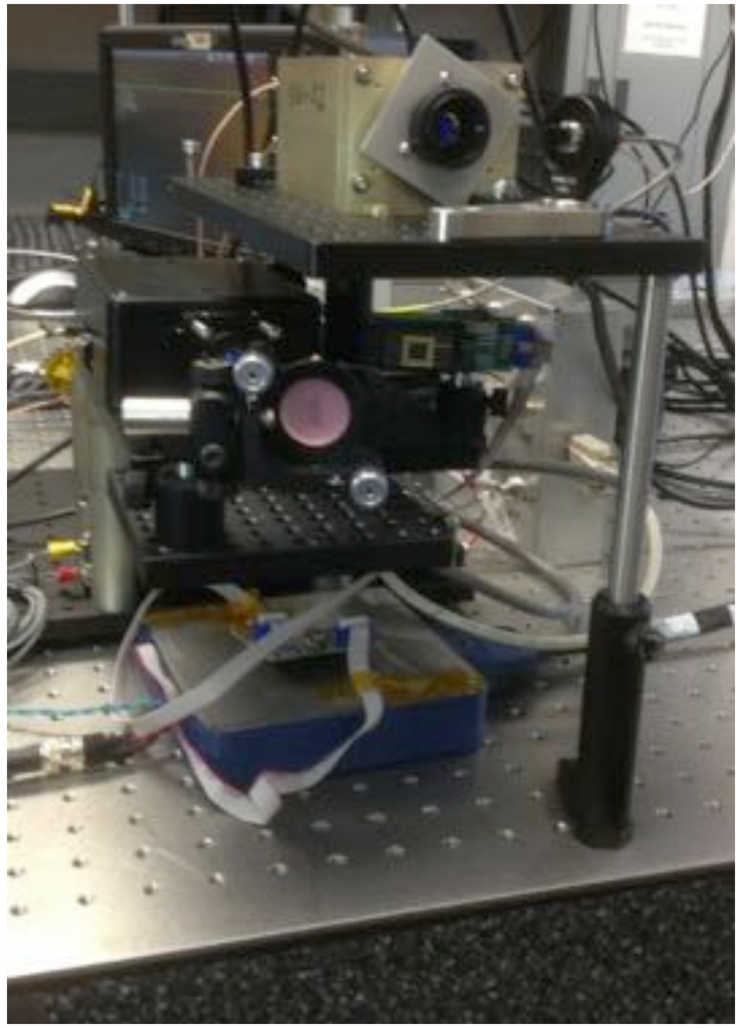
Sensing Setup



Shape output

Lidar imaging of topography, NASA

External infrastructure



Lidar

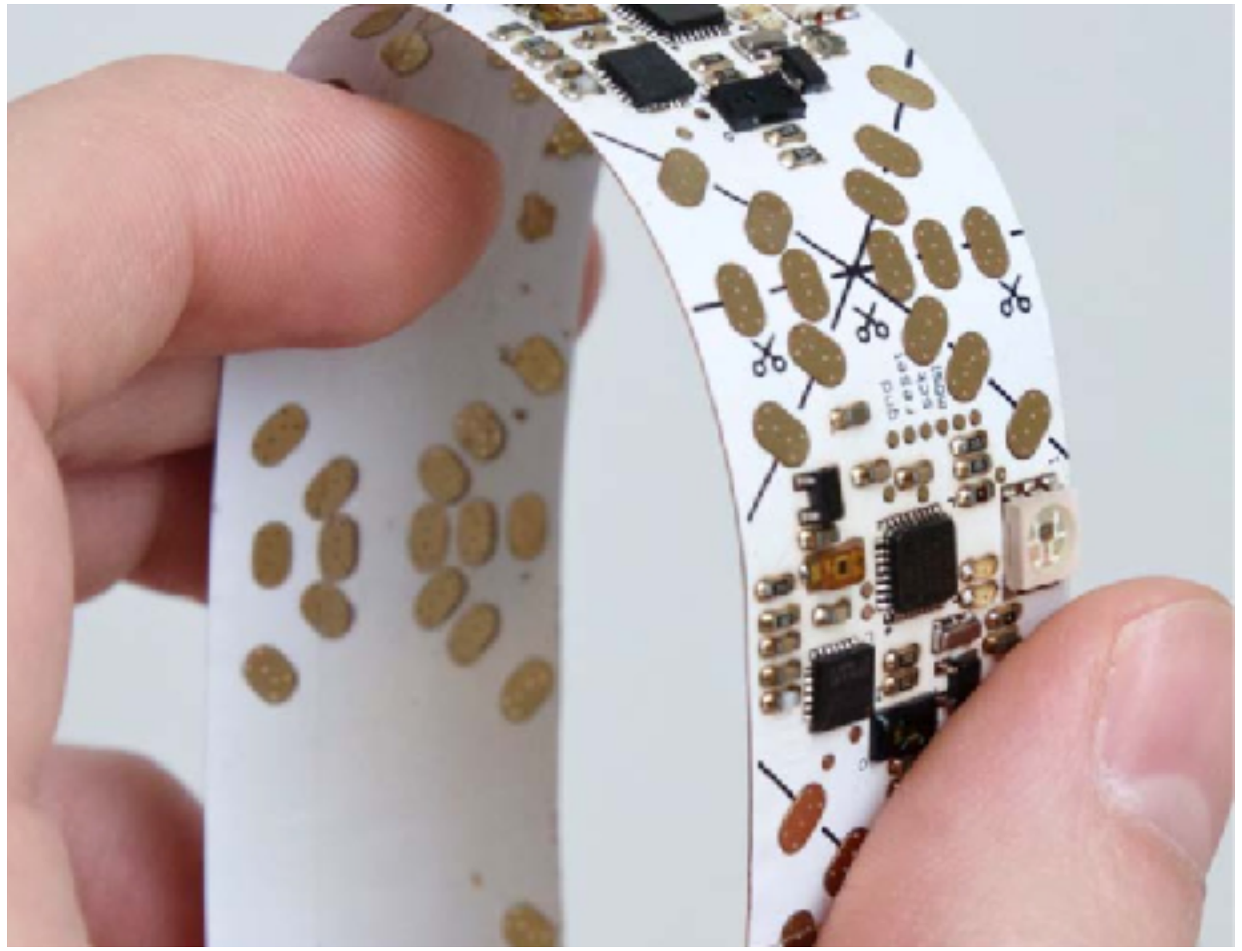
external sensors need to be static

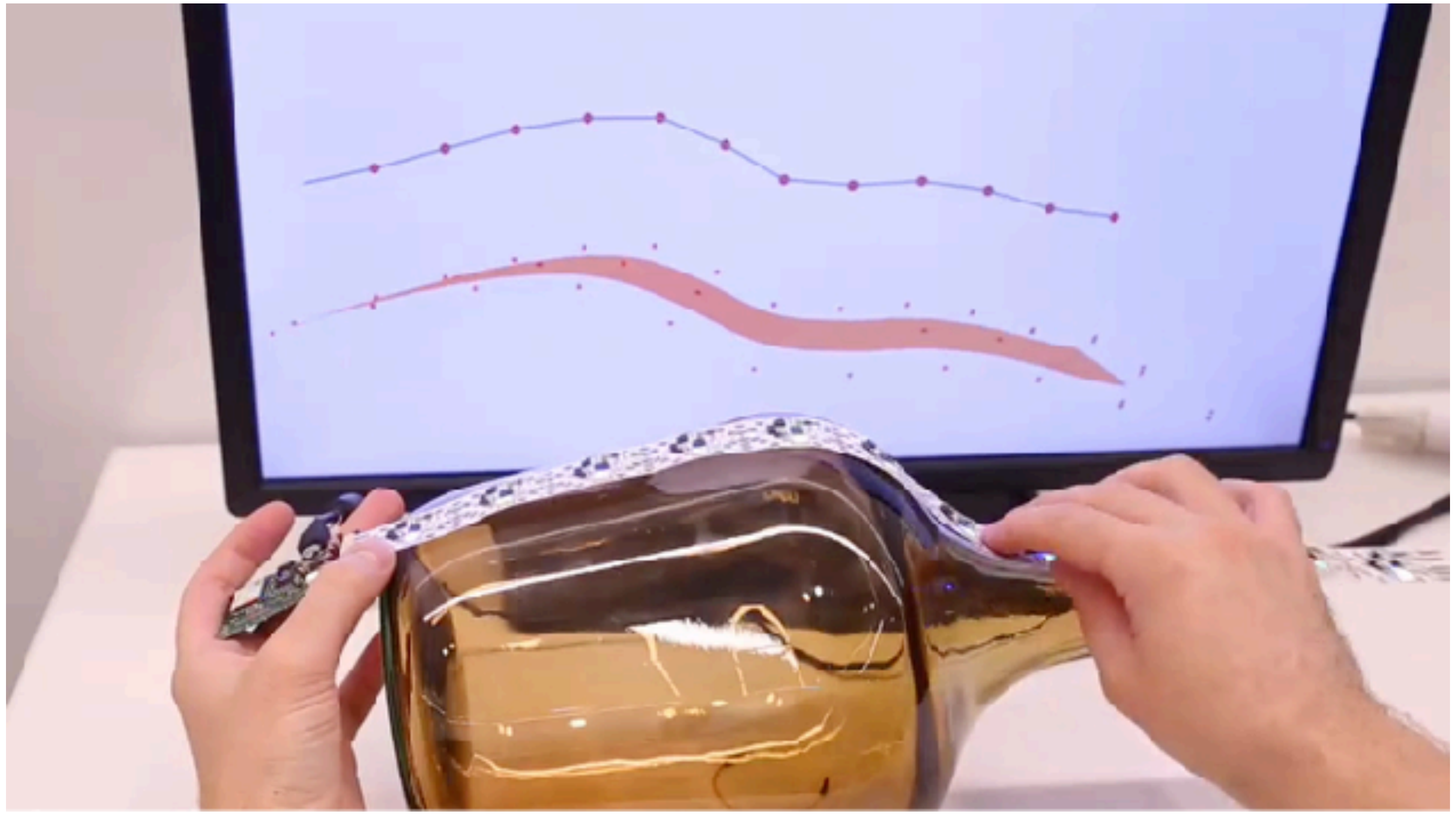
surfaces need to be in direct line-of-sight

subjected to the lighting environment

Lidar imaging of topography, NASA

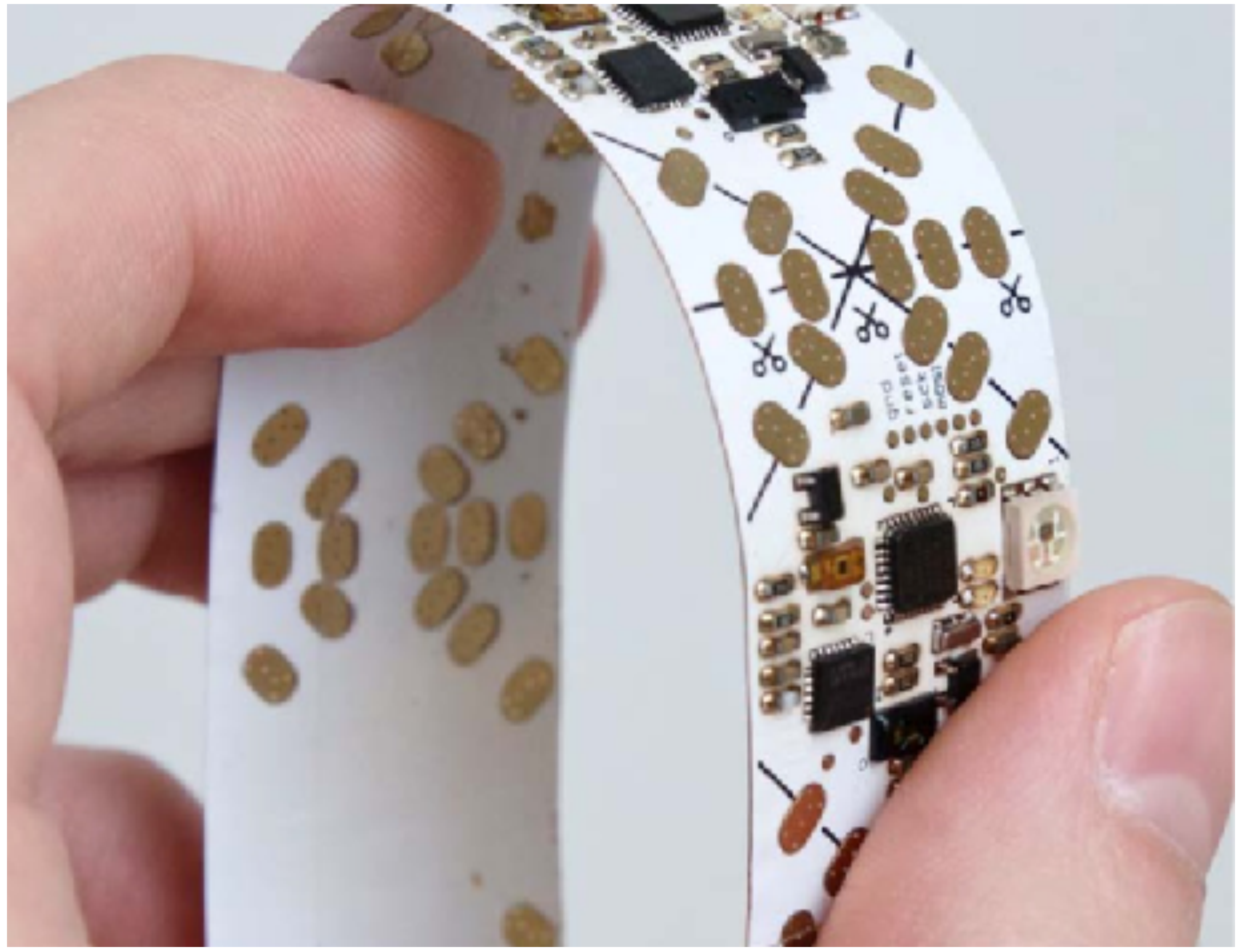
Smart Fabrics & Materials using Specialized Sensors





Sensortape, UIST 2015

Smart Fabrics & Materials using Specialized Sensors



expensive, $100 per meter (SensorTape)

delicate electronic sensors, not waterproof

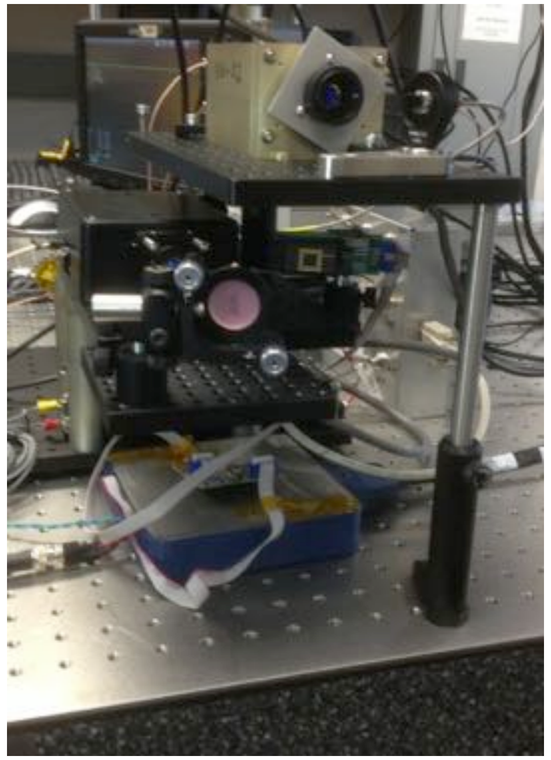
require battery/power

Sensortape, UIST 2015

WiSh	Prior solutions

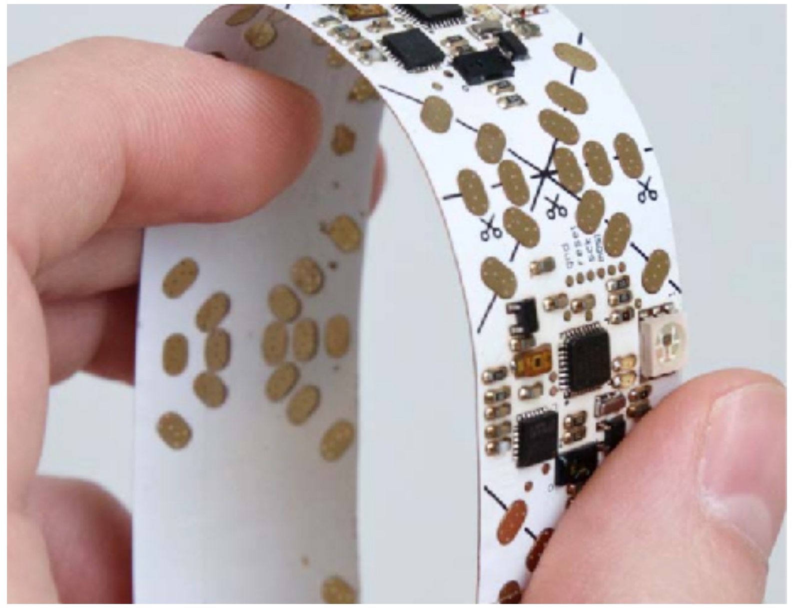
non-line-of-sight objects,
mobile, ad-hoc

v.s.



battery-free surfaces,
durable,
cheap

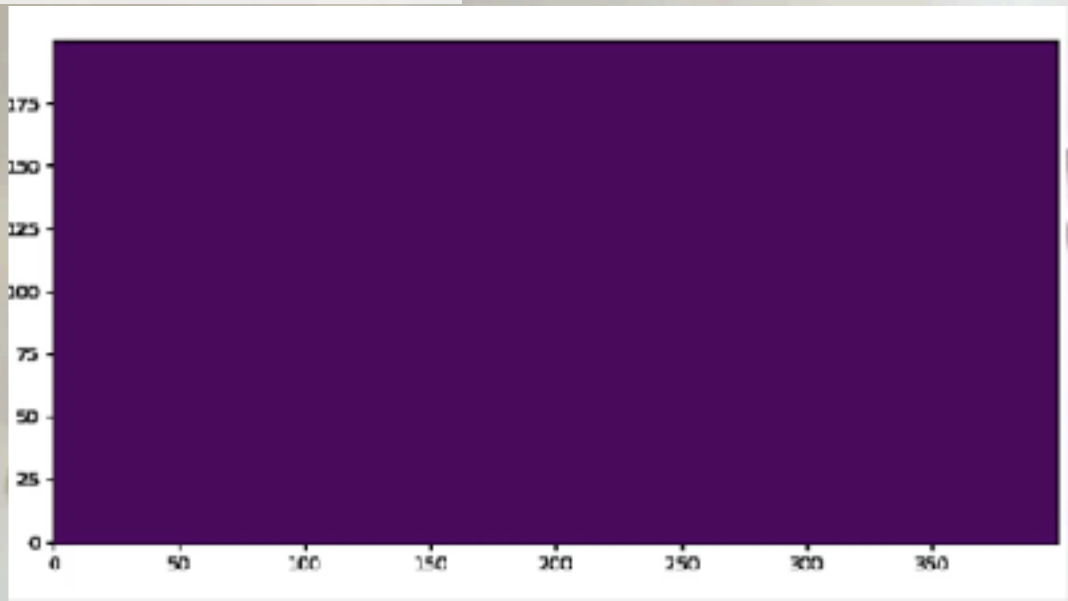
v.s.



WiSh

a generic solution makes ordinary surfaces shape-aware.

using low-cost, waterproof, lightweight, battery-free RFIDs



Infer the curve shape by sensing the tags on the surface.

WiSh Key Primitives

Reverse the architecture: mobile readers & stationary tags

massive passive RFID tags

a mobile reader

Reverse the architecture: mobile readers & stationary tags

massive passive RFID tags

a mobile reader under the vehicle

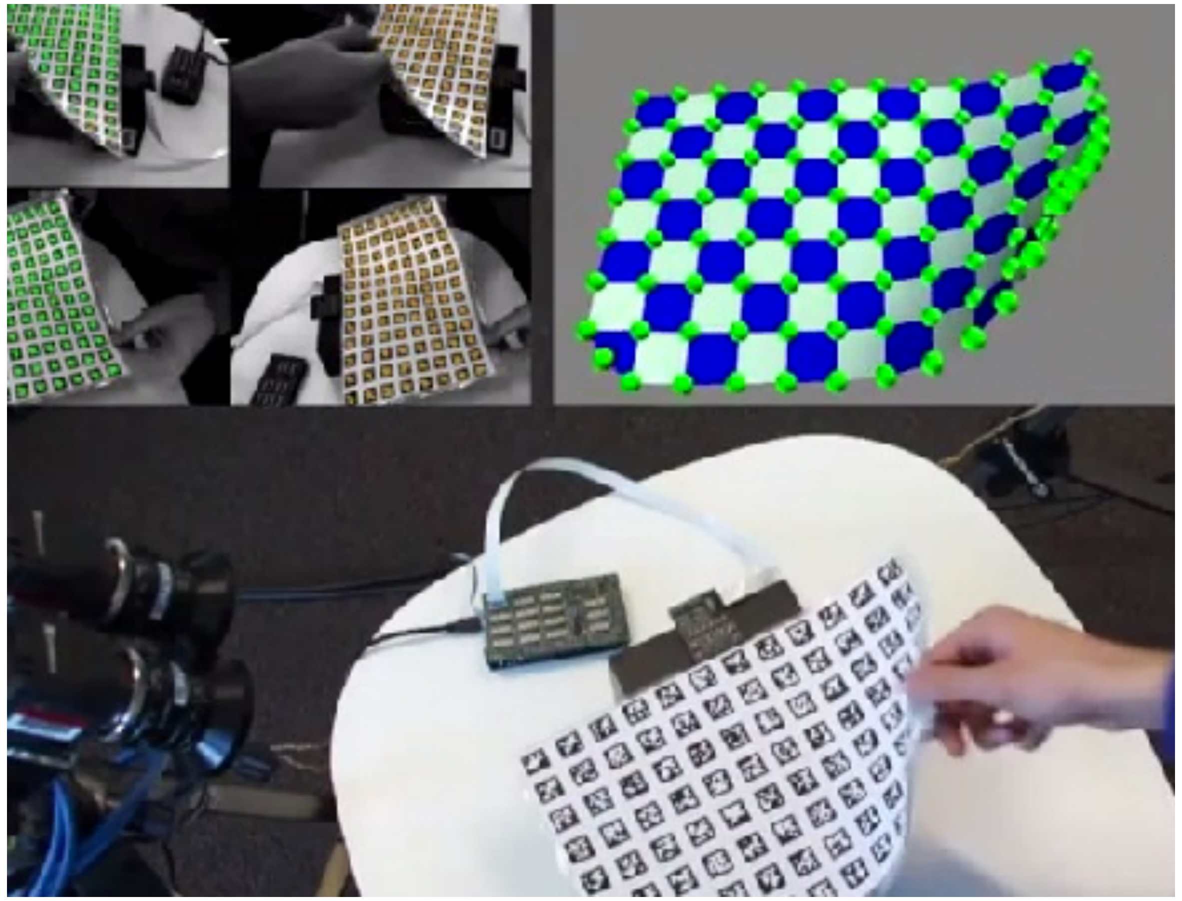
intuition

RFID backscatter communication for shape sensing

6A4D-E34E
6A4D-E393
6A4E-03B5
6A4D-EAB1

How can we reconstruct the curve shape from the RFID backscatter observations?

Data driven

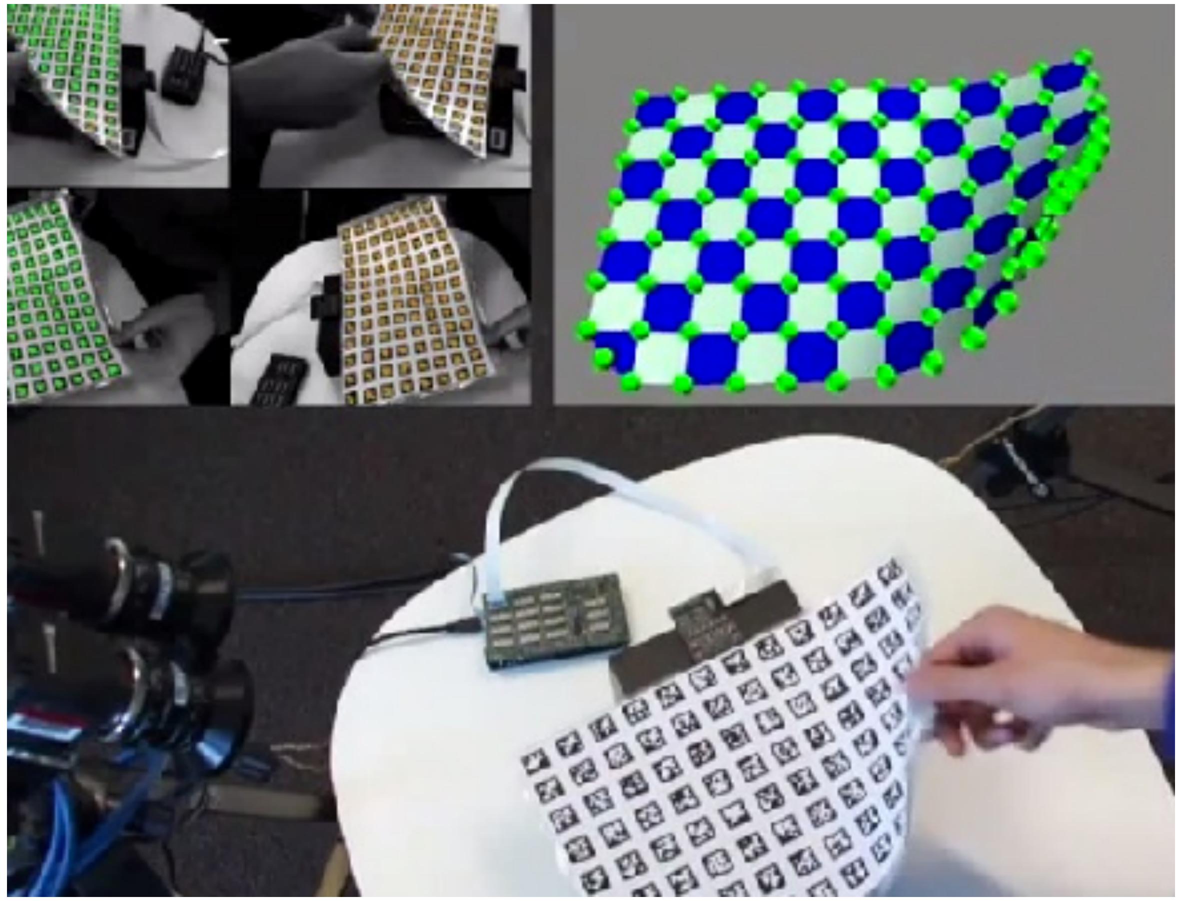


FlexSense [UIST 2014]

Triangulation

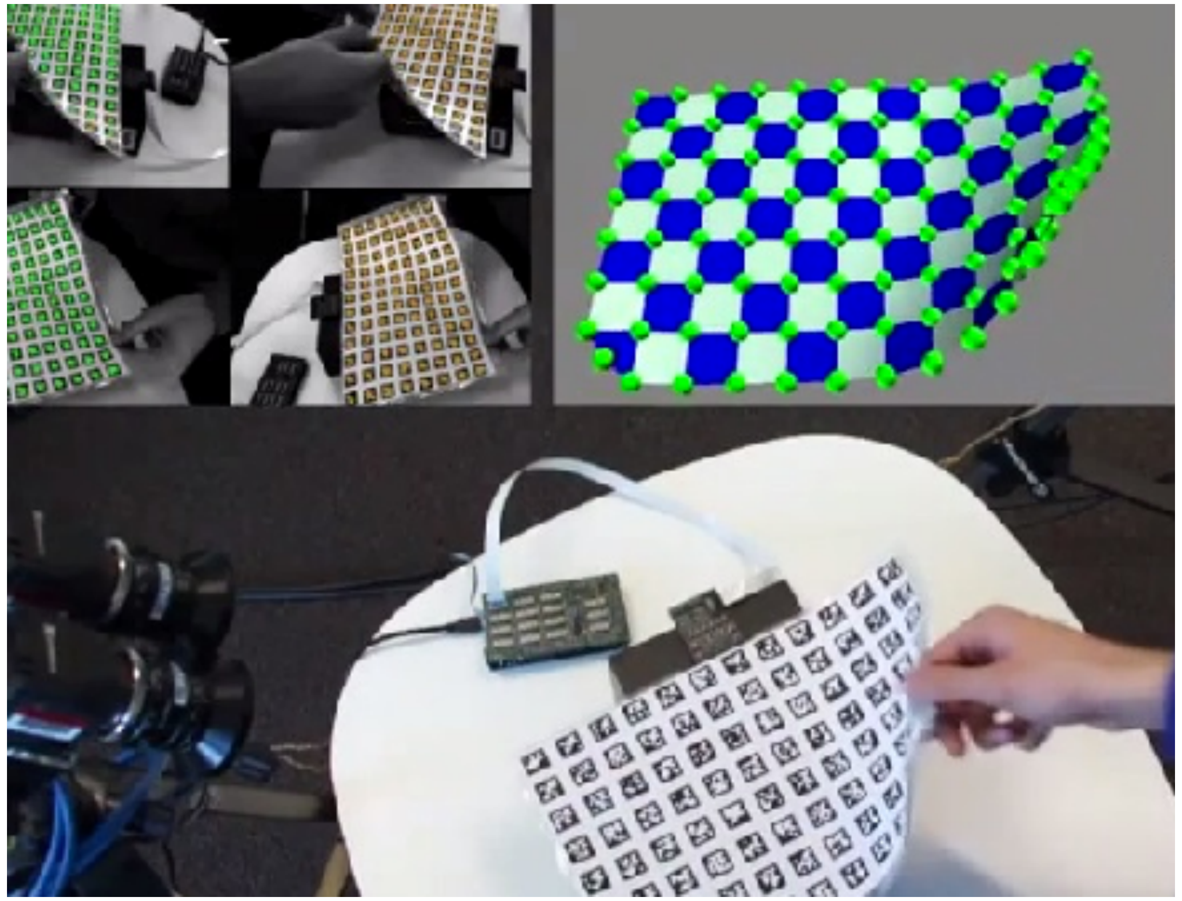
Tagoram [MOBICOM 2014]

Data driven



FlexSense [UIST 2014]

~~Data driven~~



FlexSense [UIST 2014]

unknown antenna positions

unknown reflectors

Triangulation

Tagoram [MobiCom 2014]

Triangulation

Multi-antenna solutions cannot be mobile.

Only one antenna at an unknown position.

Tagoram [MOBICOM 2014]

Shape sensing is a special problem

Only one mobile antenna
at an unknown position

Unknown multi-path reflectors

negative side

Shape sensing is a special problem

Only one mobile antenna
at an unknown position

Instrument RFID tags in
a planned pattern

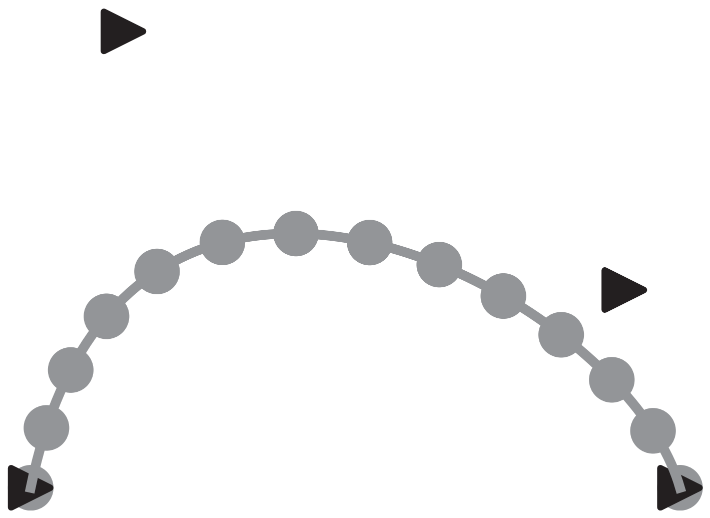
Unknown multi-path reflectors

Surfaces in the real world are
not arbitrary geometries

negative side

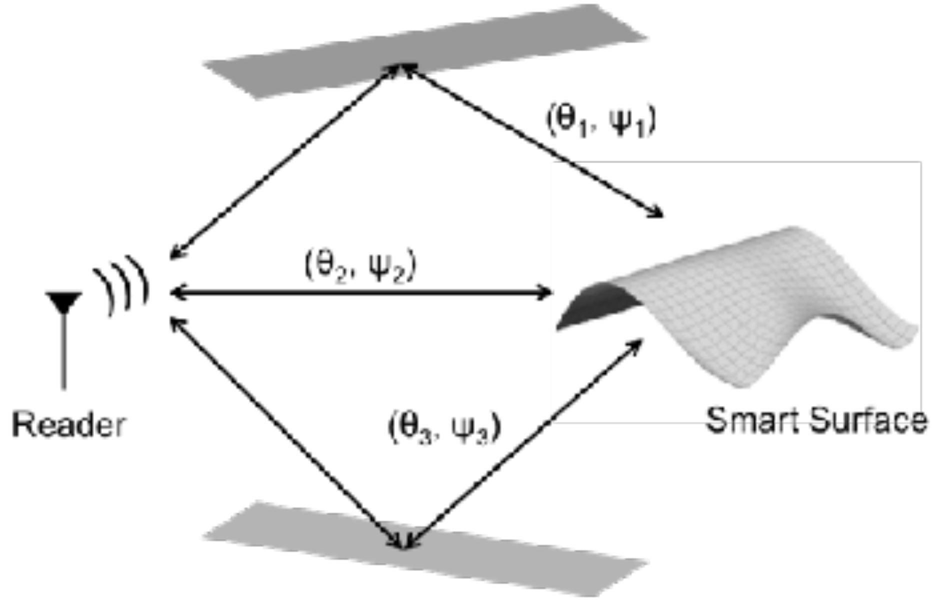
positive side

Solution overview



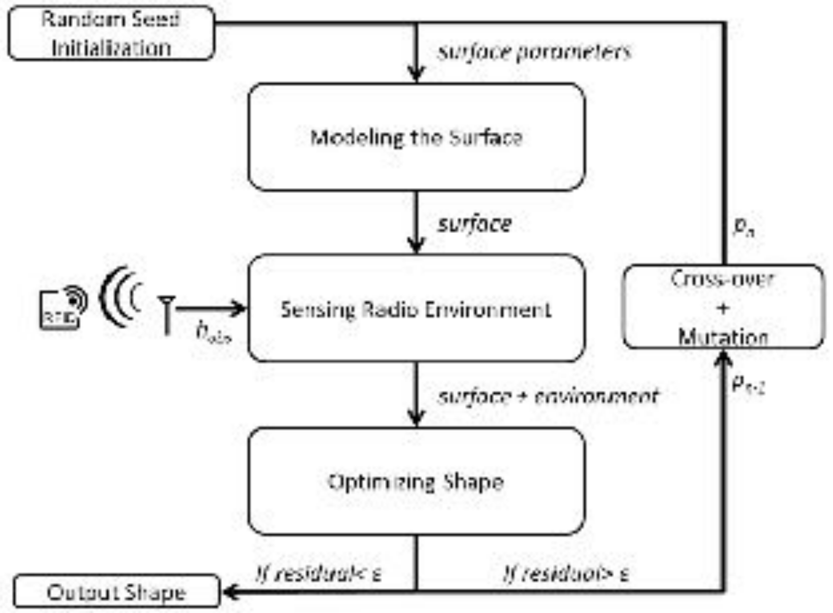
Shape representation

reduce the number of unknown variables



Shape modeling

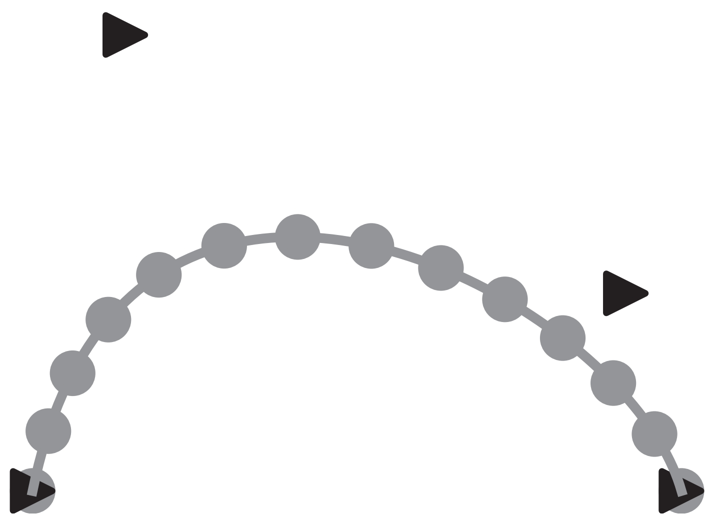
overcome multipath



Shape optimization

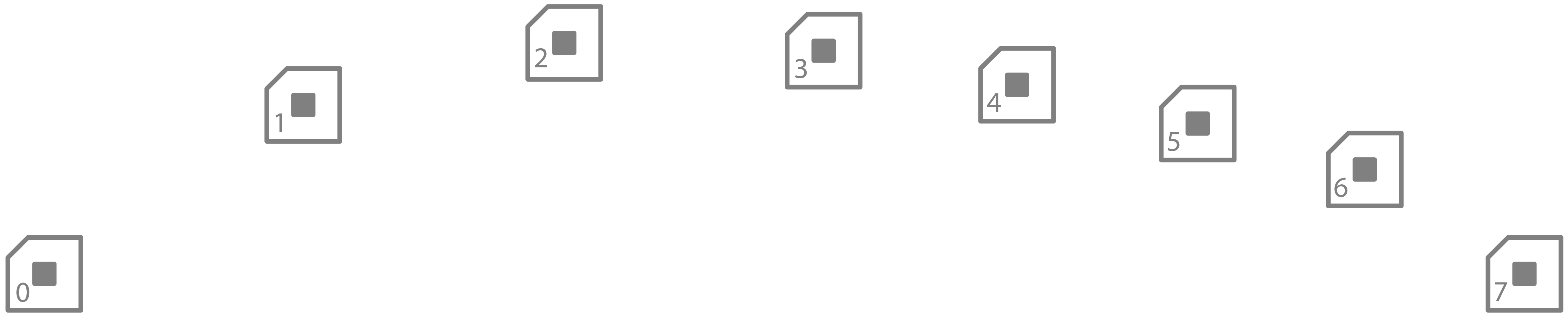
solution search

1 shape representation



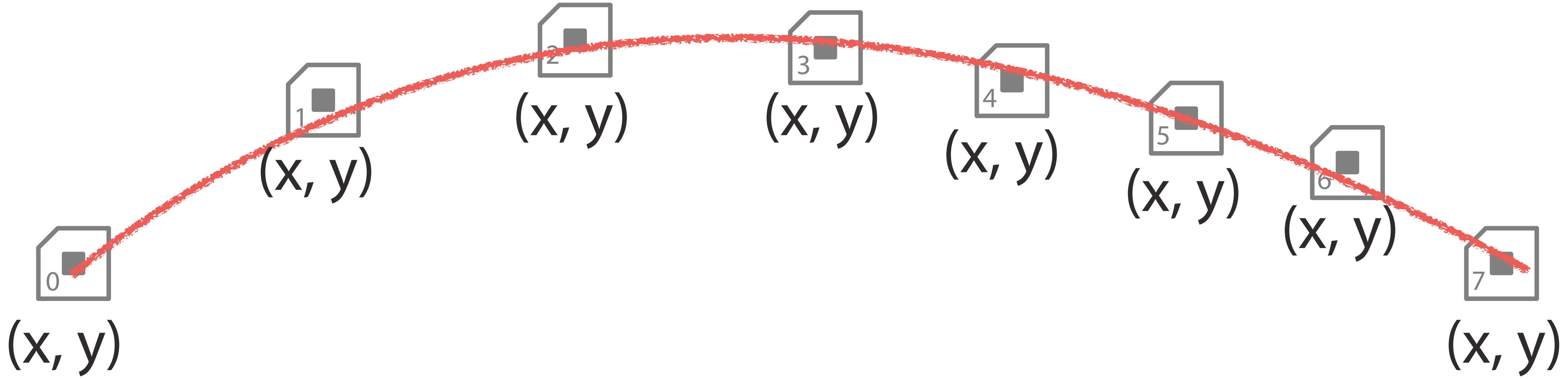
system design

WiSh models the surface through tags



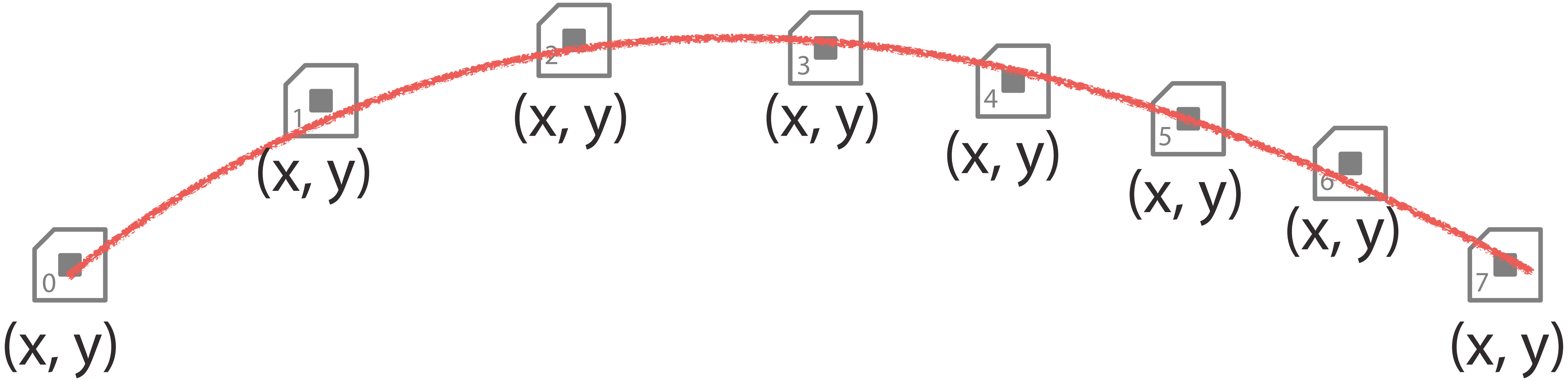
WiSh models the surface through tags

if we know the tag positions,
we can reconstruct the curve.



WiSh models the surface through tags

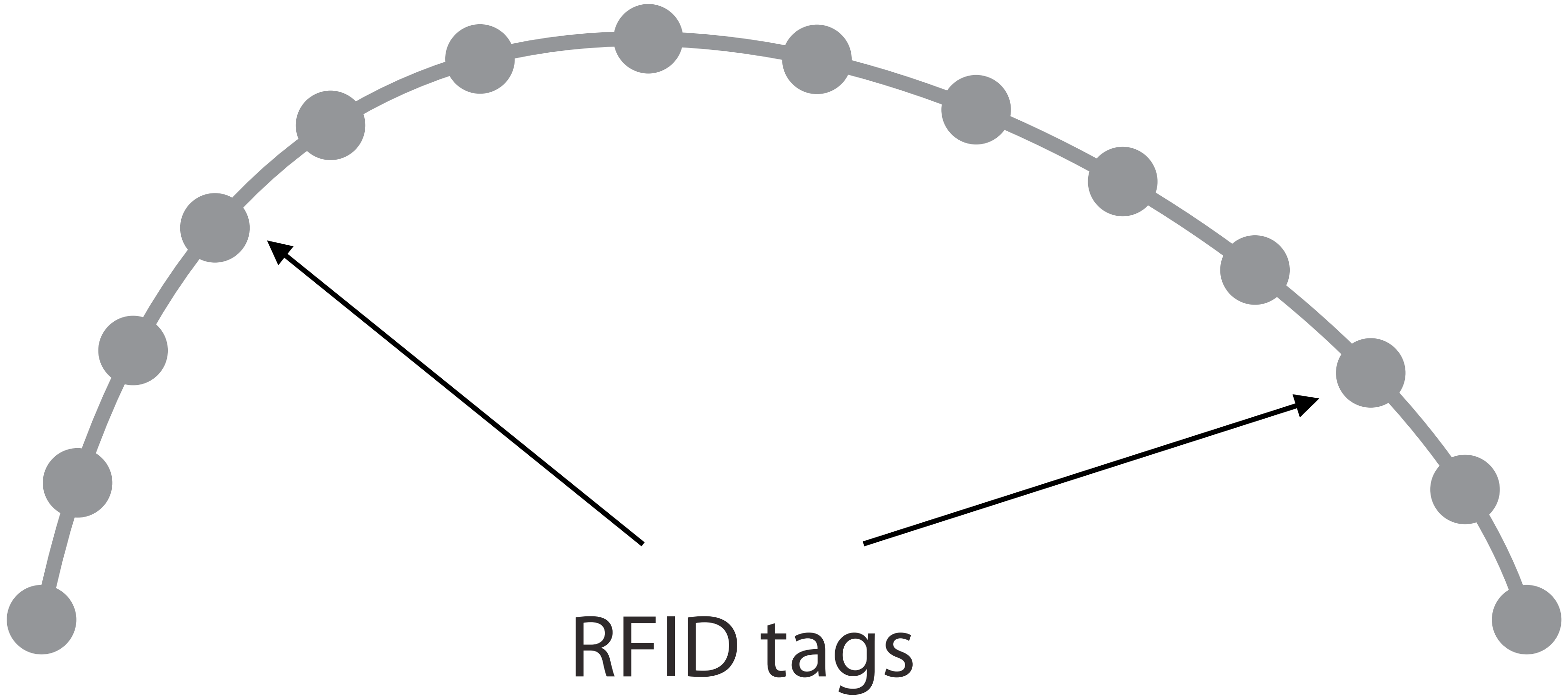
We only have 1 measurement per tag,
but we have 2 variables per tag.



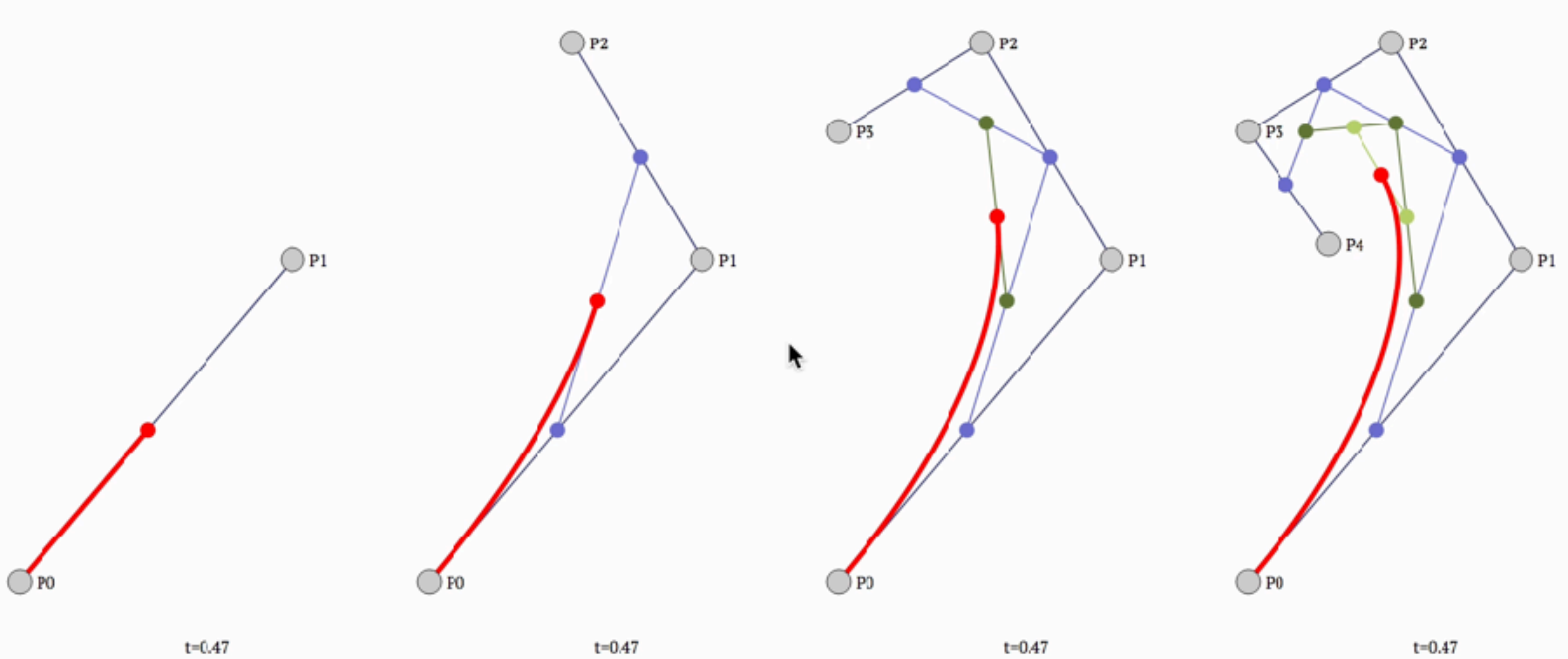
Too less equations but too many variables.

RFID tags on the real-world curve

Tags are constrained to the surface,
so their positions are not independent.



Parametric Bézier curve

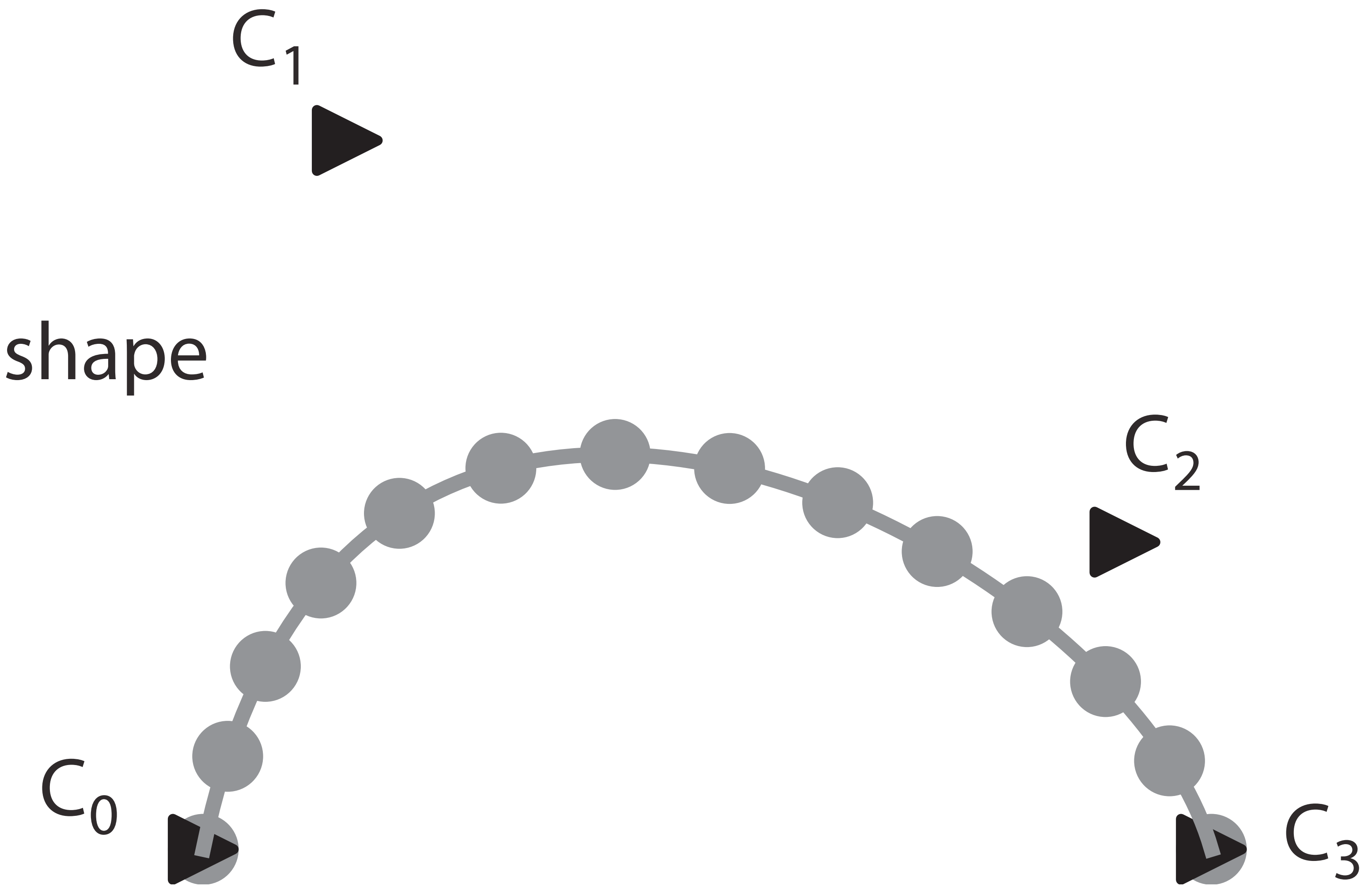


$$S(p = \{\mathbf{C}_i\}, t) = \sum_{i=0}^{n} \binom{n}{i} (1-t)^{n-i} (t)^i \mathbf{C}_i$$

Cubic (3rd order) Bézier curve

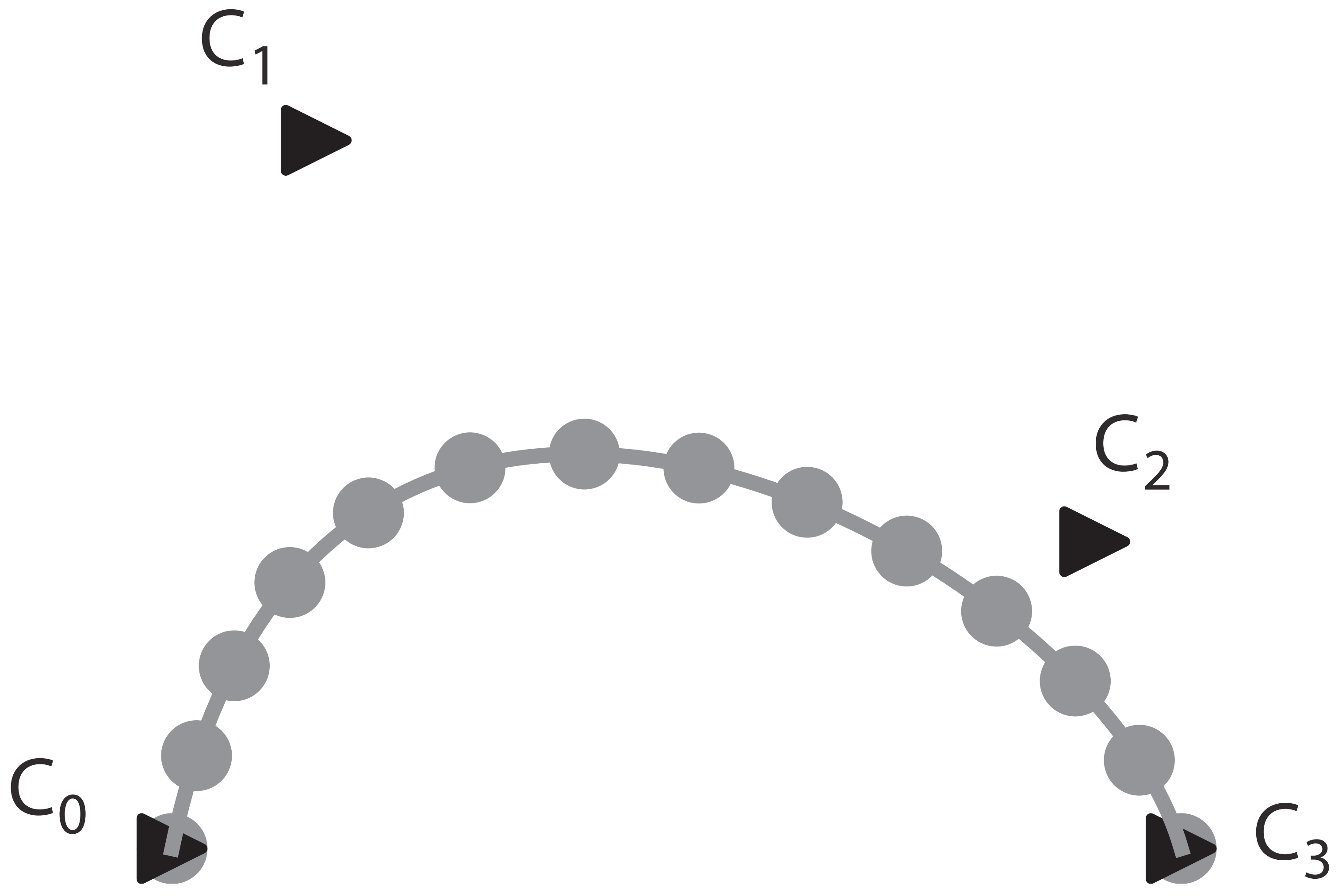
four control points determines the shape

simple but fits most natural curves



shape primitive representations

C_0	$x_0 = 0, y_0 = 0$
C_1	$x_1 \qquad , y_1$
C_2	$x_2 \qquad , y_2$
C_3	$x_3 \qquad , y_3 = 0$

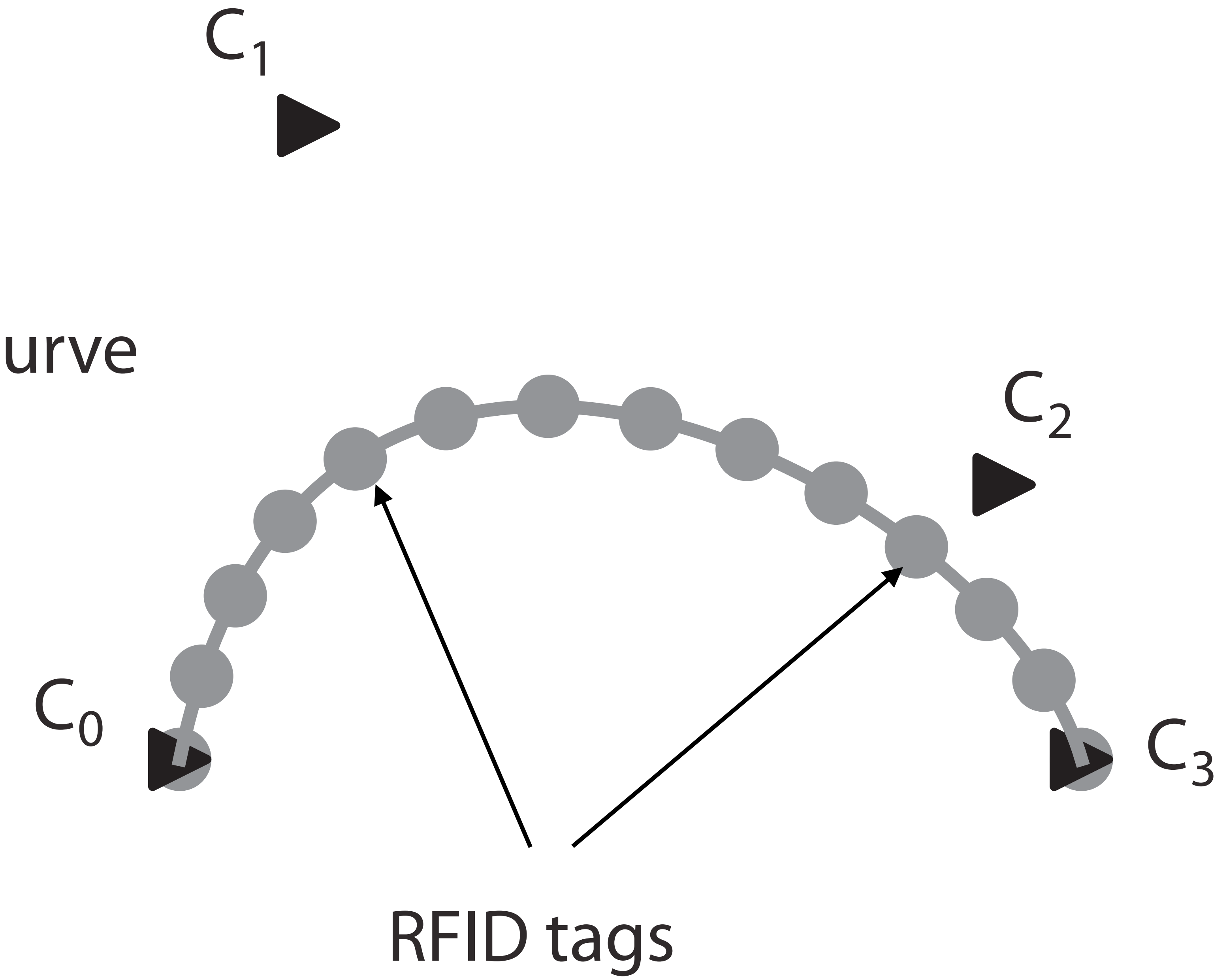


5 unknown variables for each curve primitive

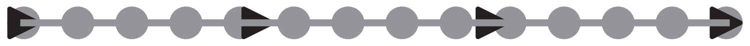
Shape => Tag positions

place RFID tags evenly on the curve

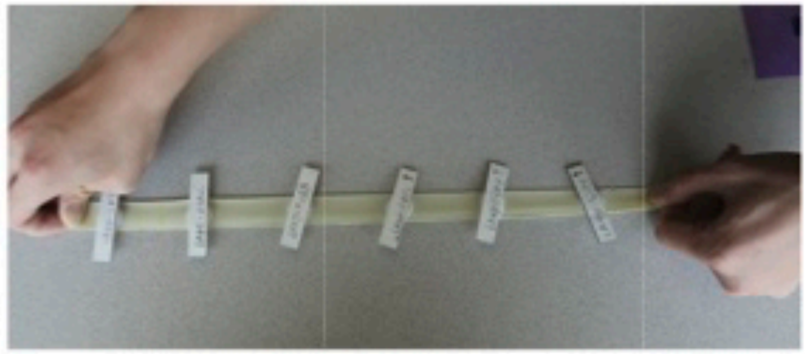
deduce tag positions based on the curve parameters



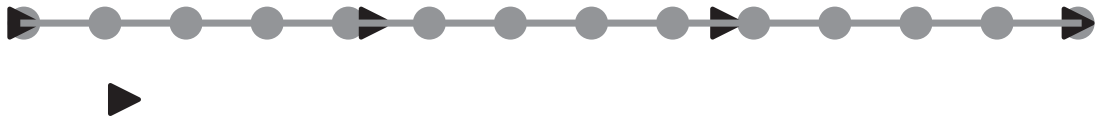
Shape representation

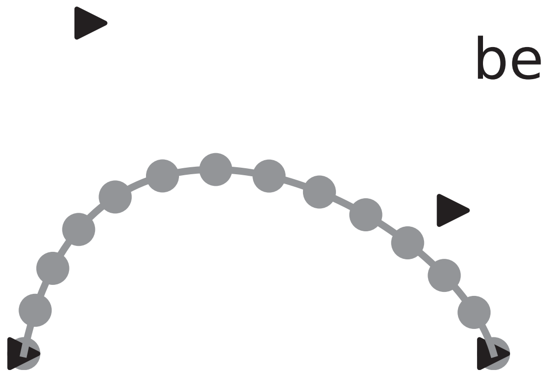


original



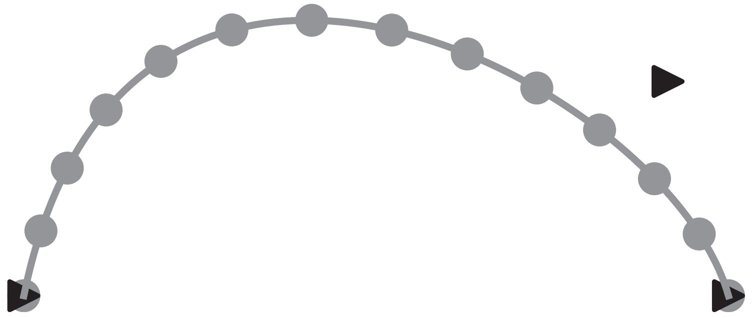
stretch (1.5 times)





bend

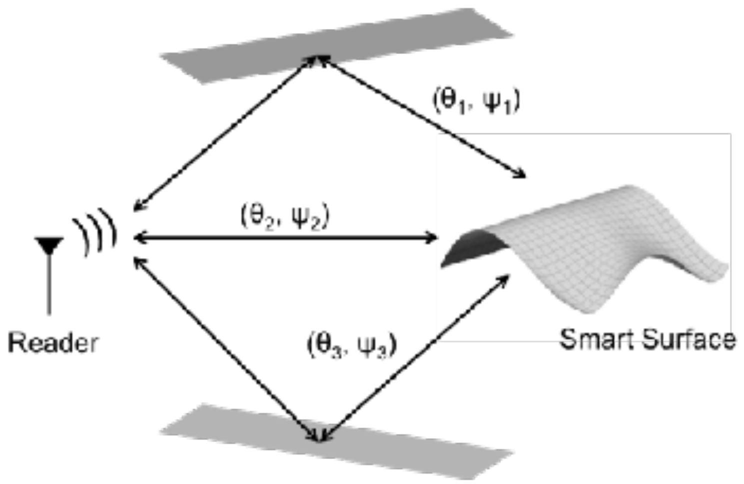
bend + stretch (1.5 times)



Bend & Stretch

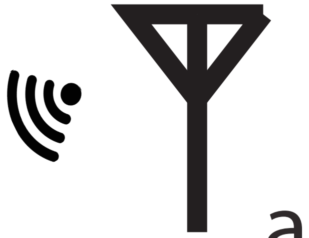
1 shape representation

2 shape modeling



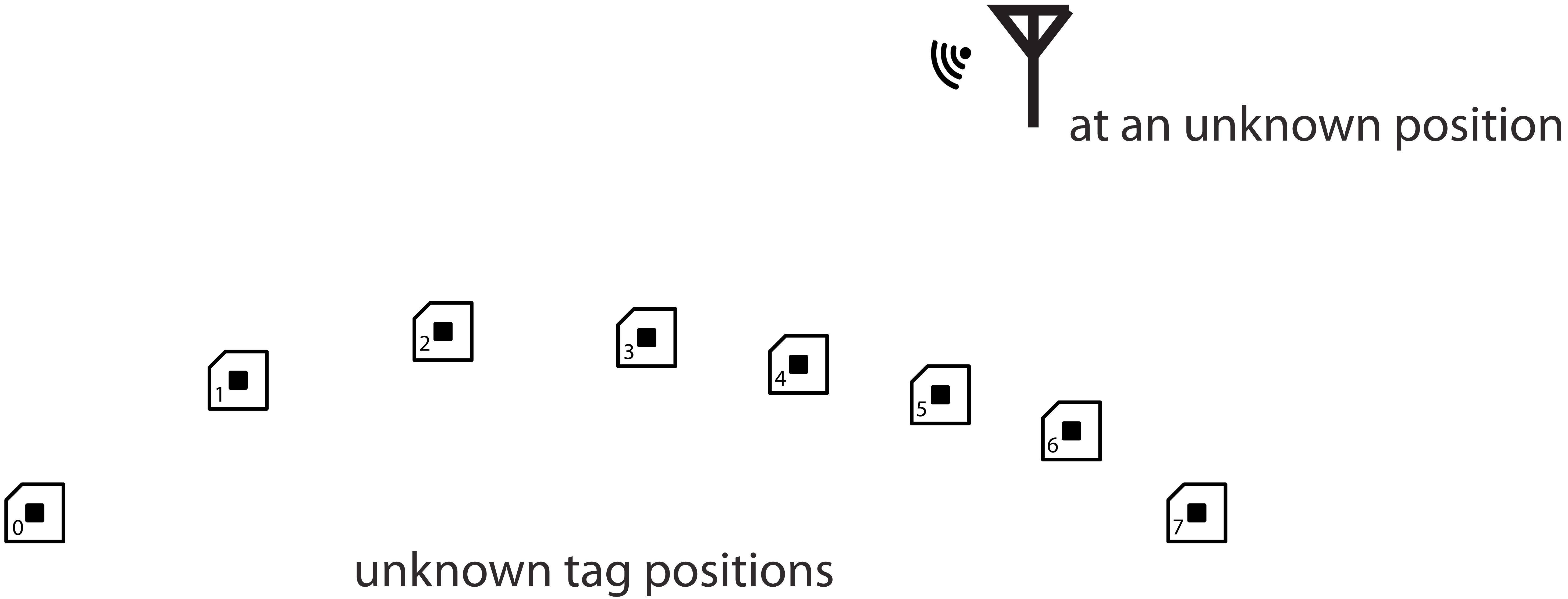
system design

Problem formulation

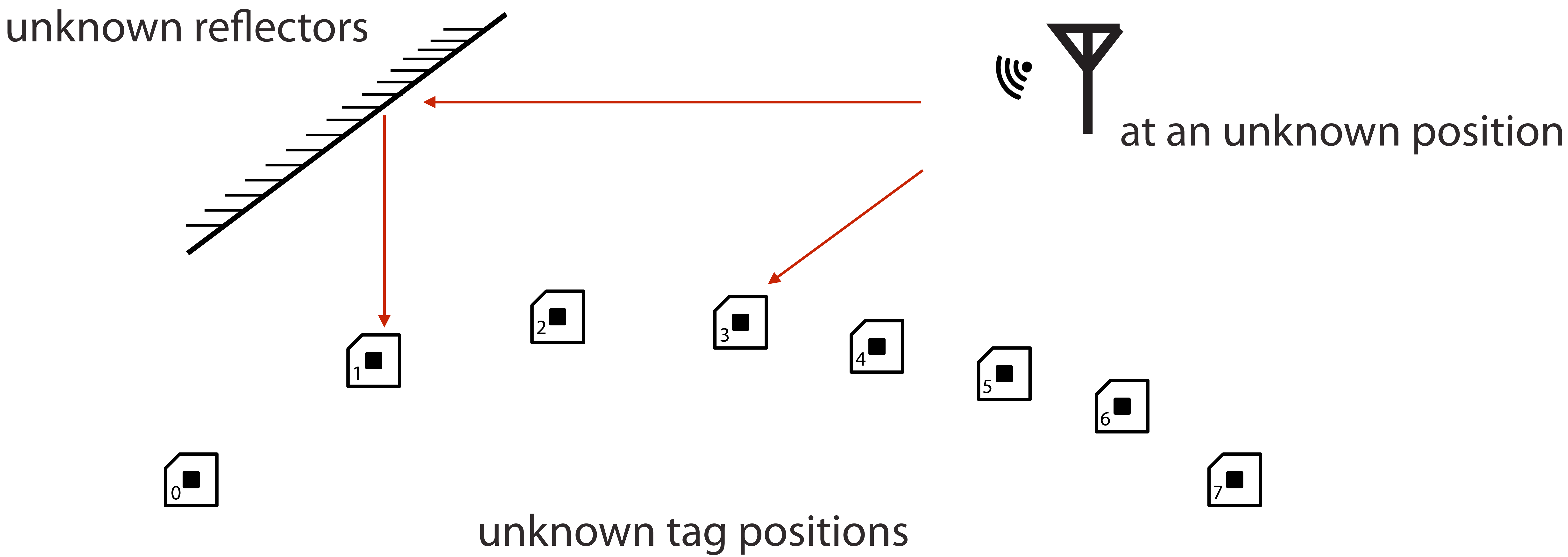


at an unknown position

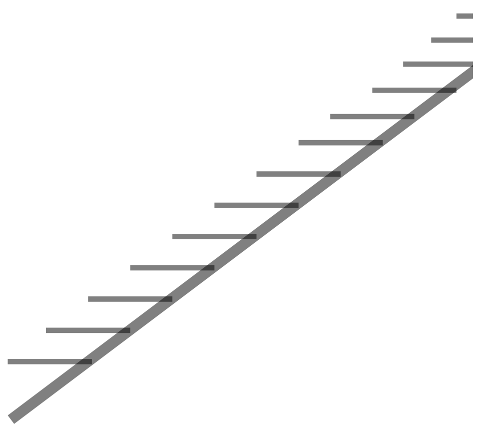
Problem formulation



Problem formulation

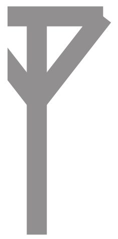


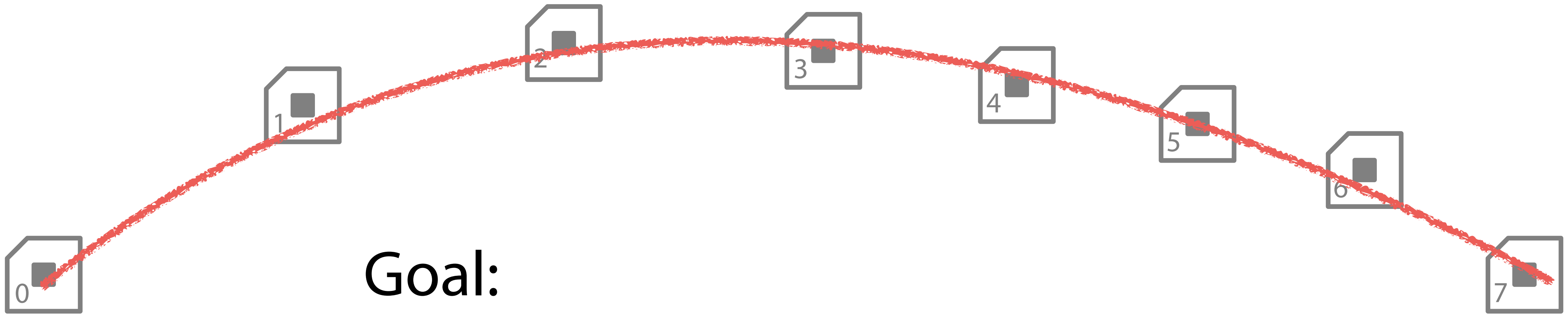
Problem formulation



Input:

One wireless channel observation
for each individual tag





Goal:

the shape representation

Curve modeling

The guess most likely is wrong.
But how wrong the guess is?

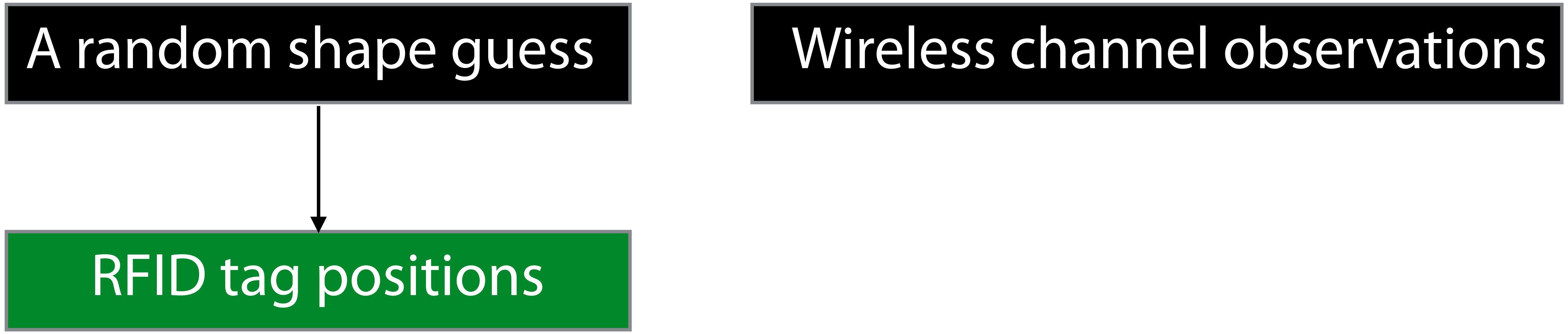
start with a random shape guess

Curve modeling

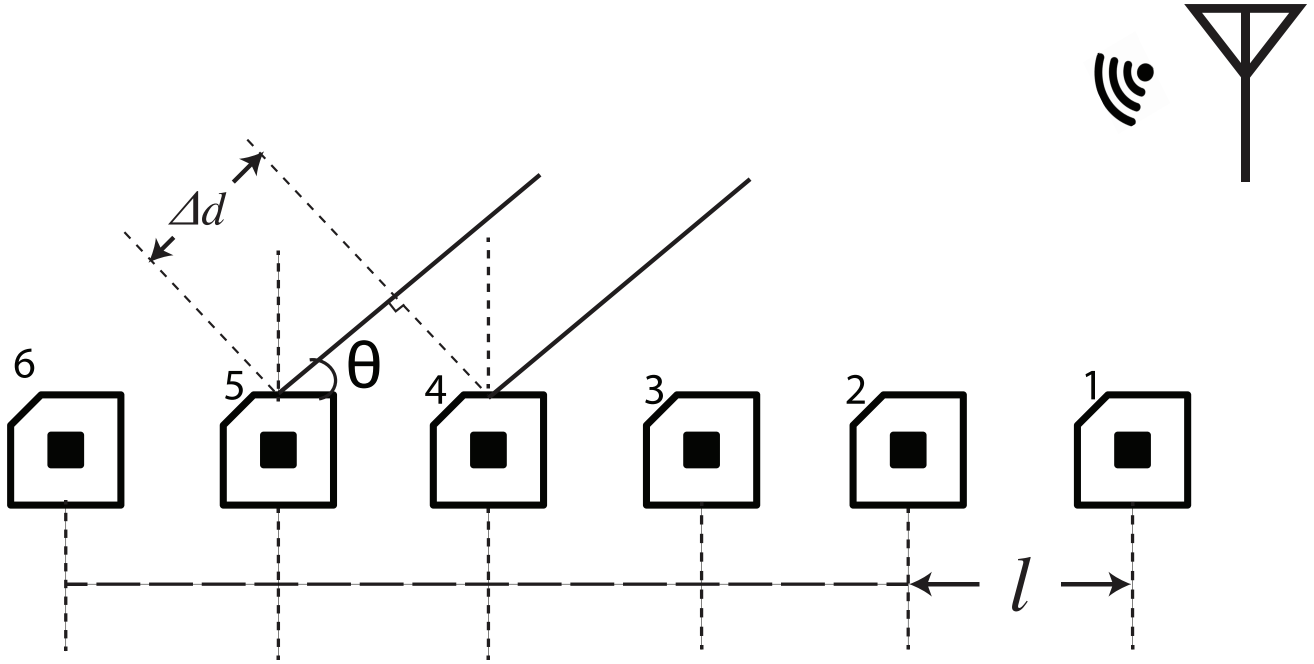
A random shape guess

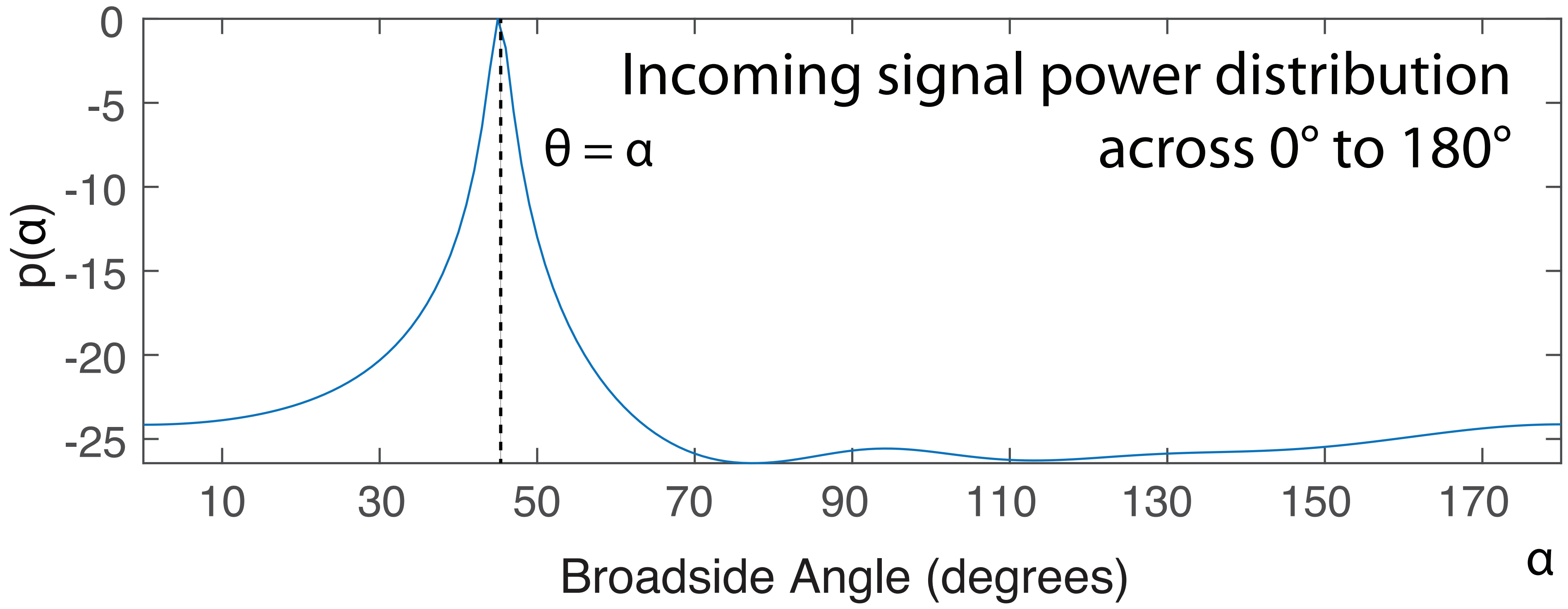
Wireless channel observations

Curve modeling



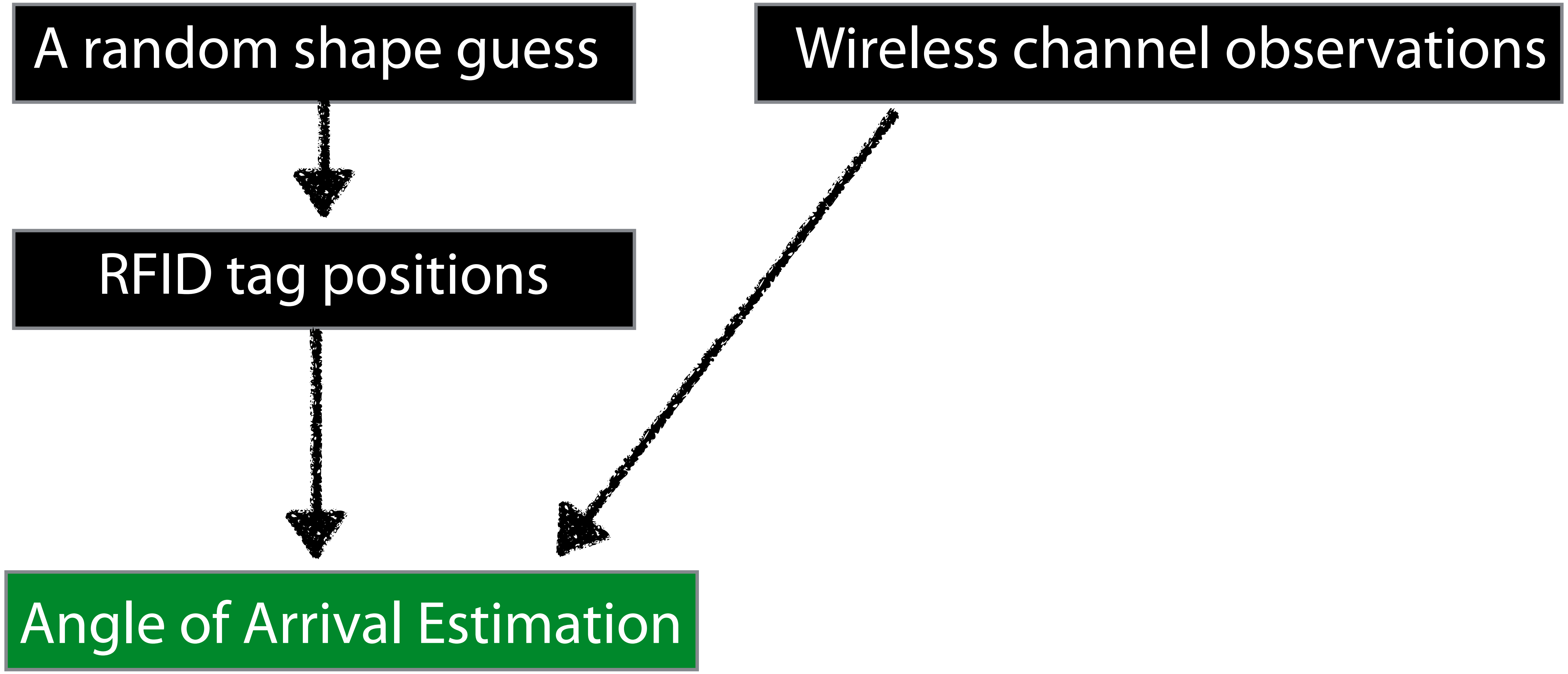
Curve modeling



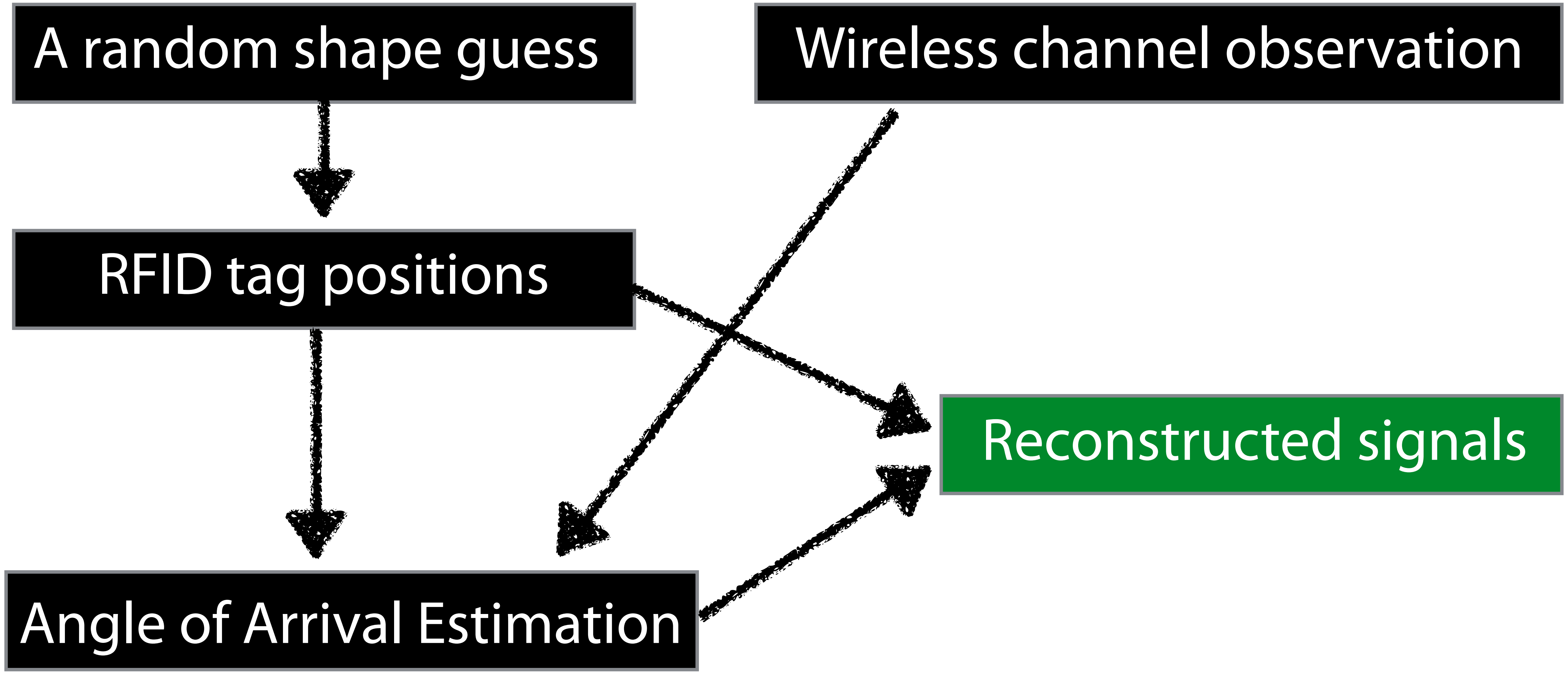


Angle of arrival (AoA) estimation

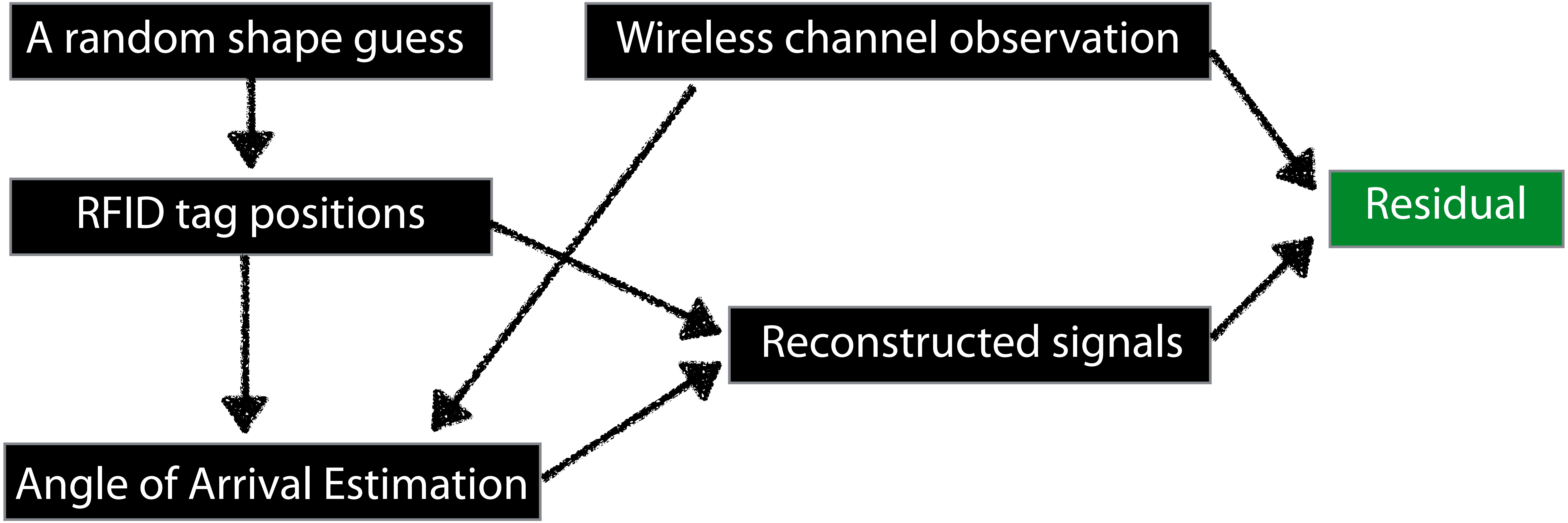
Curve modeling



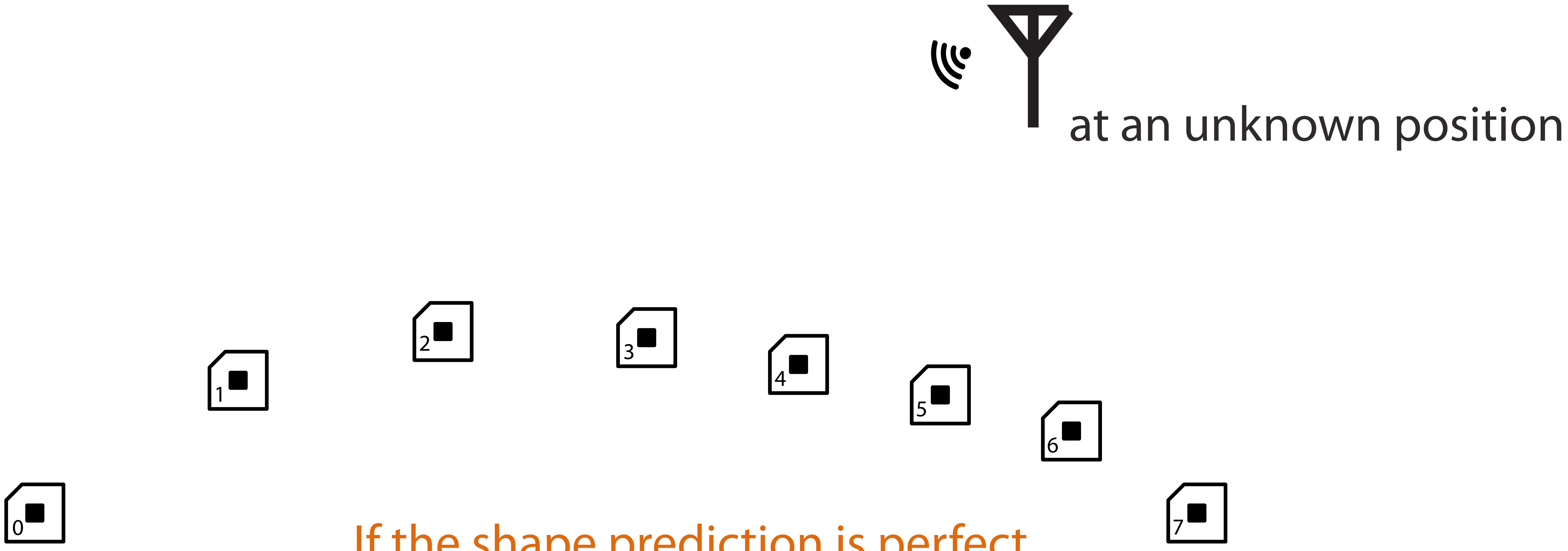
Curve modeling



Curve modeling

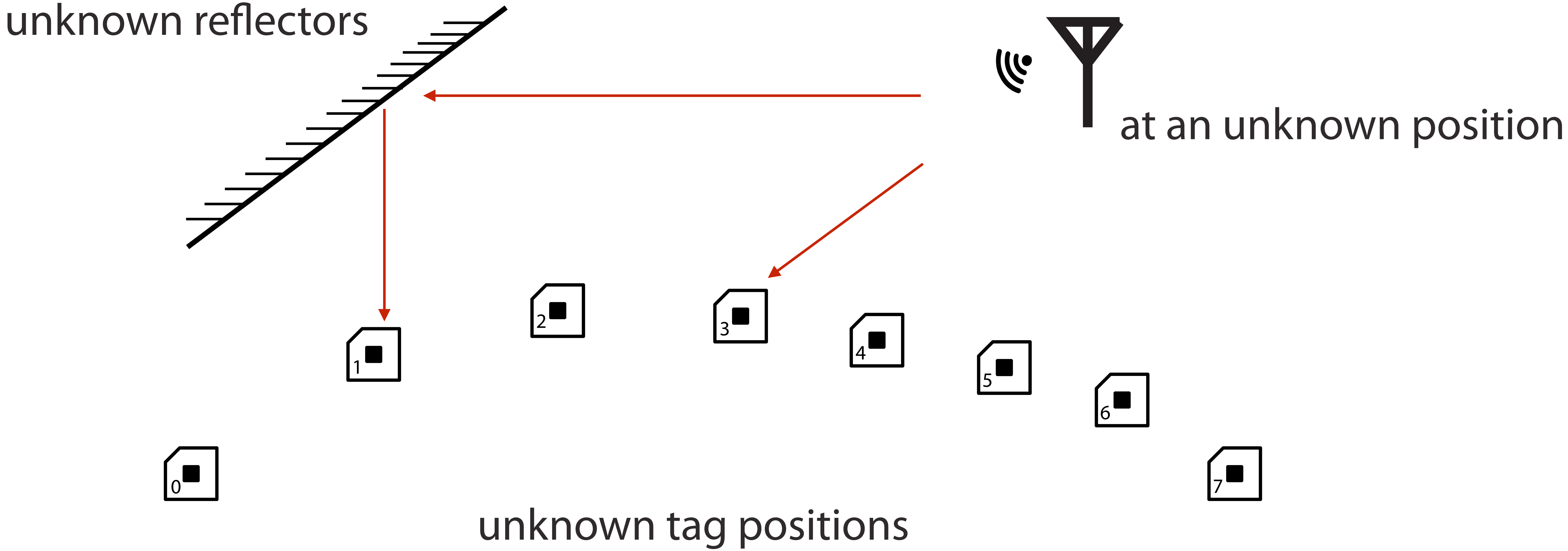


Curve modeling

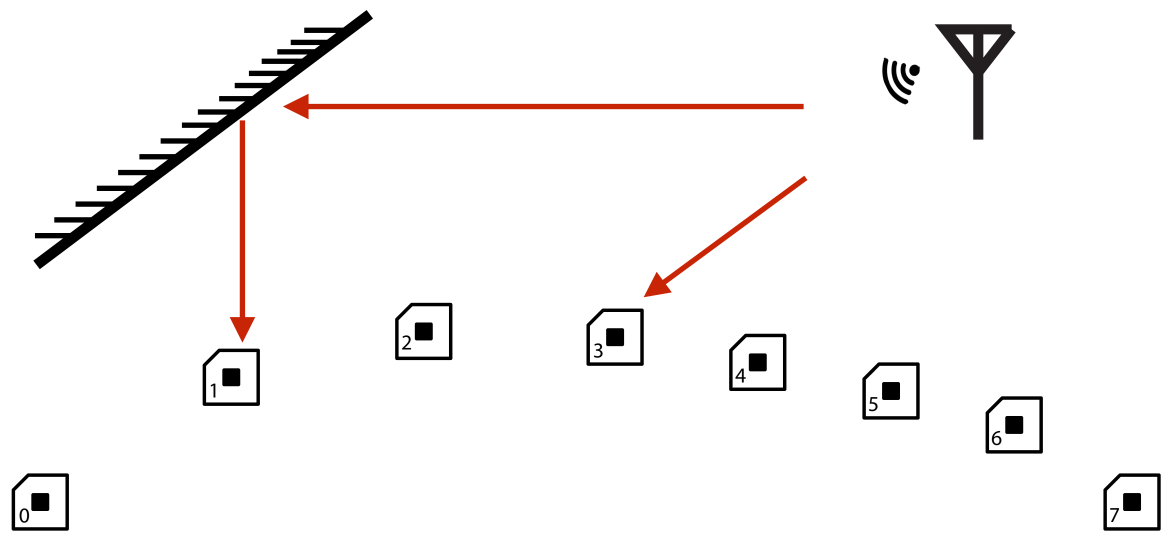


If the shape prediction is perfect,
the residual would be 0.

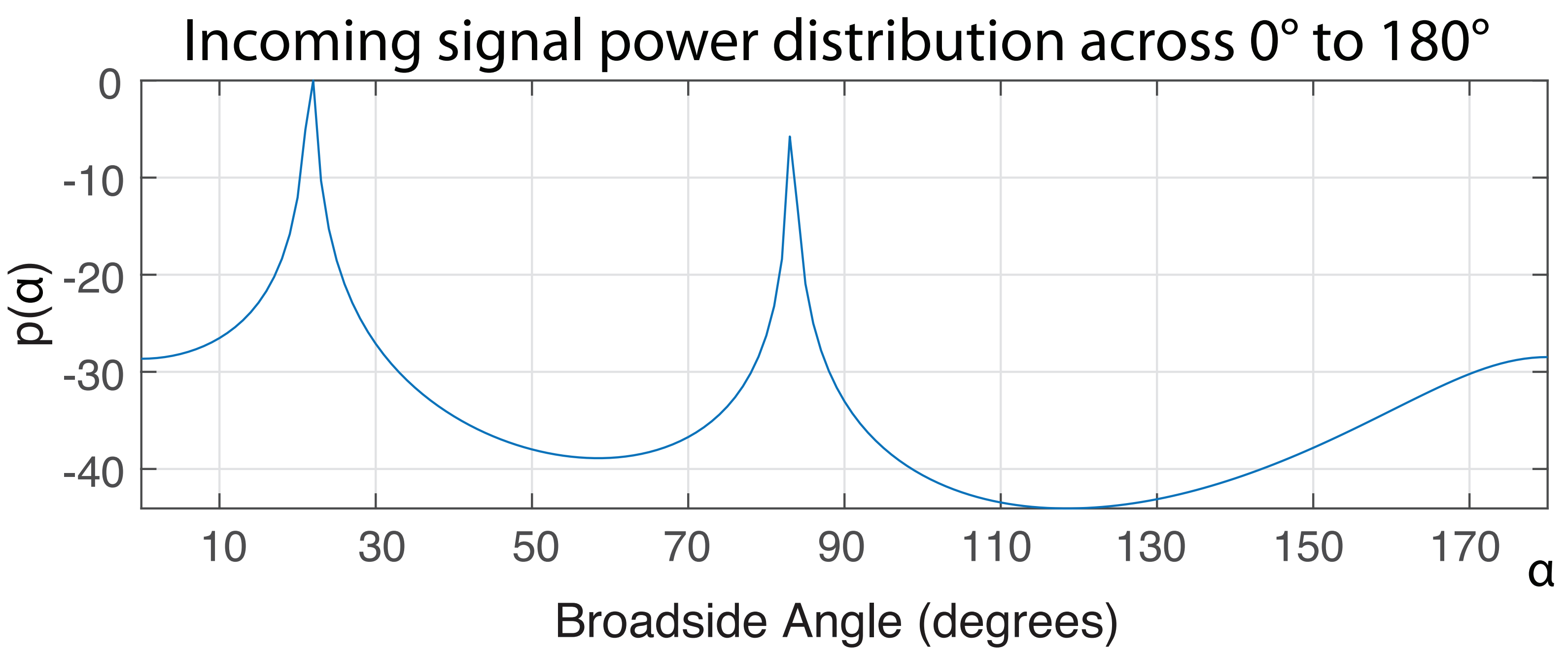
Multipath environment



Multipath environment



Two signals: reader & reflector

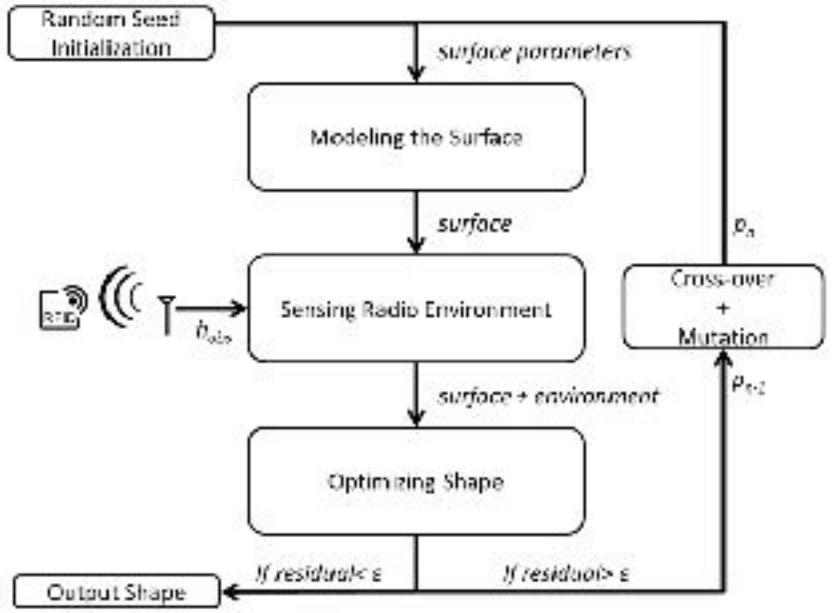


Two peaks in arrival of angles estimation

1 shape representation

2 shape modeling

3 shape optimization



system design

Problem formulation

Input:
One wireless channel observation
for each individual tag

Shape modeling:
Evaluate the goodness-of-fit
of any individual surface

Goal:
The shape representation

Problem formulation

Input:
One wireless channel observation
for each individual tag

Shape modeling:
Evaluate the goodness-of-fit
of any individual surface

Brute force search?

Output:
The shape representation

Problem formulation

Input:
One wireless channel observation
for each individual tag

Shape modeling:
Evaluate the goodness-of-fit
of any individual surface

Gradient descent?

Output:
The shape representation

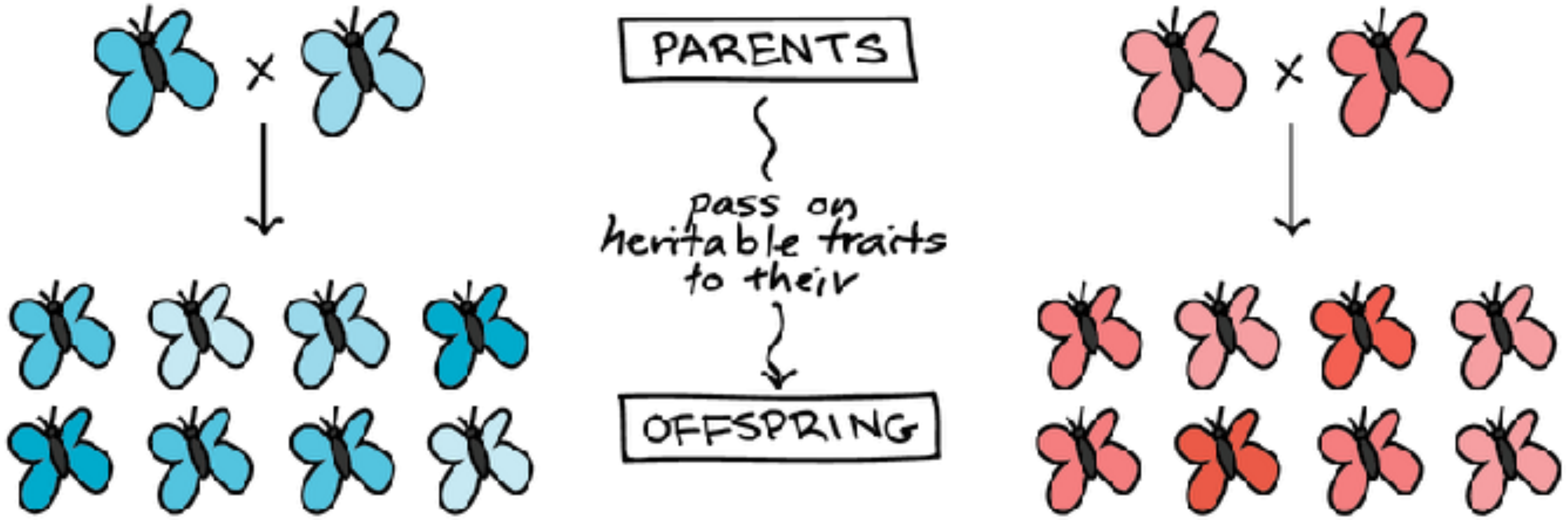
A genetic algorithm

DNA:

Initialization:

Natural selection:

The Next Generation:



A genetic algorithm

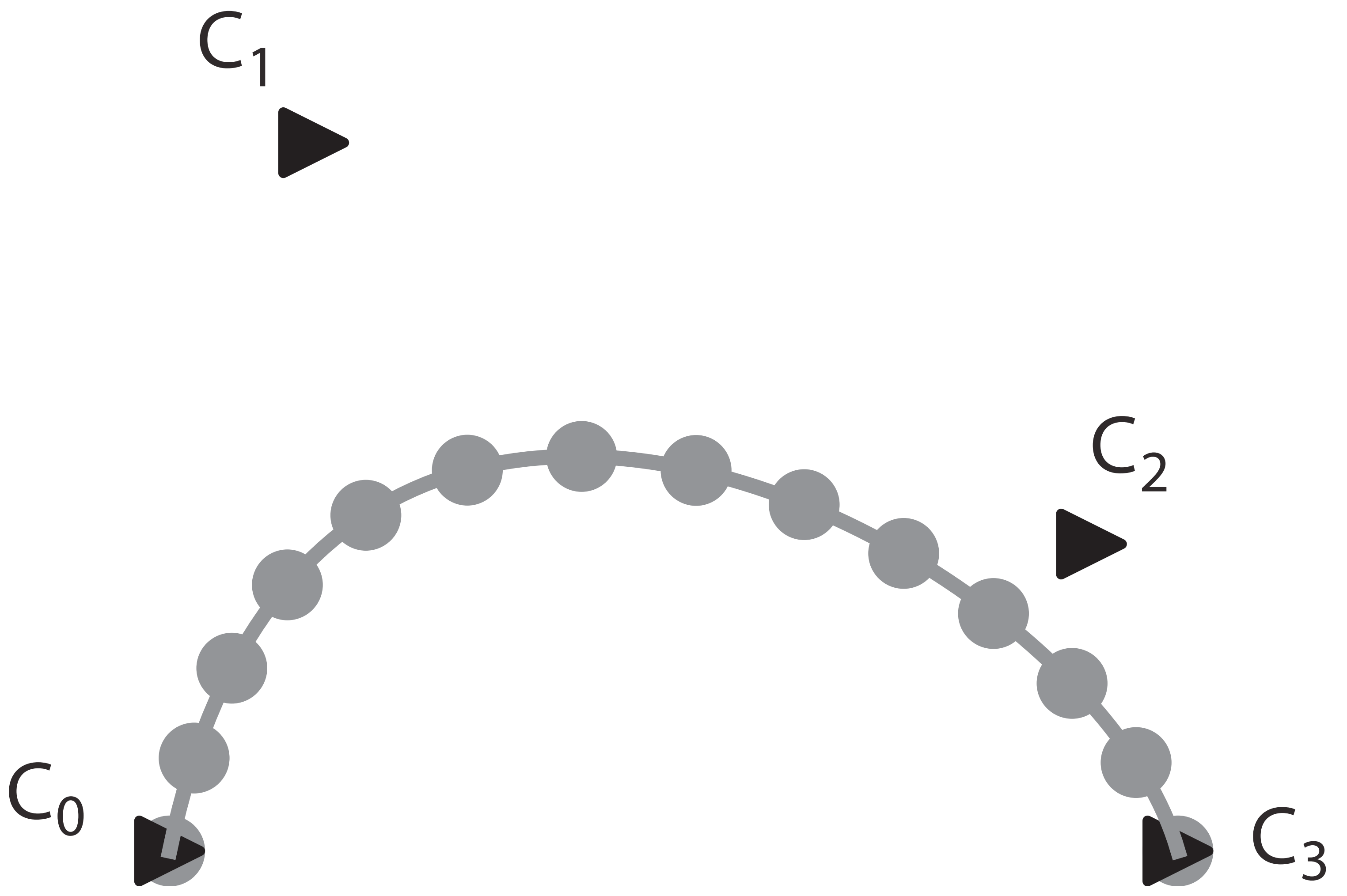
DNA:
the unknown shape parameters: x_1, y_1, x_2, y_2, x_3

C_0 $x_0 = 0, y_0 = 0$

C_1 x_1 , y_1

C_2 x_2 , y_2

C_3 x_3 , $y_3 = 0$



A genetic algorithm

DNA:
  the unknown shape parameters

Initialization:
  randomly generate n shapes.

A genetic algorithm

DNA:
  the unknown shape parameters

Initialization:
  randomly generate n shapes.

Natural selection:
  eliminate candidates that poorly fit the observed channel.

A genetic algorithm

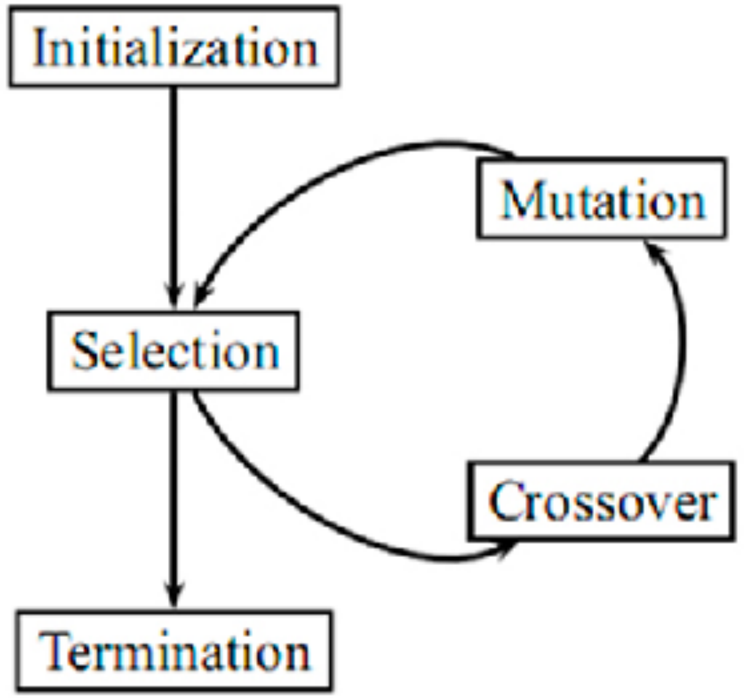
DNA:
the unknown shape parameters

Initialization:
randomly generate n shapes.

Natural selection:
eliminate shapes that poorly fit the observed channel.

The Next Generation:
cross-over: average DNAs to result in a hybrid shape.
mutation: randomly alters the DNAs.

A genetic algorithm

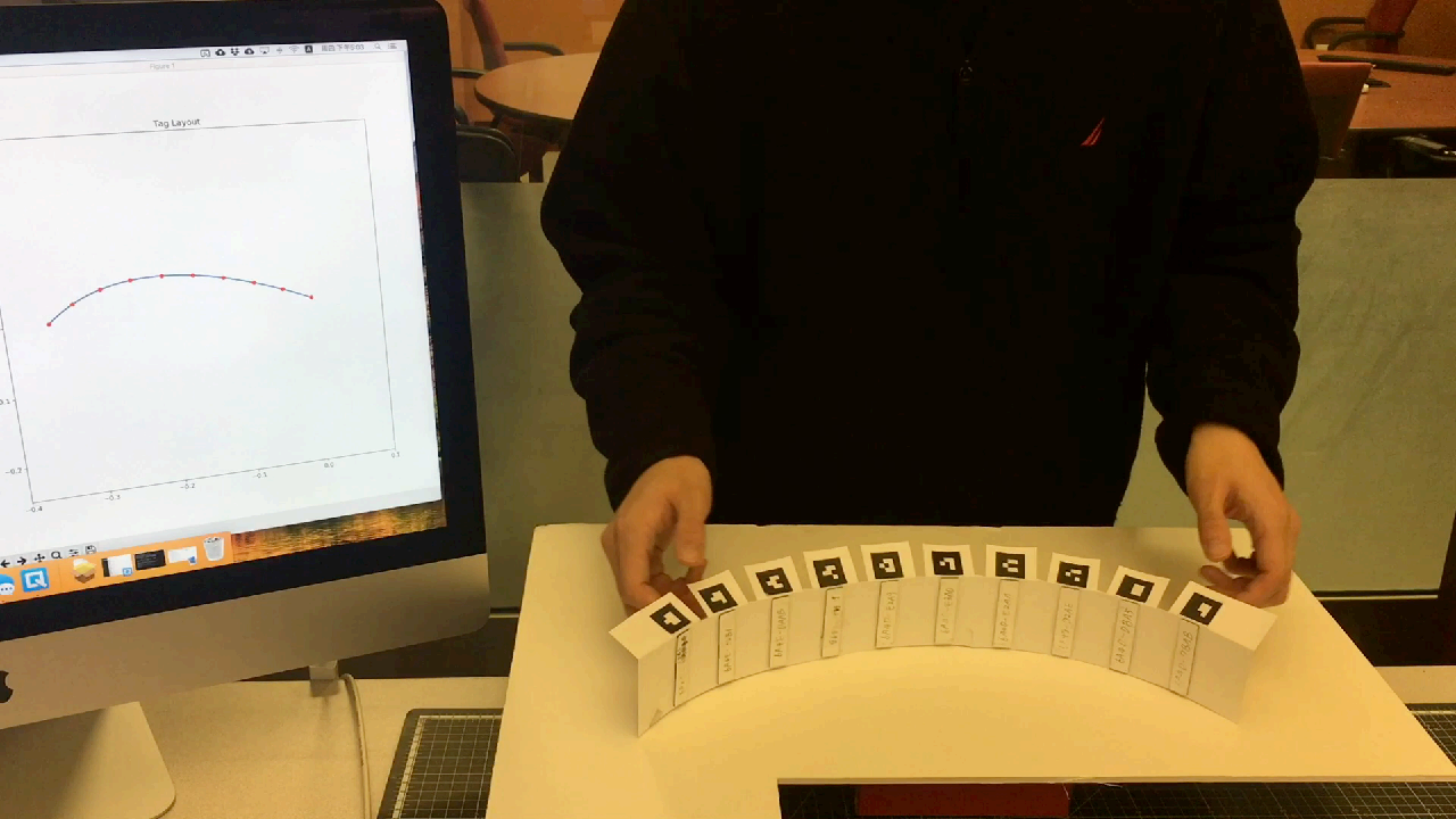


DNA:
  the unknown shape parameters

Initialization:
  randomly generate n shapes.

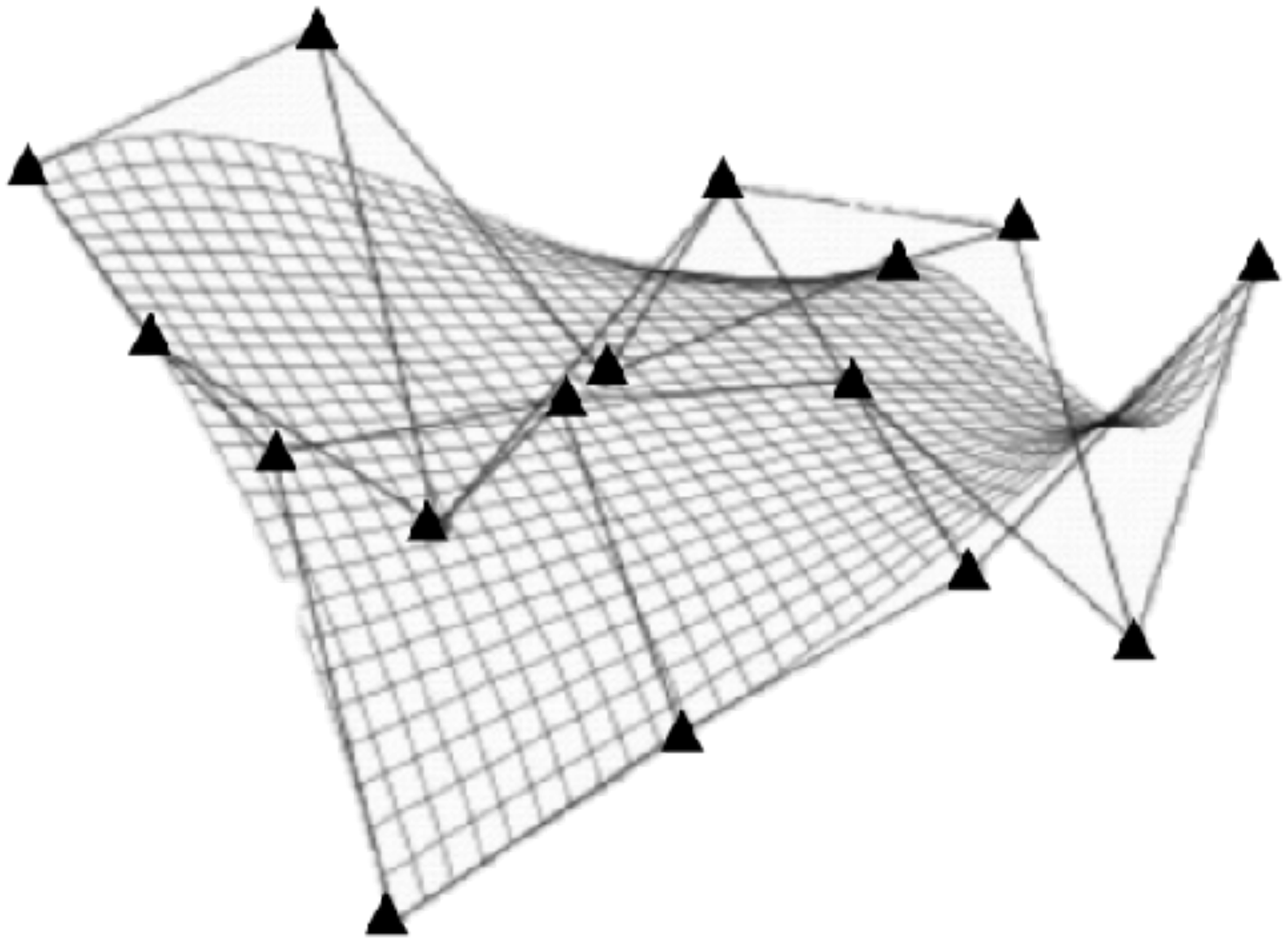
Natural selection:
  eliminate shapes that poorly fit the observed channel.

The Next Generation:
  cross-over: average DNAs to result in a hybrid shape.
  mutation: randomly alters the DNAs.


Tag Layout

Curve => surface

the production of two
orthogonal Bézier curves



4 surface stitching for large complex surfaces

5 material modeling: stiffness & elasticity

6 RFID tag orientations

See details in our paper.

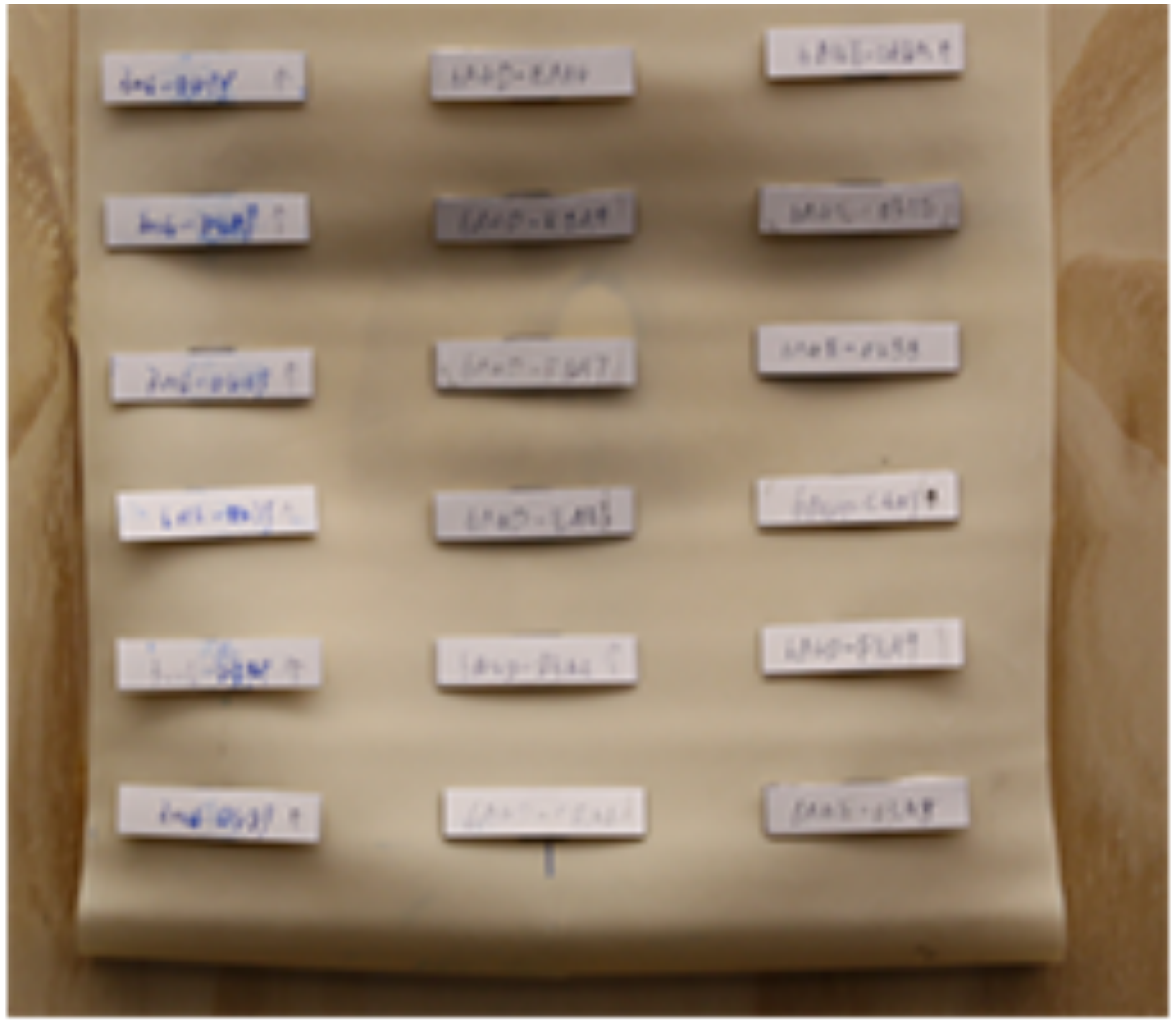
system design

evaluation

Tag spacing, Multipath, Fabric materials, Stress

WiSh prototypes

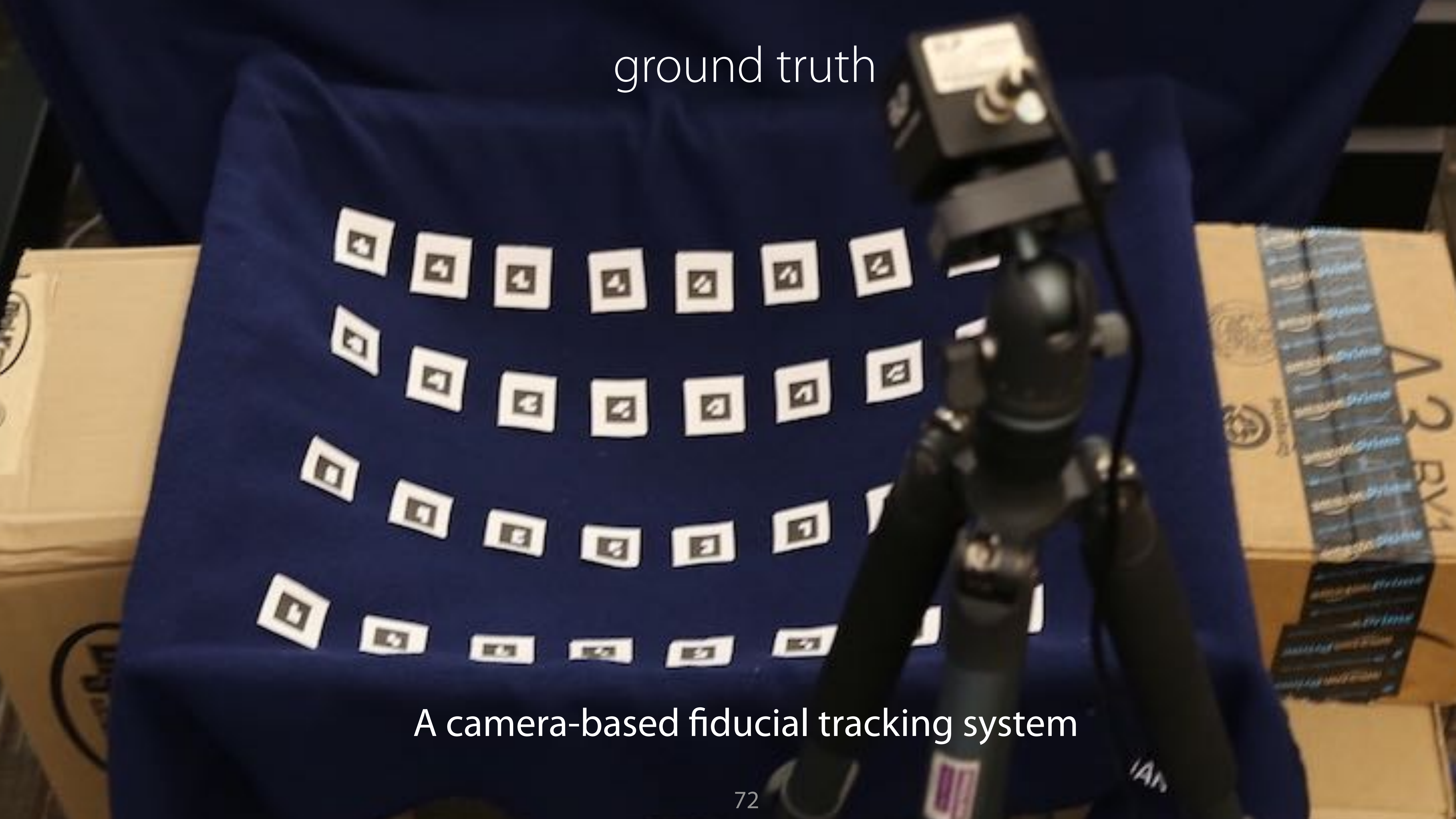
Tags on cotton surface



Tags on rubber surface

rubber string

ground truth



A camera-based fiducial tracking system

Microbenchmark: tag spacing

3 string prototypes with different tag spacings

18 tags, 2cm spacing

13 tags, 3cm spacing

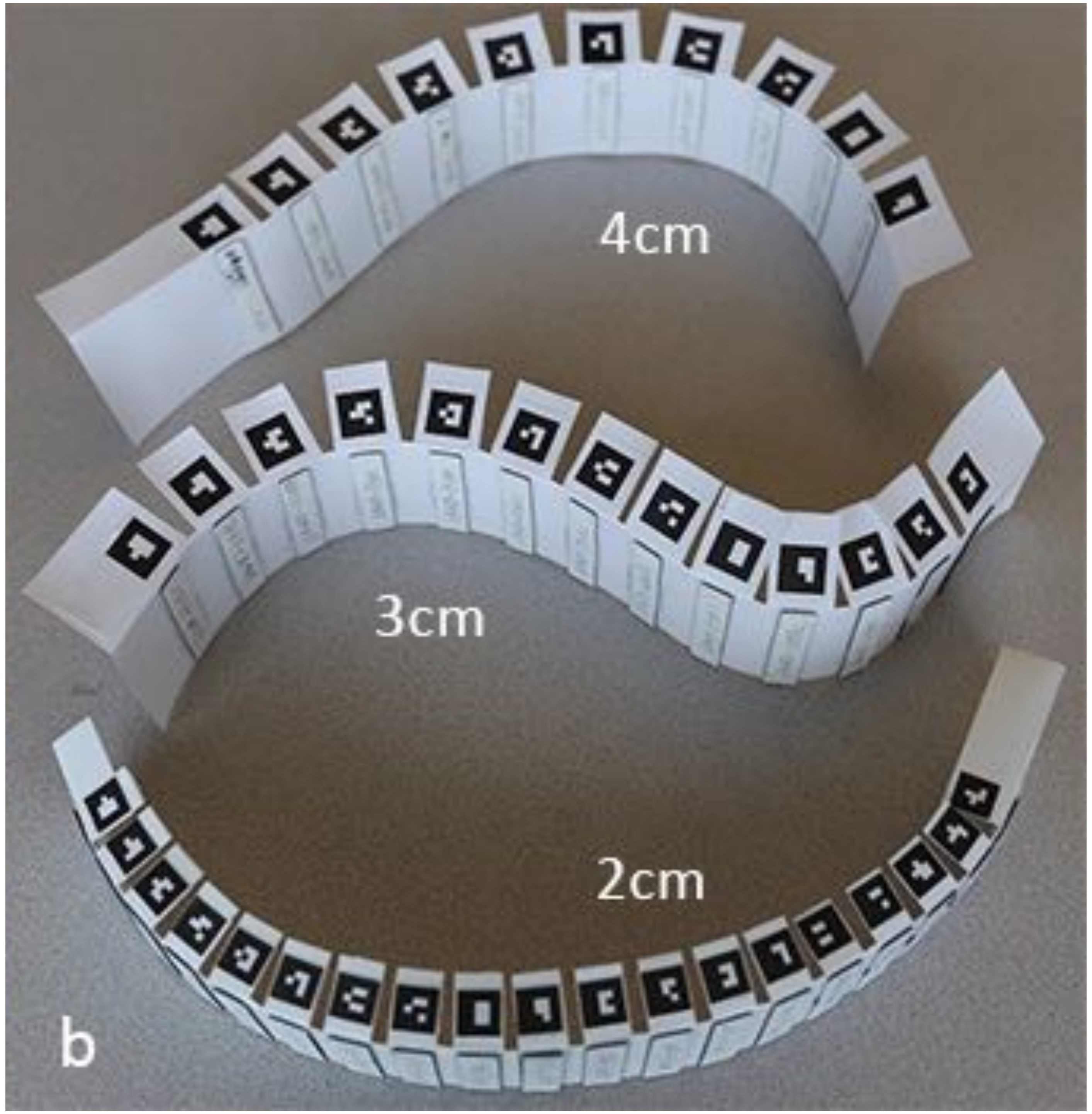
10 tags, 4cm spacing

3 types of shapes:

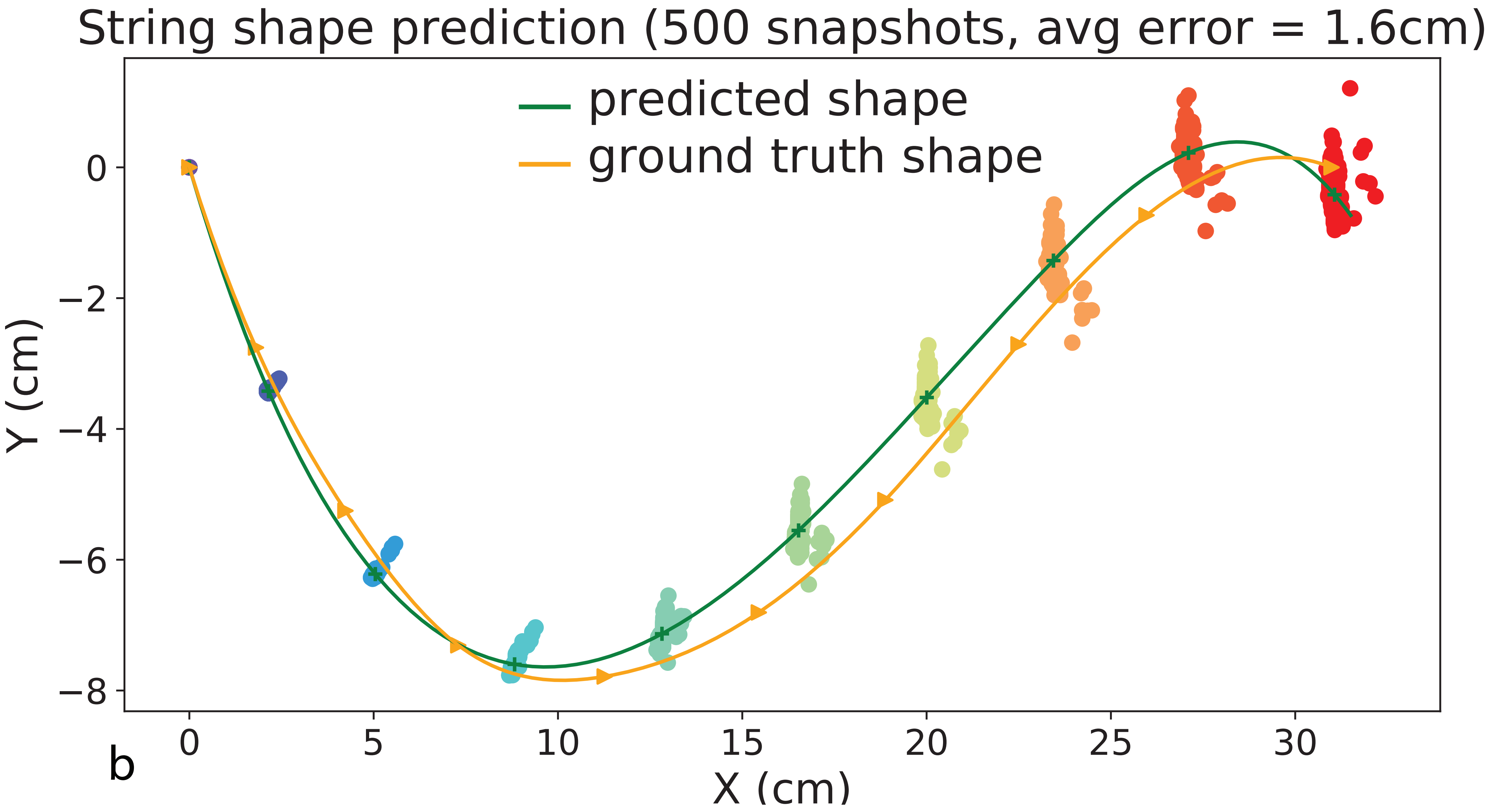
concave, convex, and wave-like.

3 shapes X 3 shapes = 9 configuration:

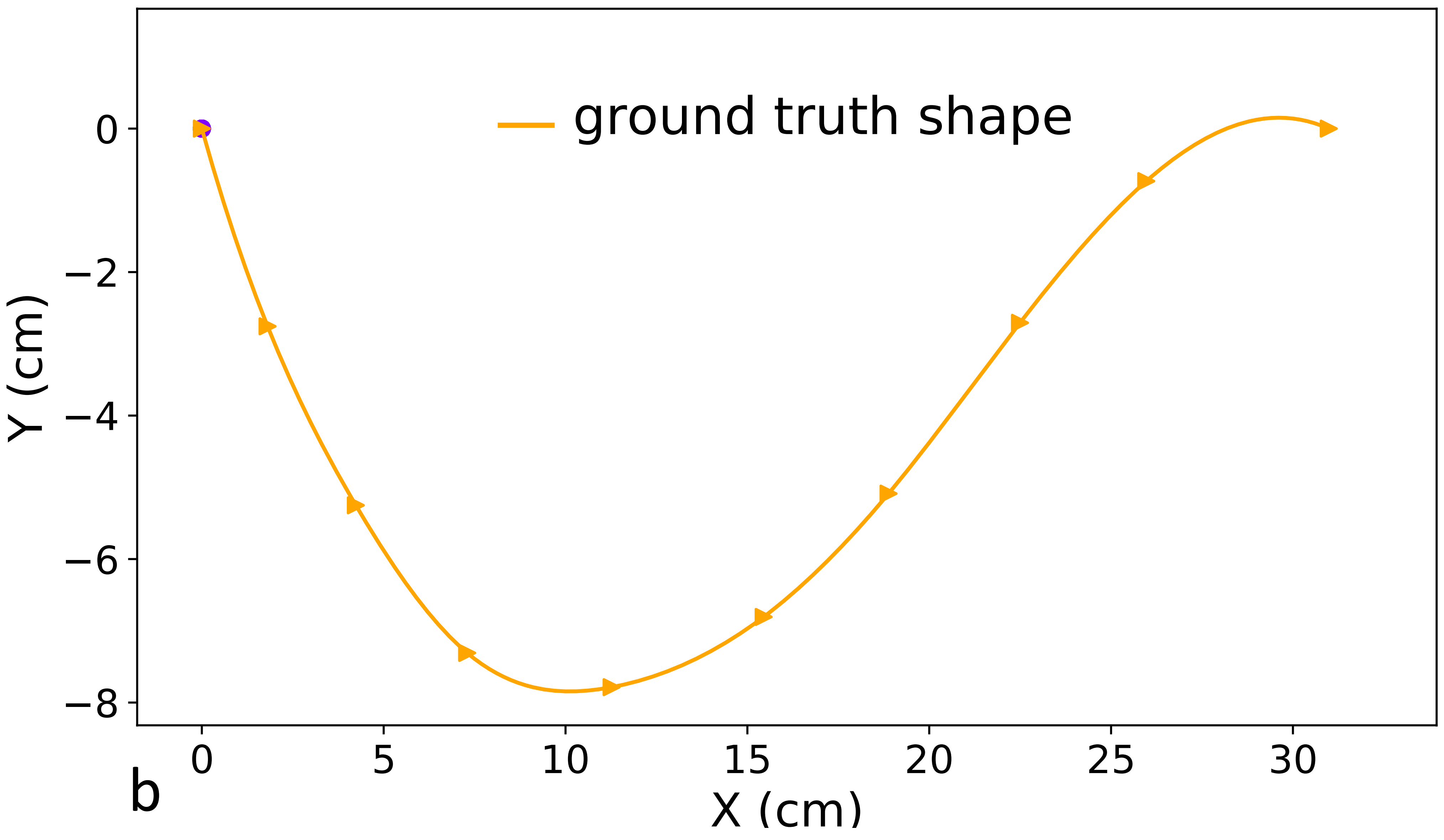
500+ shape predictions for each config



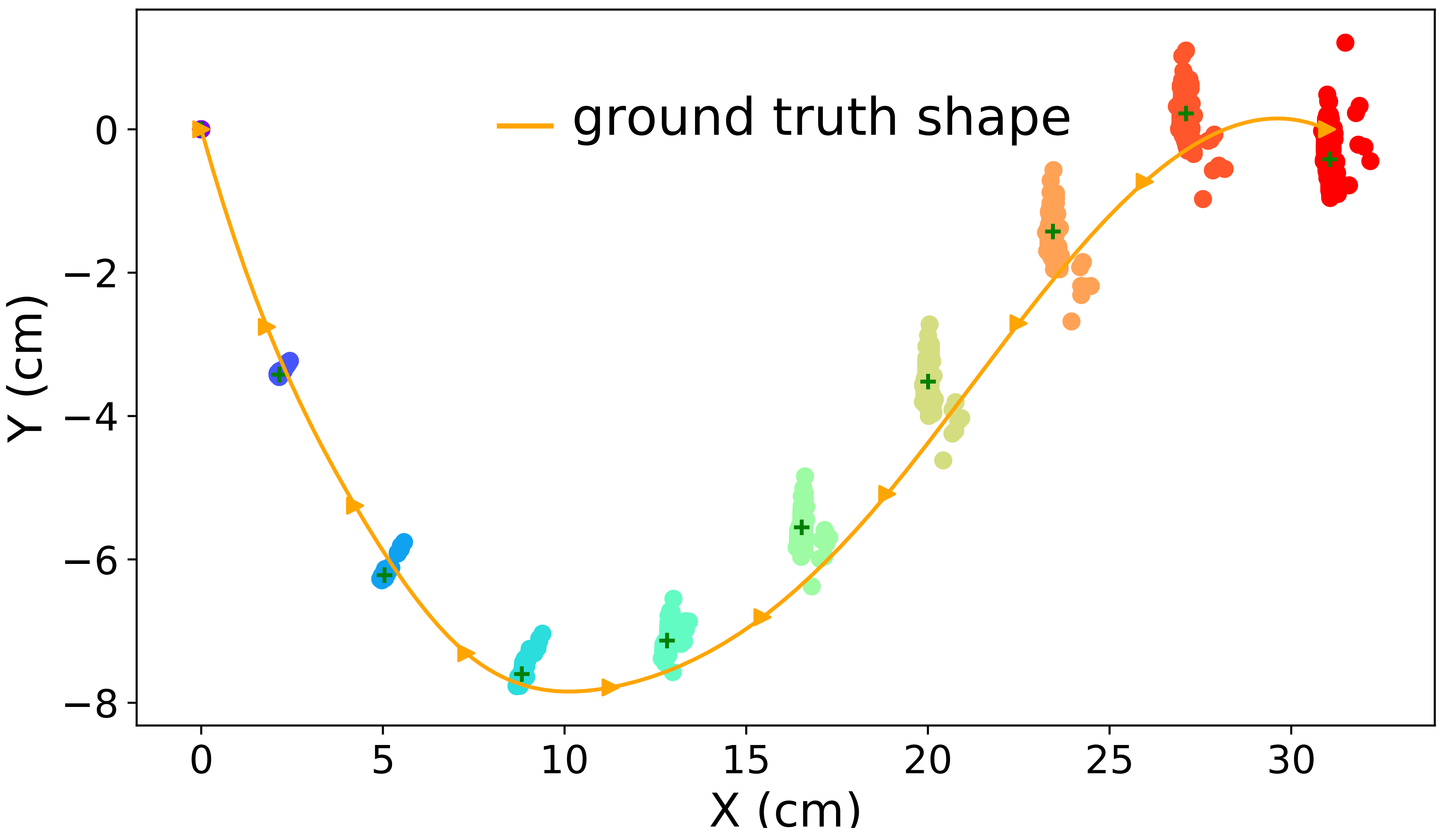
results: individual shape predictions



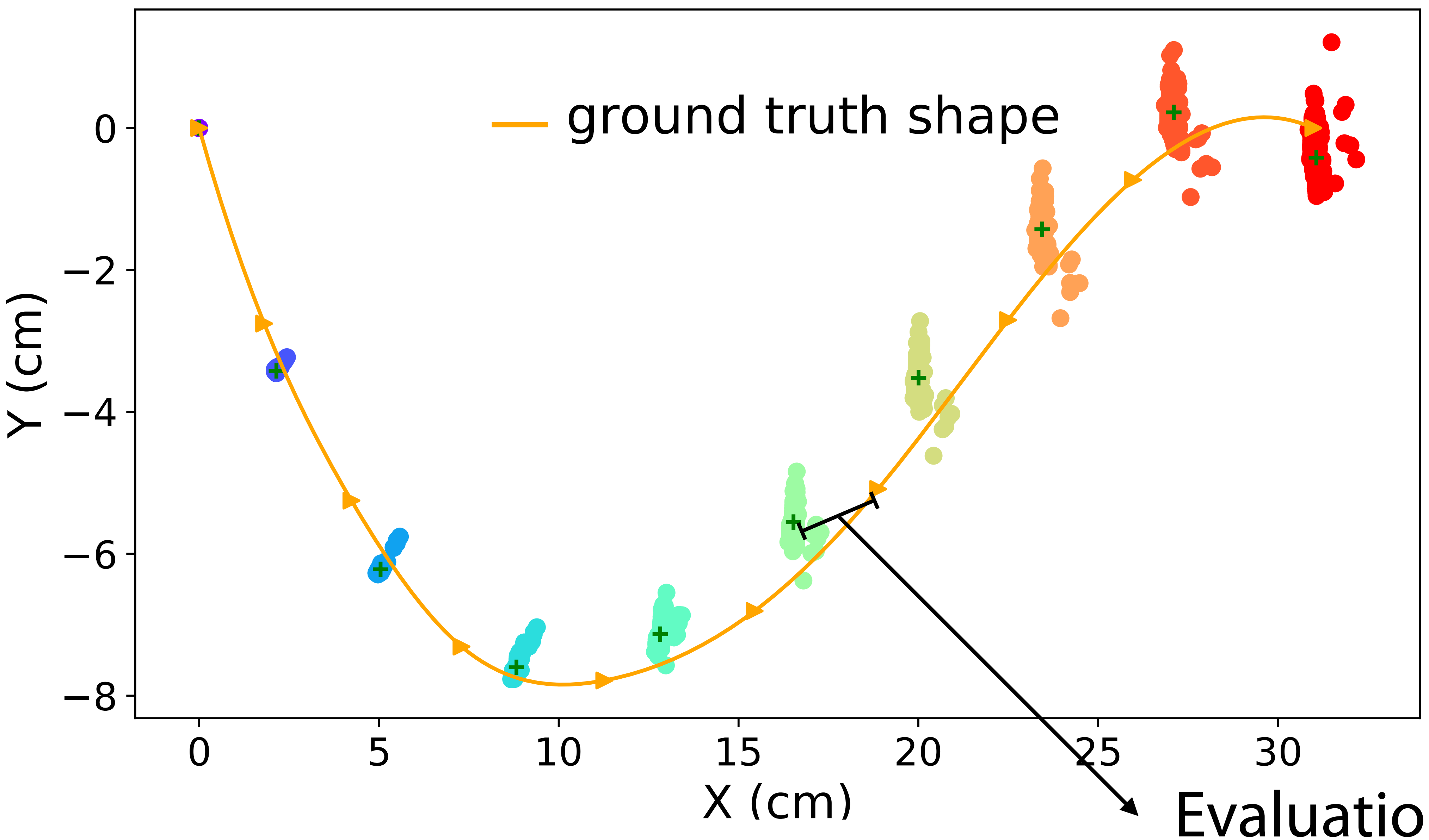
results: an individual shape prediction



results: an individual shape prediction

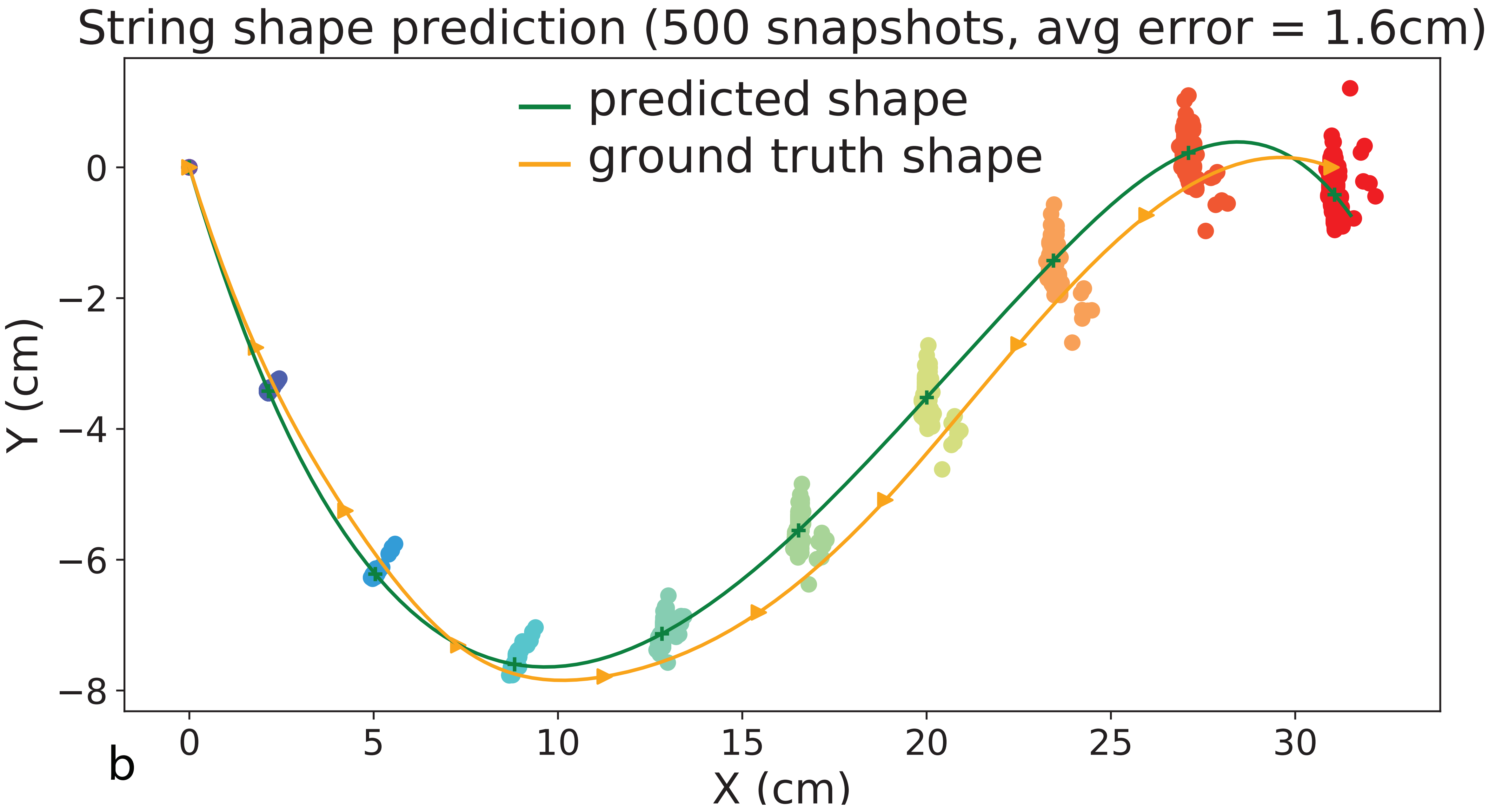


results: an individual shape prediction

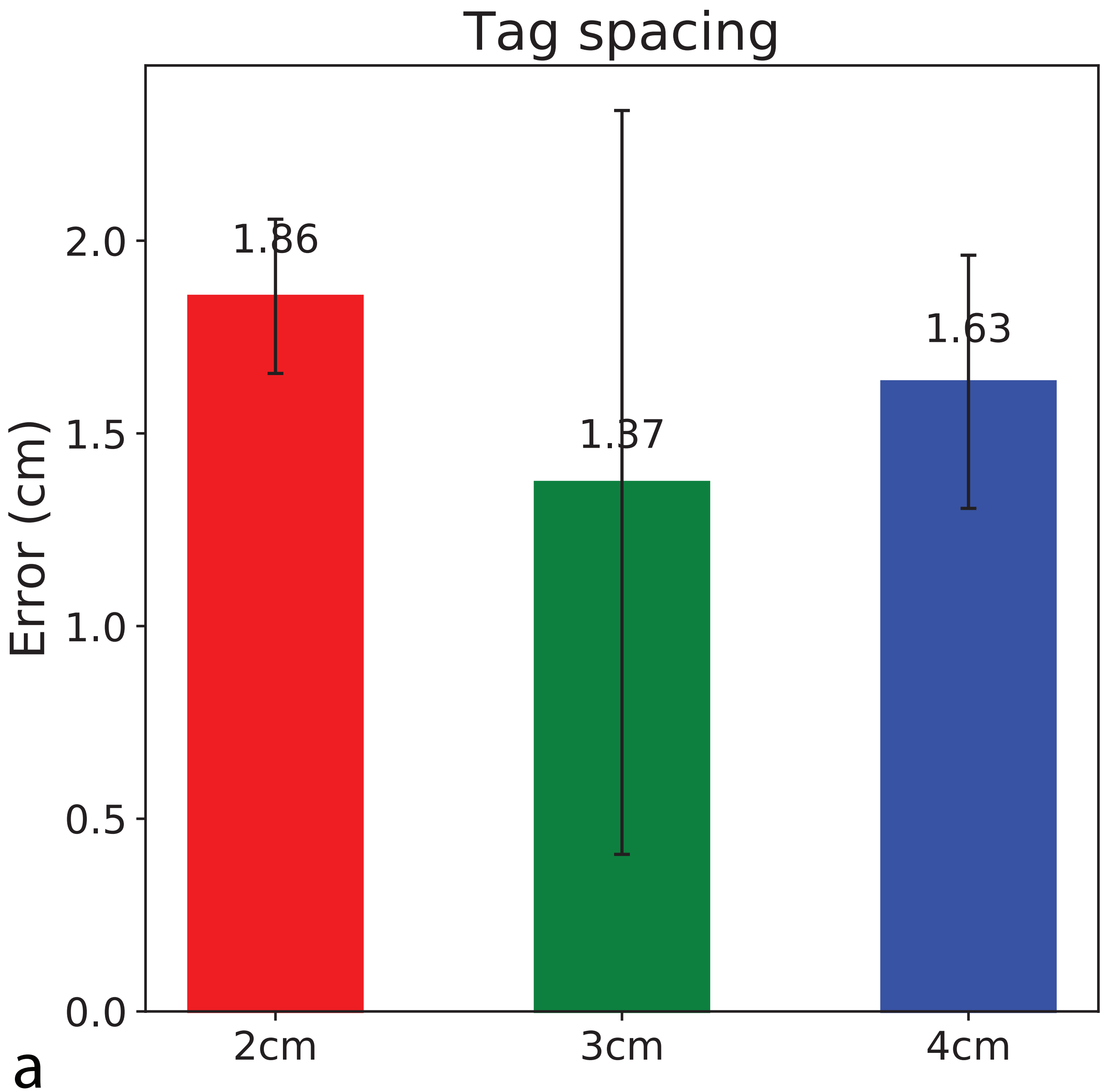


Evaluation metrics:
mean distance offset

results: an individual shape prediction



results: overall stats



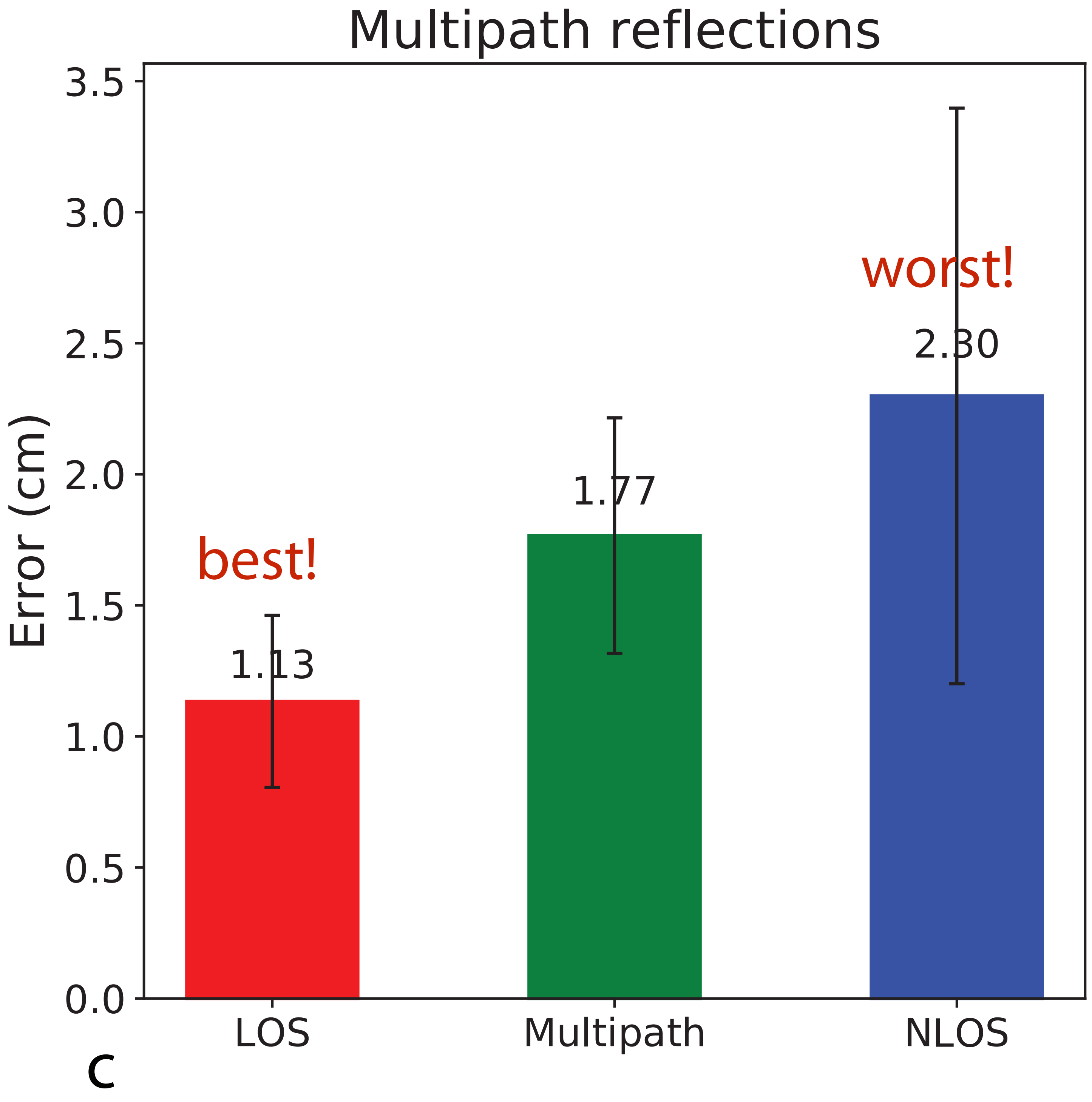
a

Evaluation metrics:

mean distance offset

an average error distance between 1.3 and 1.9 cm.

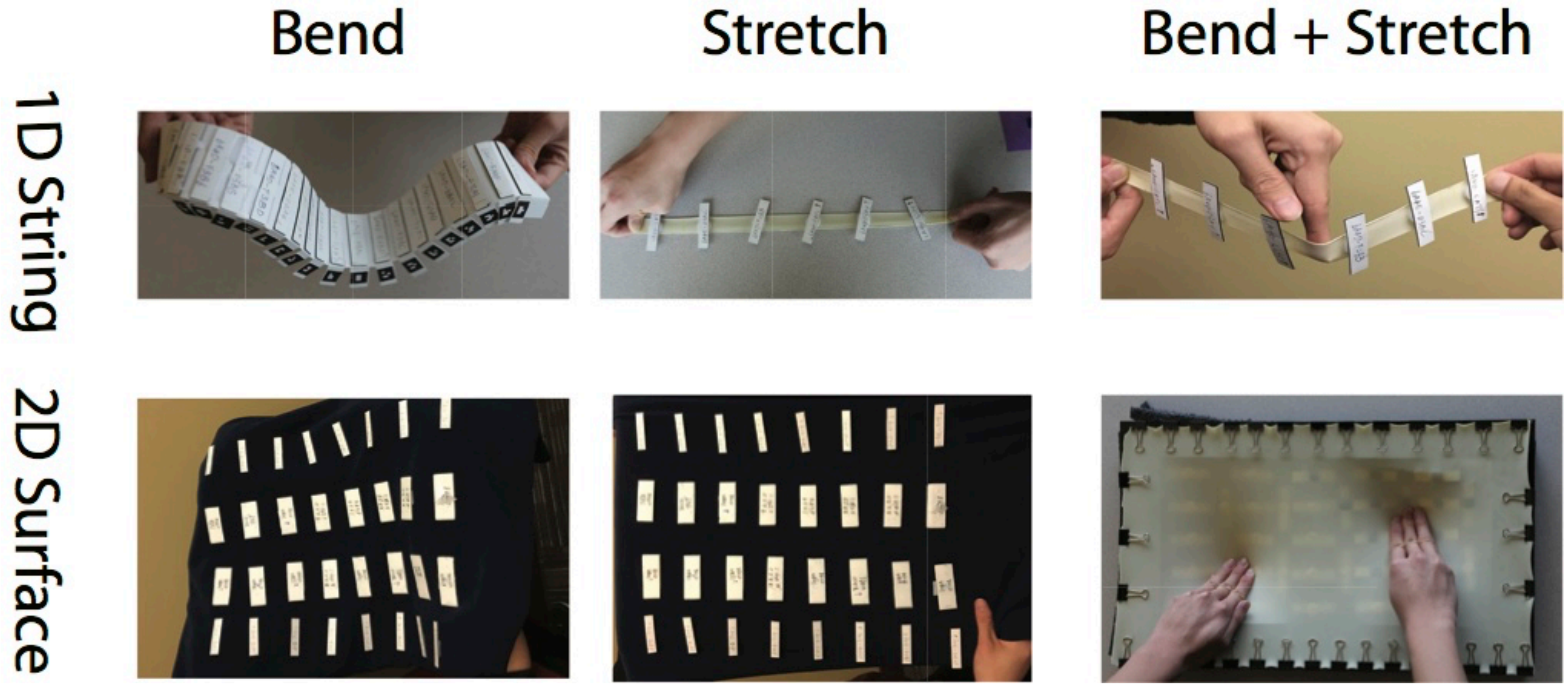
results: multipath



all configurations have high quality predictions.

an average offset between 1.1 and 2.3 cm.

different materials & stress => See paper



applications

Bridges, 3D Touch screen, Spine posture, Breath, Smart carpet, ….

Shape-aware bridges

massive passive RFID tags

One in 4 US highway bridges are in need of serious repair.

Visual inspections are costly.

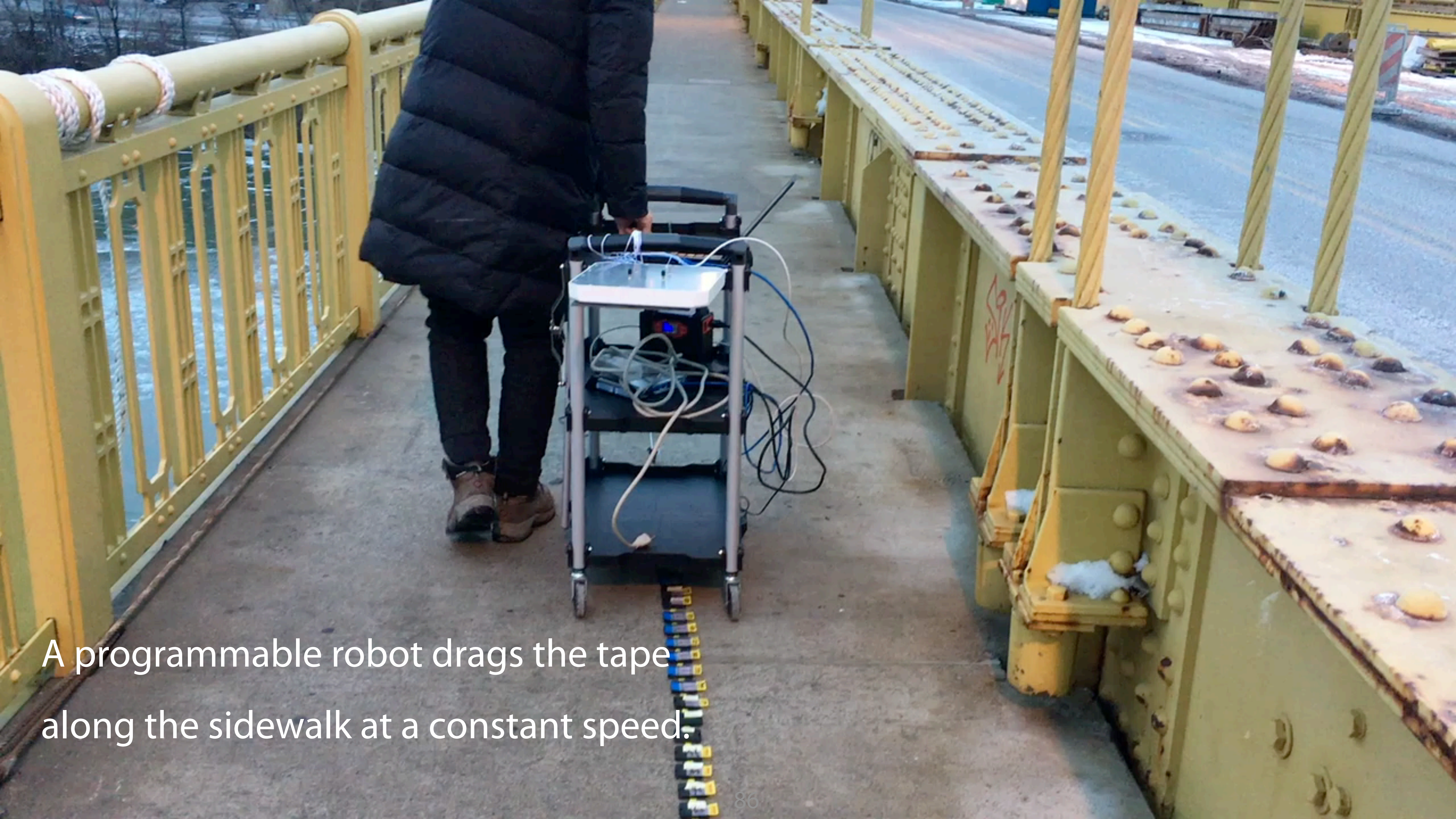

388-meter long suspension bridge
Pittsburgh 10th Street Bridge

Shape sensing tape

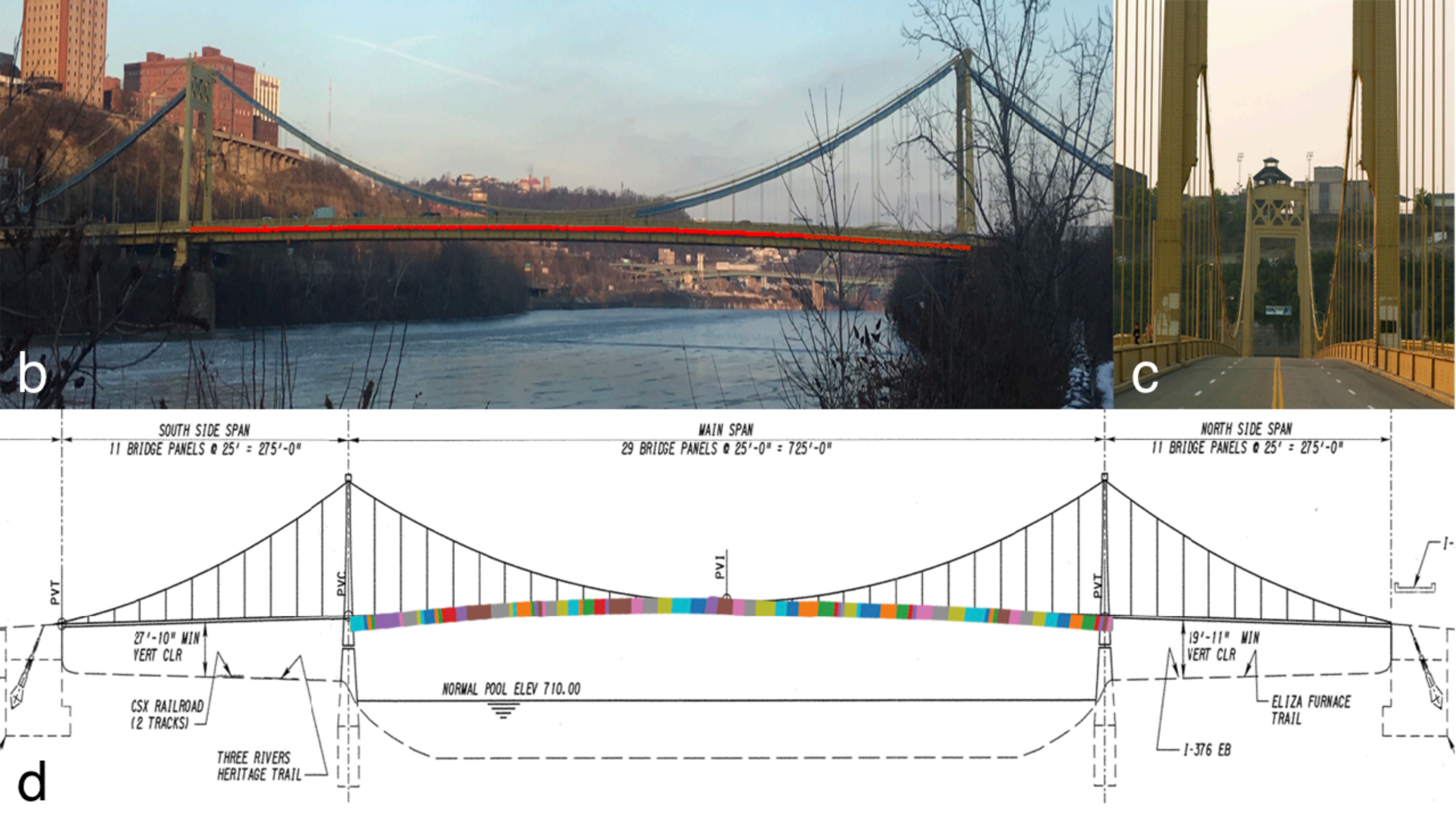
50 tags on a 5-meter string

with an evenly 7cm tag spacing

A programmable robot drags the tape
at a constant speed.


A programmable robot drags the tape
along the sidewalk at a constant speed.


b
c


b
c
d
SOUTH SIDE SPAN
11 BRIDGE PANELS @ 25' = 275'-0"
MAIN SPAN
29 BRIDGE PANELS @ 25'-0" = 725'-0"
NORTH SIDE SPAN
11 BRIDGE PANELS @ 25' = 275'-0"
PVT
PVC
PVI
PVT
27'-10" MIN VERT CLR
19'-11" MIN VERT CLR
NORMAL POOL ELEV 710.00
CSX RAILROAD (2 TRACKS)
THREE RIVERS HERITAGE TRAIL
ELIZA FURNACE TRAIL
I-376 EB

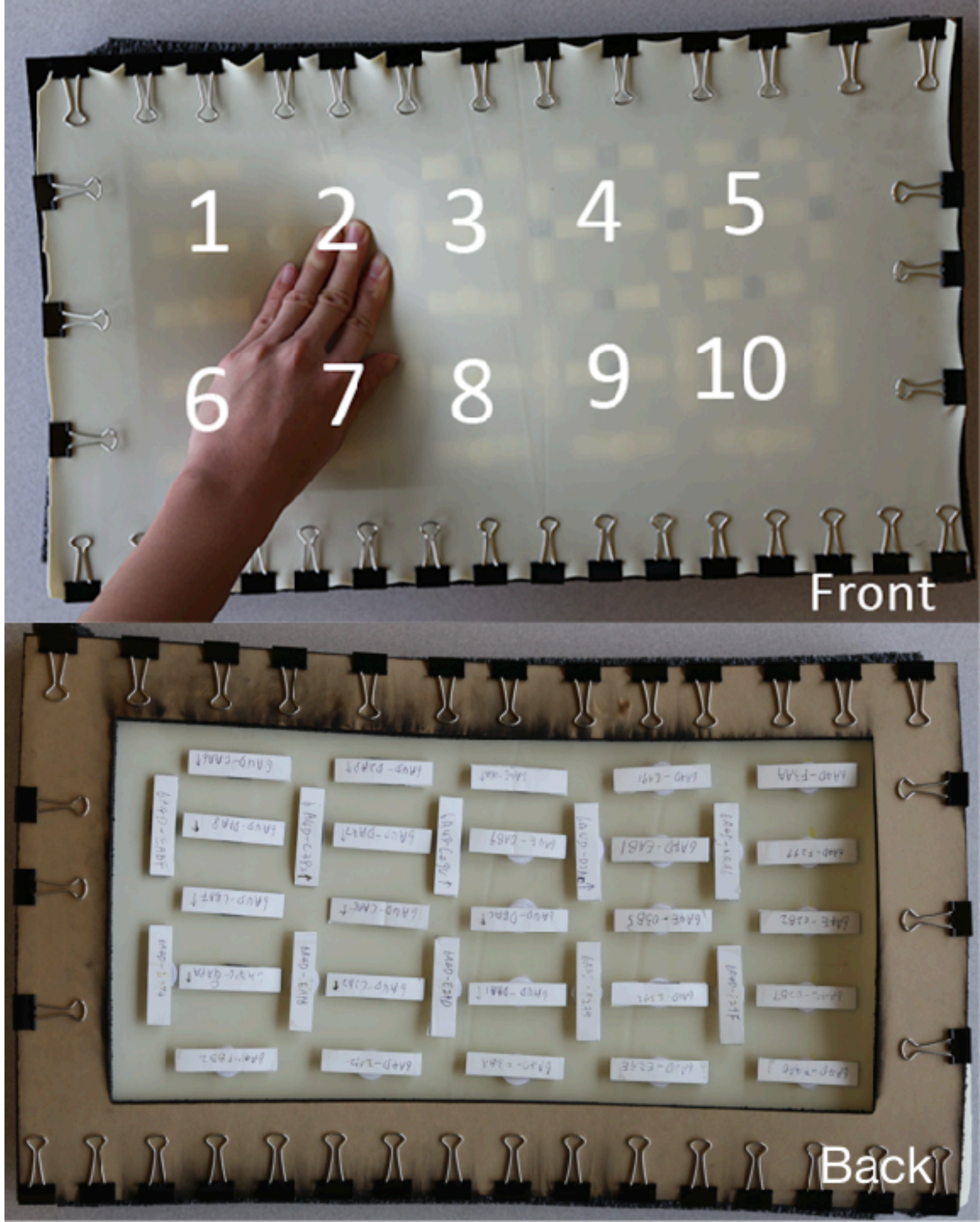
RFID 3D Touch screen

turning any soft object (e.g. toys, walls, etc.) into an interactive surface.

laser cut an 40 cm x 20 cm acrylic frame

wrap the frame with a latex rubber surface

place 35 RFID tags on the back



RFID 3D Touch screen

touch prediction
mean accuracy: **87%**

Actual Key Number (rows) / Predicted Key Number (columns)

	1	2	3	4	5	6	7	8	9	10
1	82.8	6.3	2.3	1.5	0.8	5.3	0.6	0.5	0.0	0.0
2	3.2	88.9	1.7	1.1	0.6	0.6	3.7	0.2	0.0	0.0
3	0.0	3.4	85.0	3.3	1.6	1.2	0.8	4.2	0.5	0.0
4	0.1	0.7	1.5	90.0	2.5	0.9	0.8	0.5	2.6	0.3
5	0.3	0.7	2.2	2.9	86.6	2.4	1.2	0.5	0.4	2.9
6	1.5	0.0	0.6	0.7	2.4	91.3	2.0	1.0	0.4	0.0
7	0.1	2.0	1.0	0.7	0.8	2.7	88.7	2.3	1.1	0.5
8	0.0	0.2	2.9	1.0	0.8	2.5	3.4	85.6	2.8	0.8
9	0.0	0.2	0.5	3.3	1.2	1.5	1.3	3.8	85.0	3.1
10	0.0	0.2	0.4	0.6	4.7	2.4	2.1	2.5	4.7	82.4

limitations

Wrinkles, folds, latency

Limitations

Wrinkles & folds

WiSh cannot model small curvatures & folds.

Sensing and Computational Latency

Raw signal refresh rate: 30 Hz;
Computing refresh rate: 2 Hz.

WiSh

Towards a **Wi**reless **Sh**ape-aware World using Passive RFIDs

Haojian Jin*

Jingxian Wang*

Zhijian Yang

Swarun Kumar

Jason Hong

Carnegie Mellon University