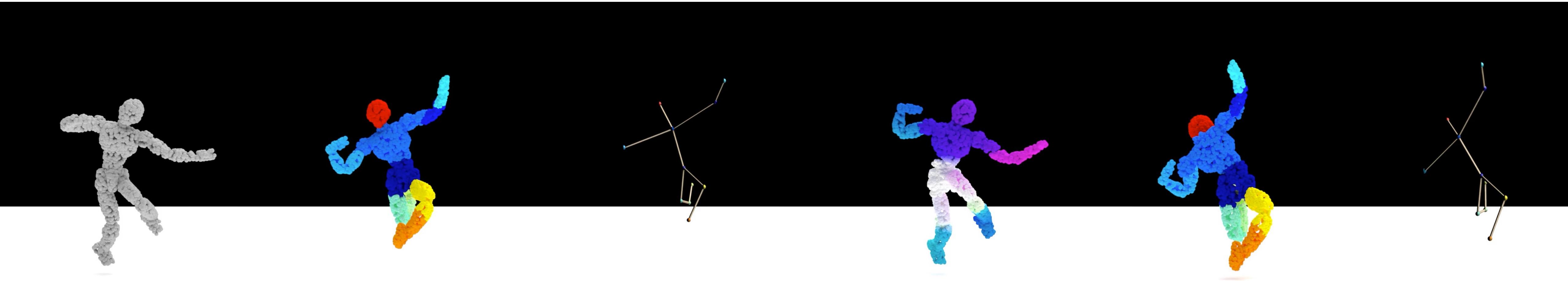
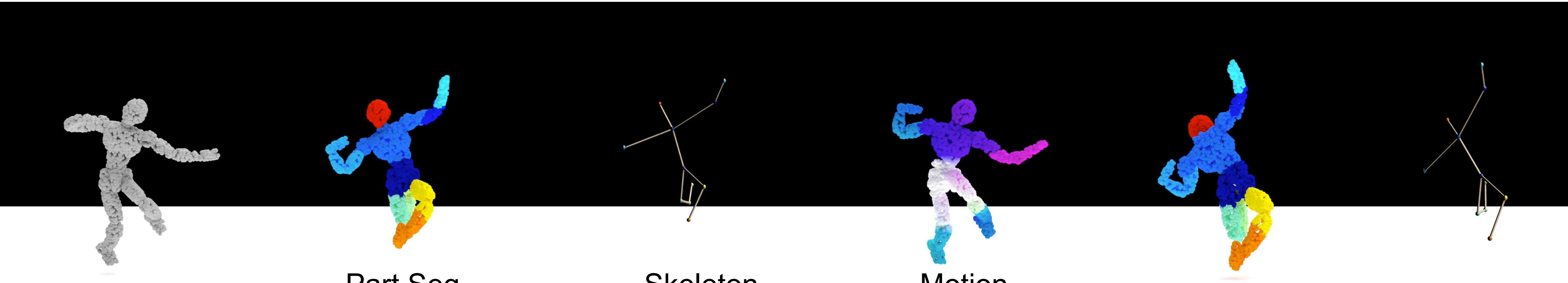
Building Rearticulable Models for Arbitrary 3D Objects from 4D Point Clouds

Shaowei Liu, Saurabh Gupta*, Shenlong Wang*

CVPR 2023



Problem setting



Articulated objects

- Definition:
  - *objects composed of more than one rigid parts (links) connected by 1DOF joints allowing rotational or translational motion*
- Joints categorized into:
  - *Revolute joint (e.g. eyeglasses)*
  - *Prismatic joint (e.g. drawer)*

Everyday articulated objects

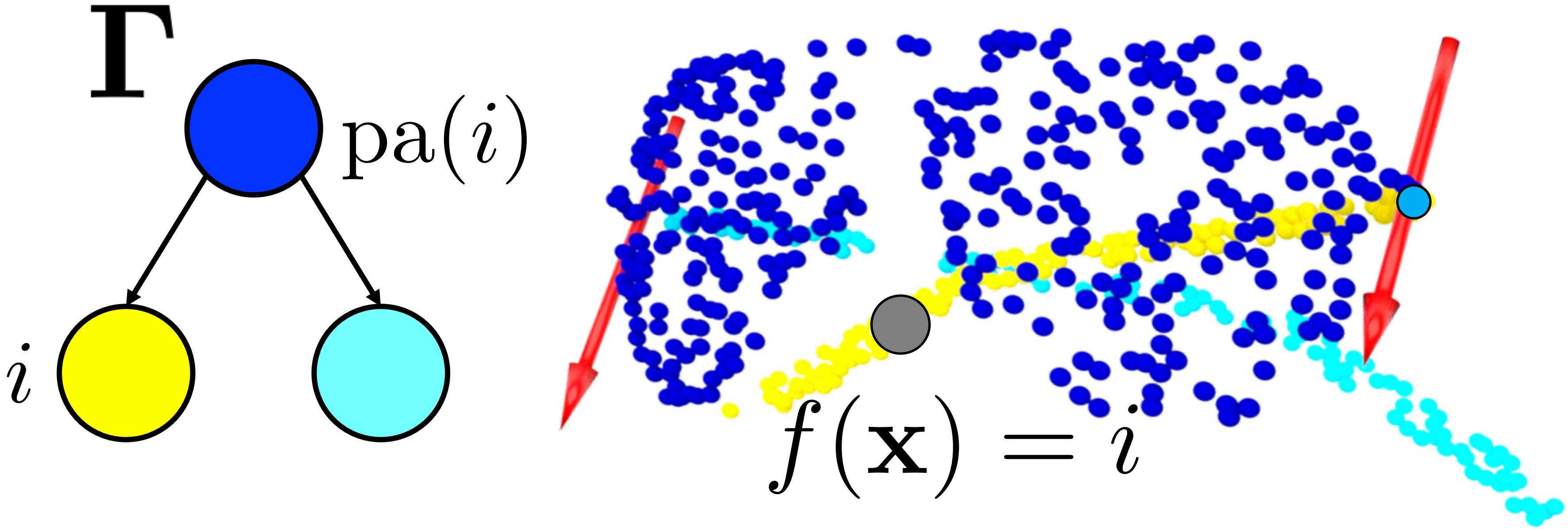
Existing solutions

- Category-specific (*e.g. human, quadrupeds*): cannot handle arbitrary parts and classes
- Category agnostic: either fixed kinematics, or do not have realistic joint constraints
- Ours: arbitrary parts / categories, realistic joint constraints, reason kinematic structure

	Arbitrary Parts	**Realistic Joint Constraints**	**Arbitrary Kinematics**
Category-specific	No	Yes	No
Ditto (CVPR 2022)	Yes	Yes	No
MultiBodySync (CVPR 2021)	Yes	No	No
WachItMove (CVPR 2022)	Yes	No	Yes
Ours	**Yes**	**Yes**	**Yes**

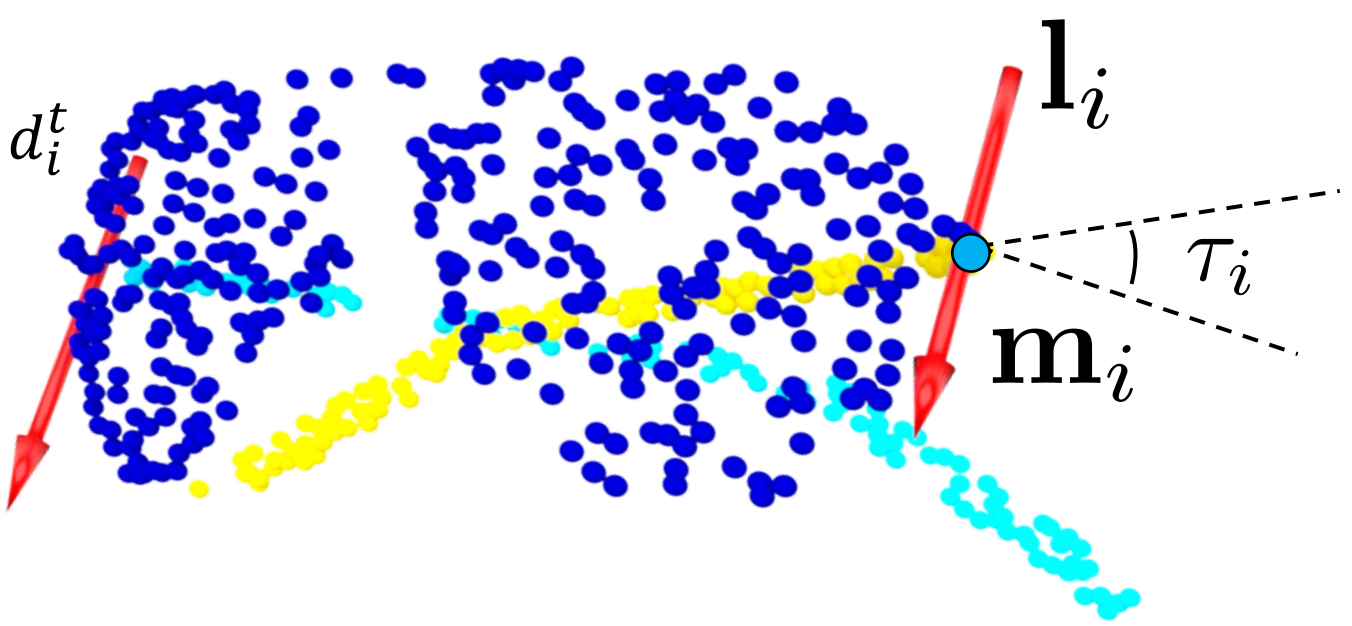
Articulation model

- Kinematic structure Γ, canonical frame part segmentation f



Articulation model

- Screw representation $T_i^t = T(s_i, \theta_i^t) \in SE(3)$
- Screw parameters $s_i = (l_i, m_i)$
  - joint axis l_i location m_i
- Screw states $\theta_i^t = (\tau_i^t, d_i^t)$
  - rotation angle τ_i^t translation d_i^t
  - revolute: $d_i^t = 0$
  - prismatic: $\tau_i^t = 0$



Optimization

- Analysis-by-synthesis
  - Reconstructed point cloud agree with observed point cloud
  - Model parameterized motion agree with observed 3D flow

$$\min_{\Gamma, f, \{s_i\}, \{\theta_i\}^t} E_{\text{geom}}(M, P) + E_{\text{flow}}(M, P)$$

skeleton kinematics

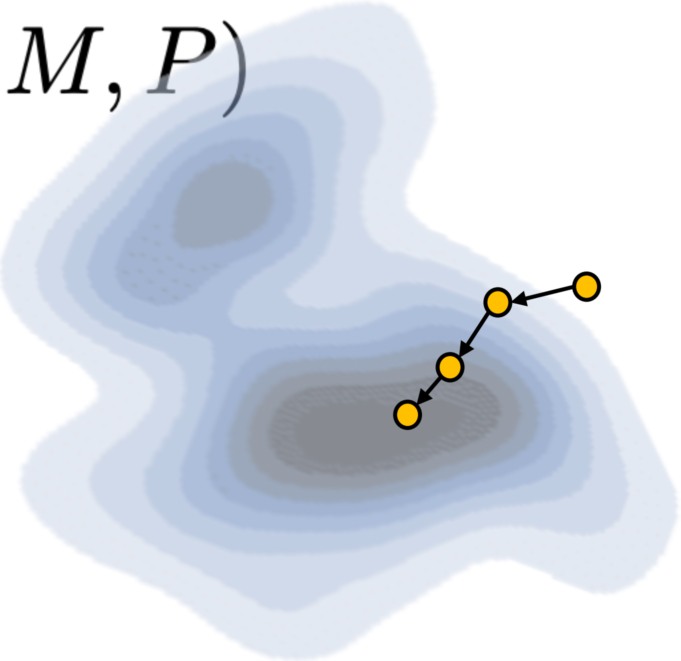
part segmentation

screw parameters

screw states

articulated point cloud

observed point cloud



Challenge & Solution

- Constraint optimization
  - Both discrete f and continuous $\{s_i\}, \{\theta_i^t\}$ optimization variables
  - Structured constraint Γ

$$\min_{\Gamma, f, \{s_i\}, \{\theta_i\}^t} E_{\text{geom}}(M, P) + E_{\text{flow}}(M, P)$$

- Relax-projection
  - Fitting a relaxed model without constraints
  - Projecting onto a valid solution space
  - Finetuning the model

Relaxation-Projection

- **Relaxation**: estimate each part independently

$$\min_{f,\{T_i\}^t} E_{\text{geom}}(M,P) + E_{\text{flow}}(M,P)$$

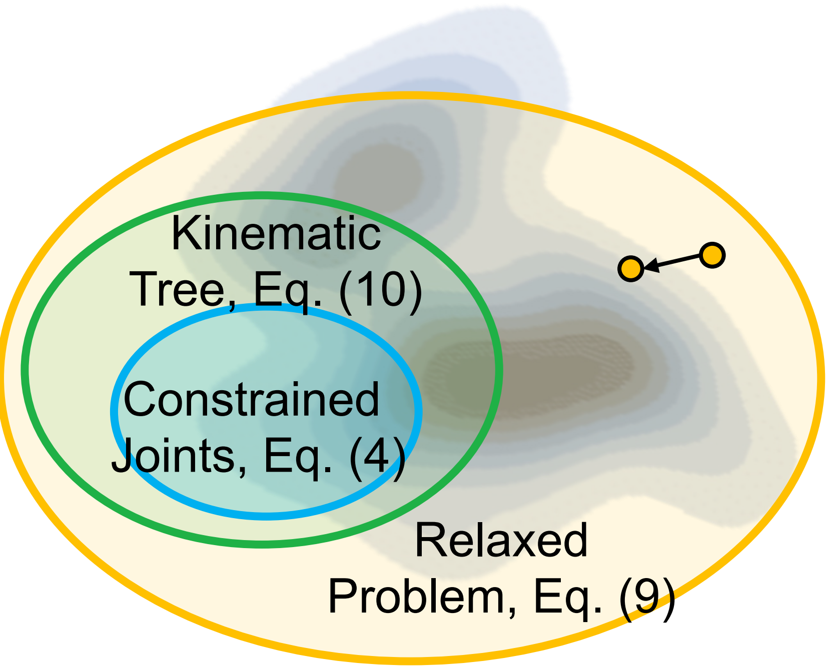
- **Projection**: project to a valid kinematic tree
  - $E_{spatial}$ measures the spatial proximity of parent-child pair
  - E_{1-DOF} measures how close the relative motion to a 1DOF

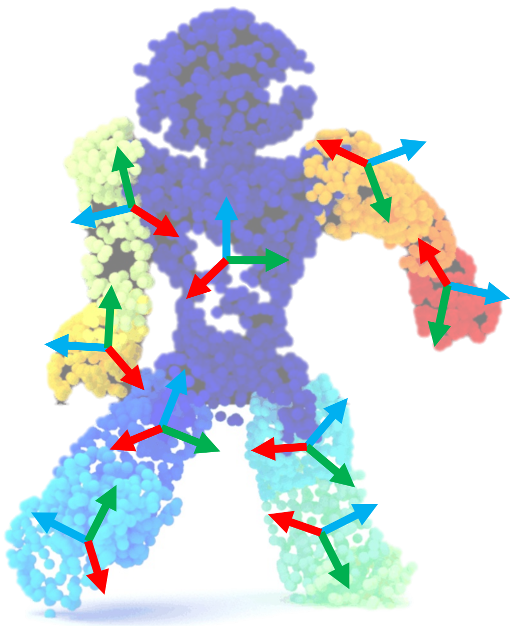
$$E_{\text{project}} = E_{\text{spatial}} + E_{1-\text{DOF}}$$

$$\min_{\Gamma,\{s_i\},\{\theta_i\}^t} E_{\text{project}}\left((\Gamma,\{s_i\},(\{\theta_i\}^t)),\{\hat{T}_i\}^t\right)$$

- **Finetune**: use projection as initialization and re-optimize

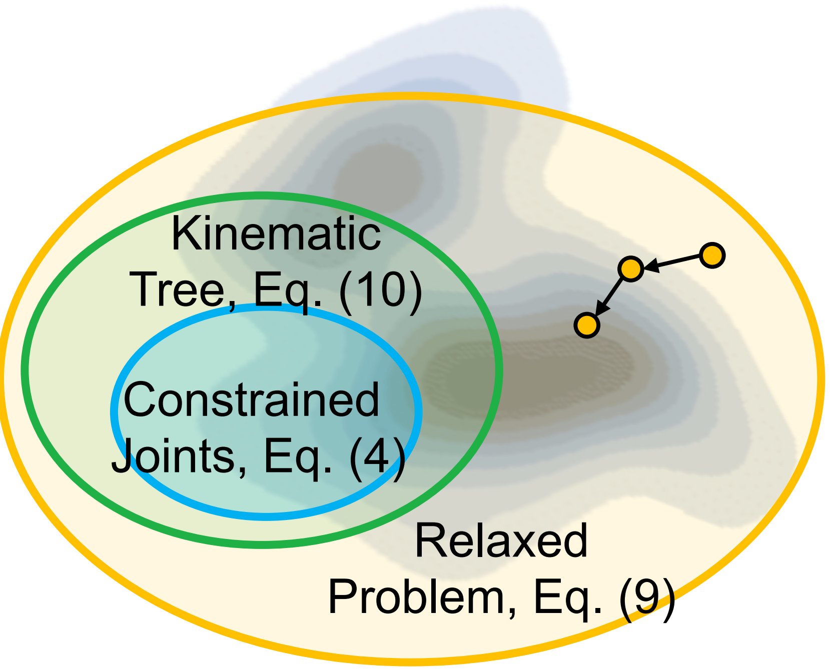
Optimization illustration

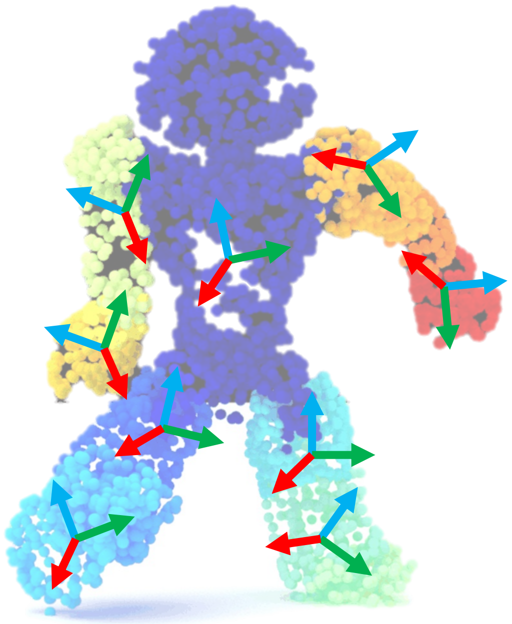




Relaxed Problem
(Part Seg &
Piece-wise 6-DOF Joints)

1. Reason 6-DOF piece-wise rigid model without kinematic constraint (**relaxation**).





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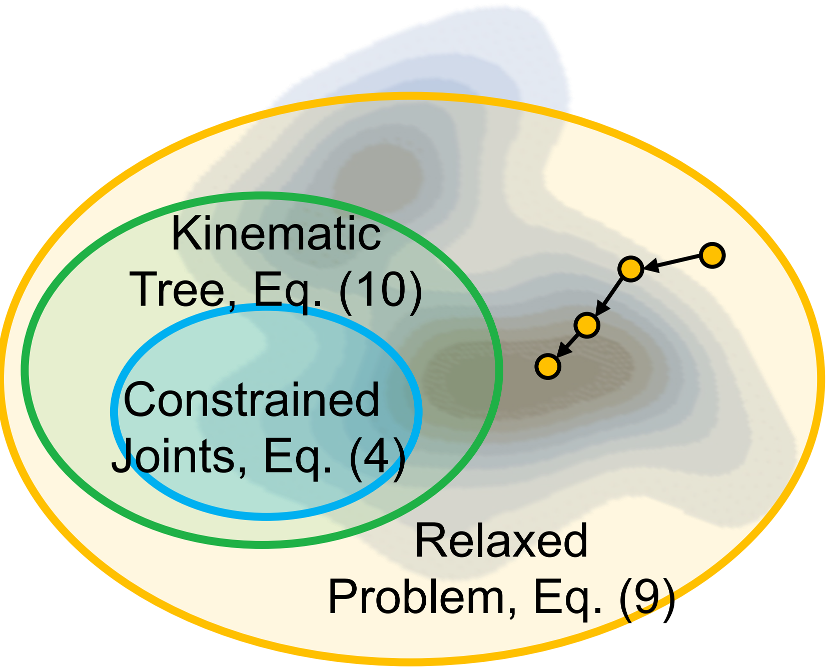

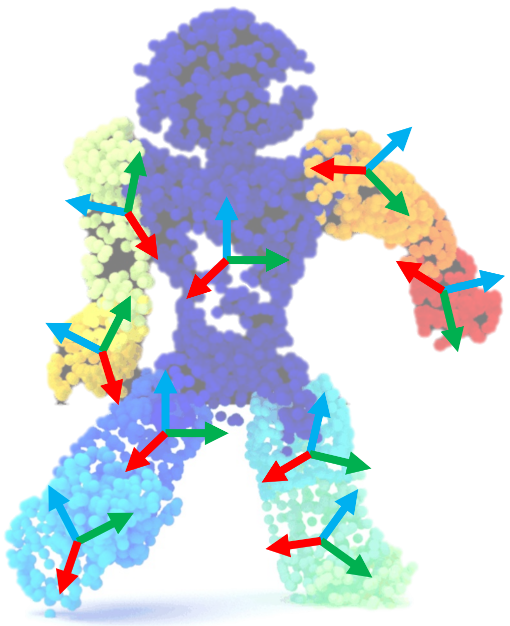

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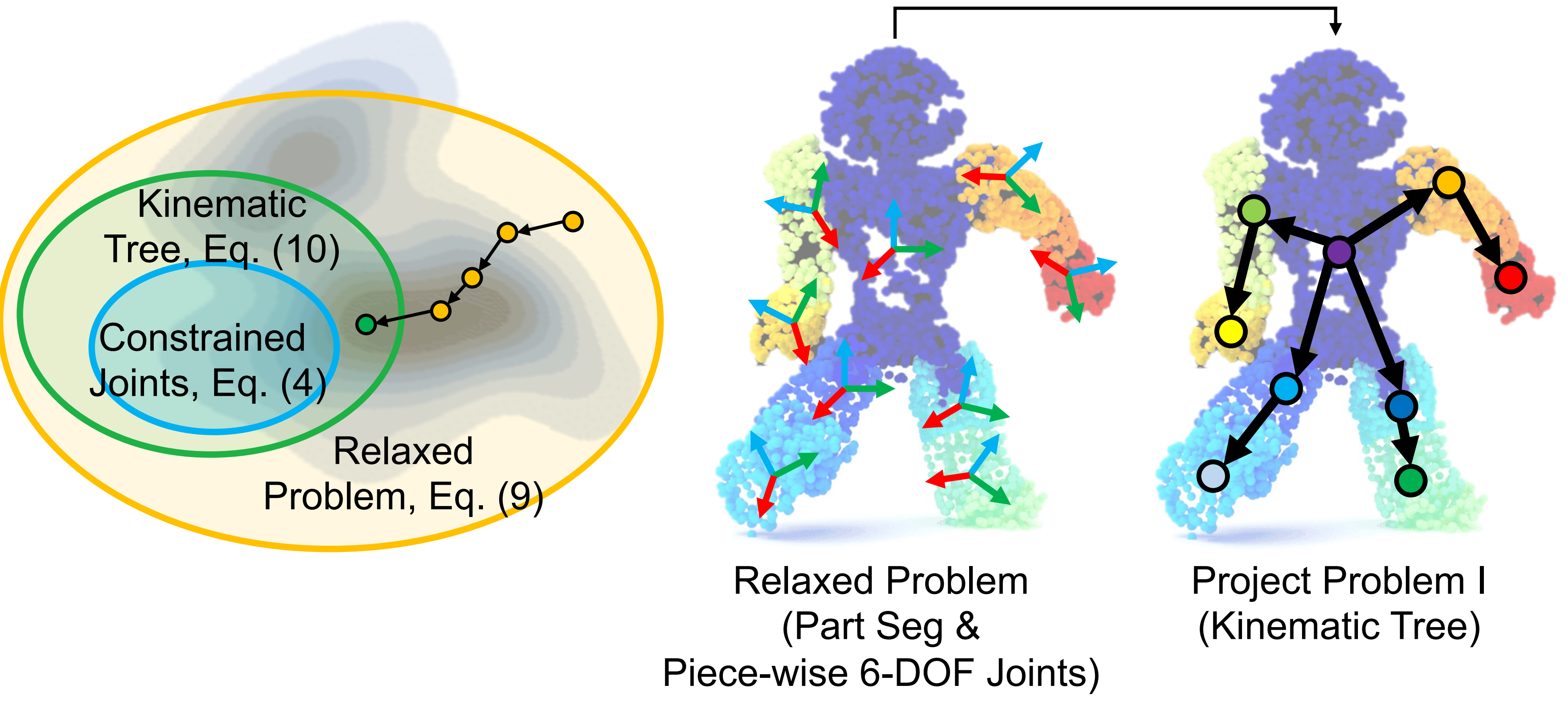
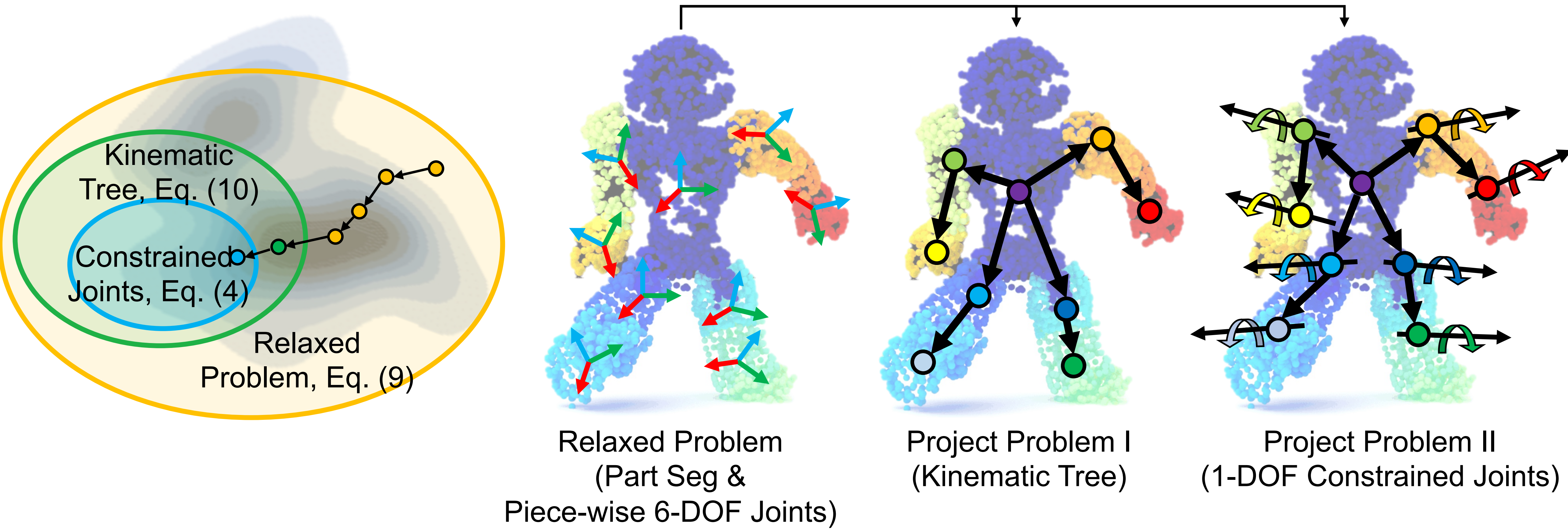
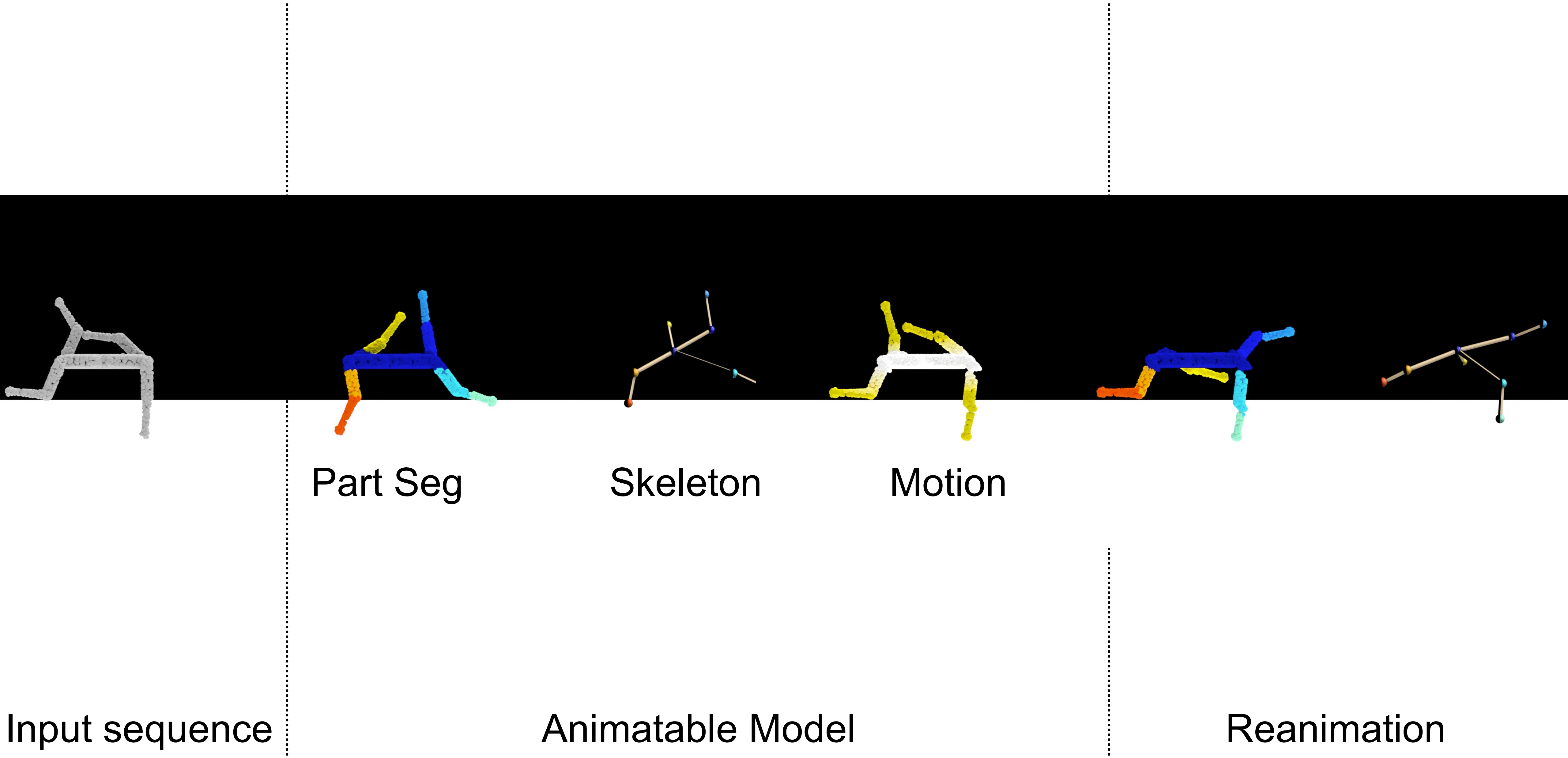


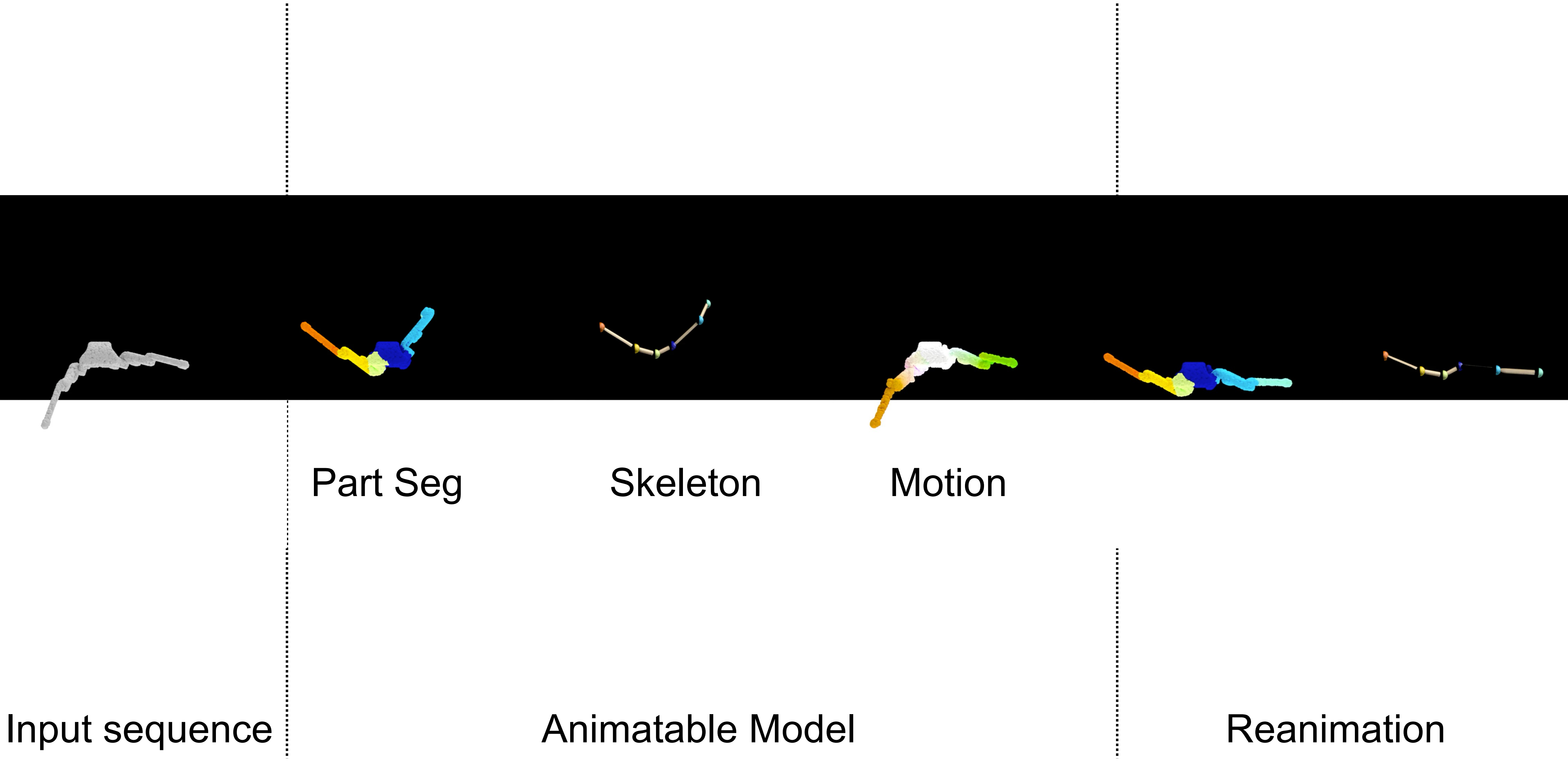
2. Casts the solution to a valid kinematic tree (**projection**).



3. Optimize the 1DOF joint parameters (**fitting**).

Experimental Results on robots


Part Seg
Skeleton
Motion
Input sequence
Animatable Model
Reanimation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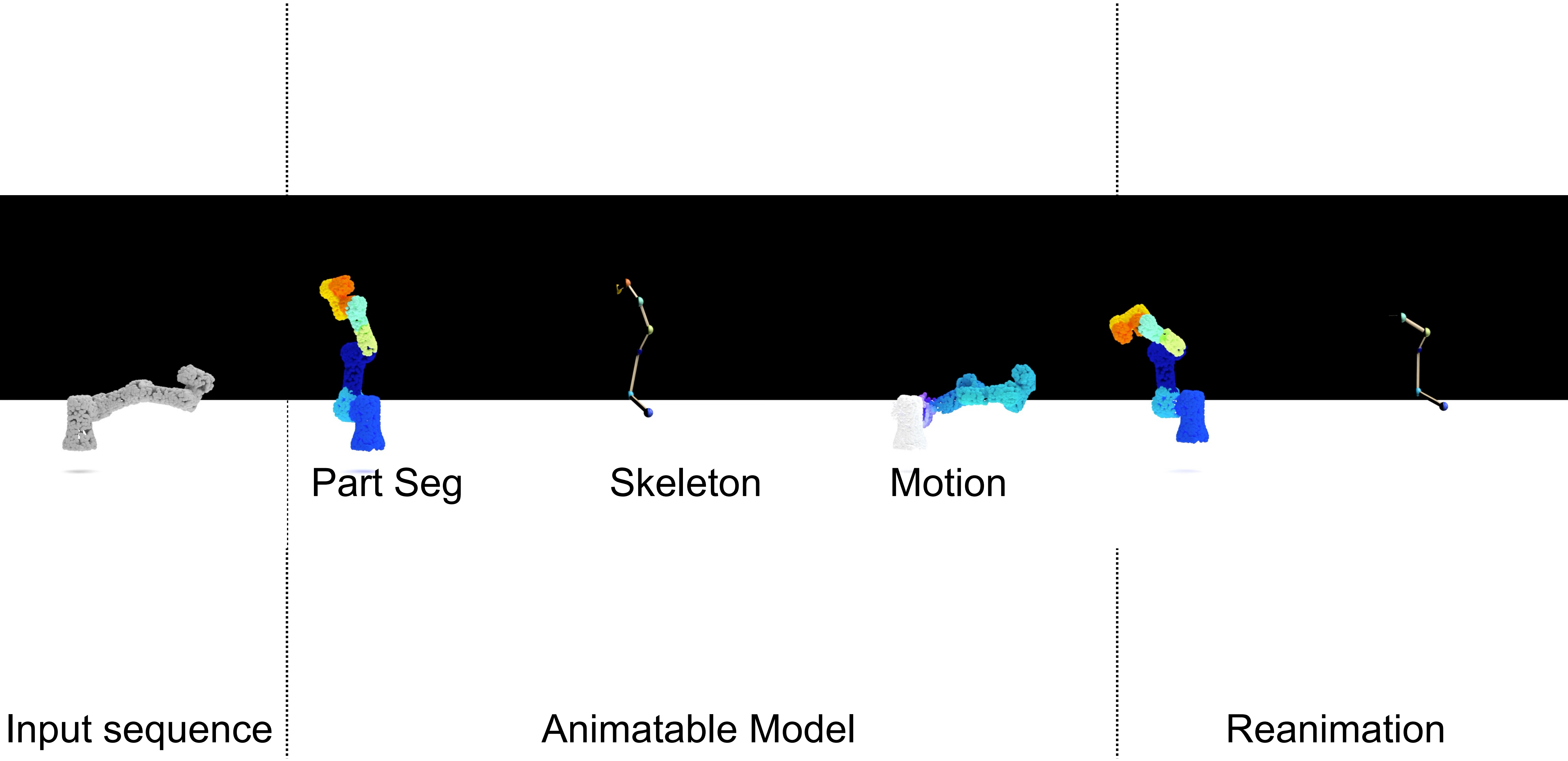
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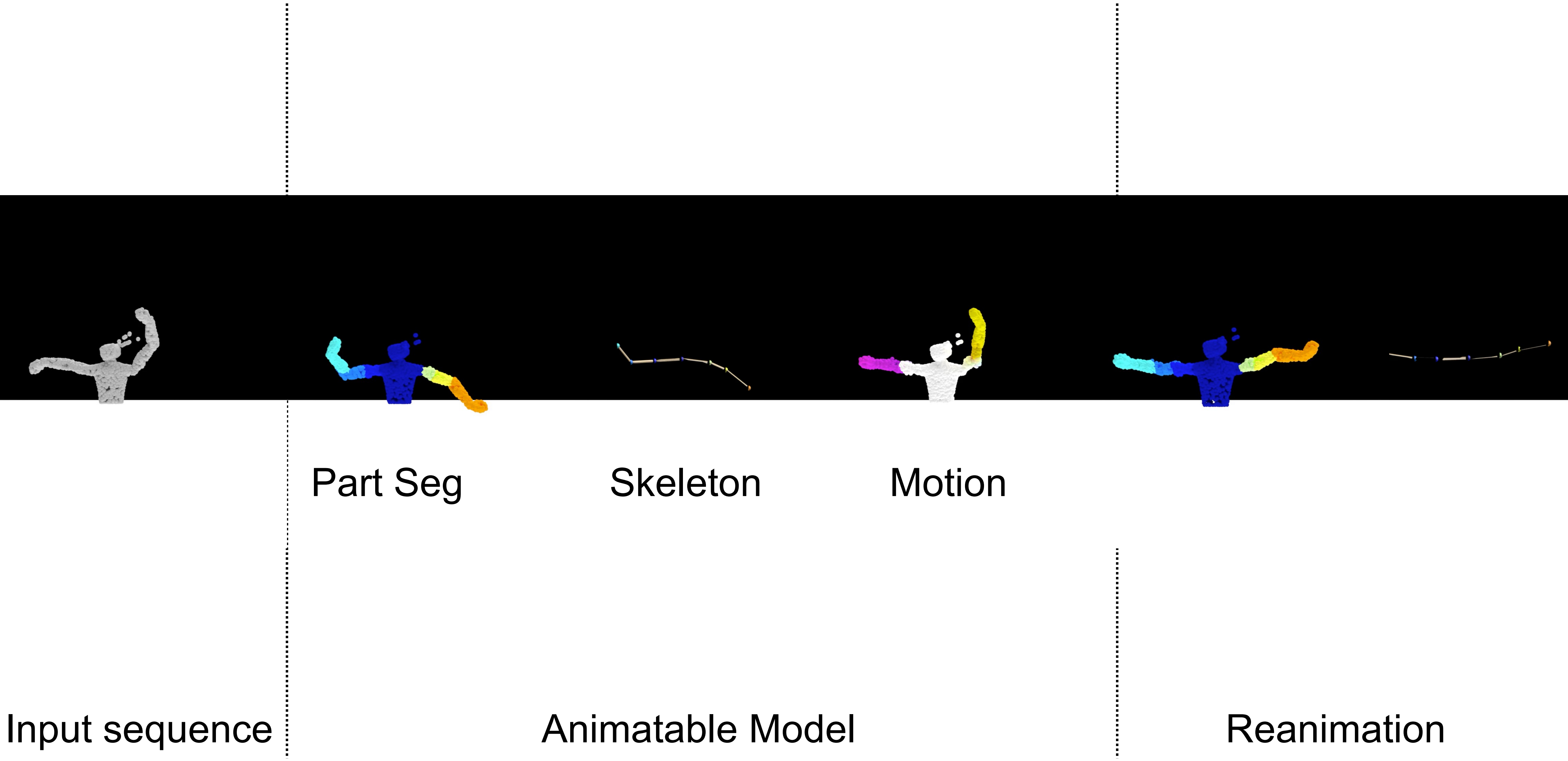
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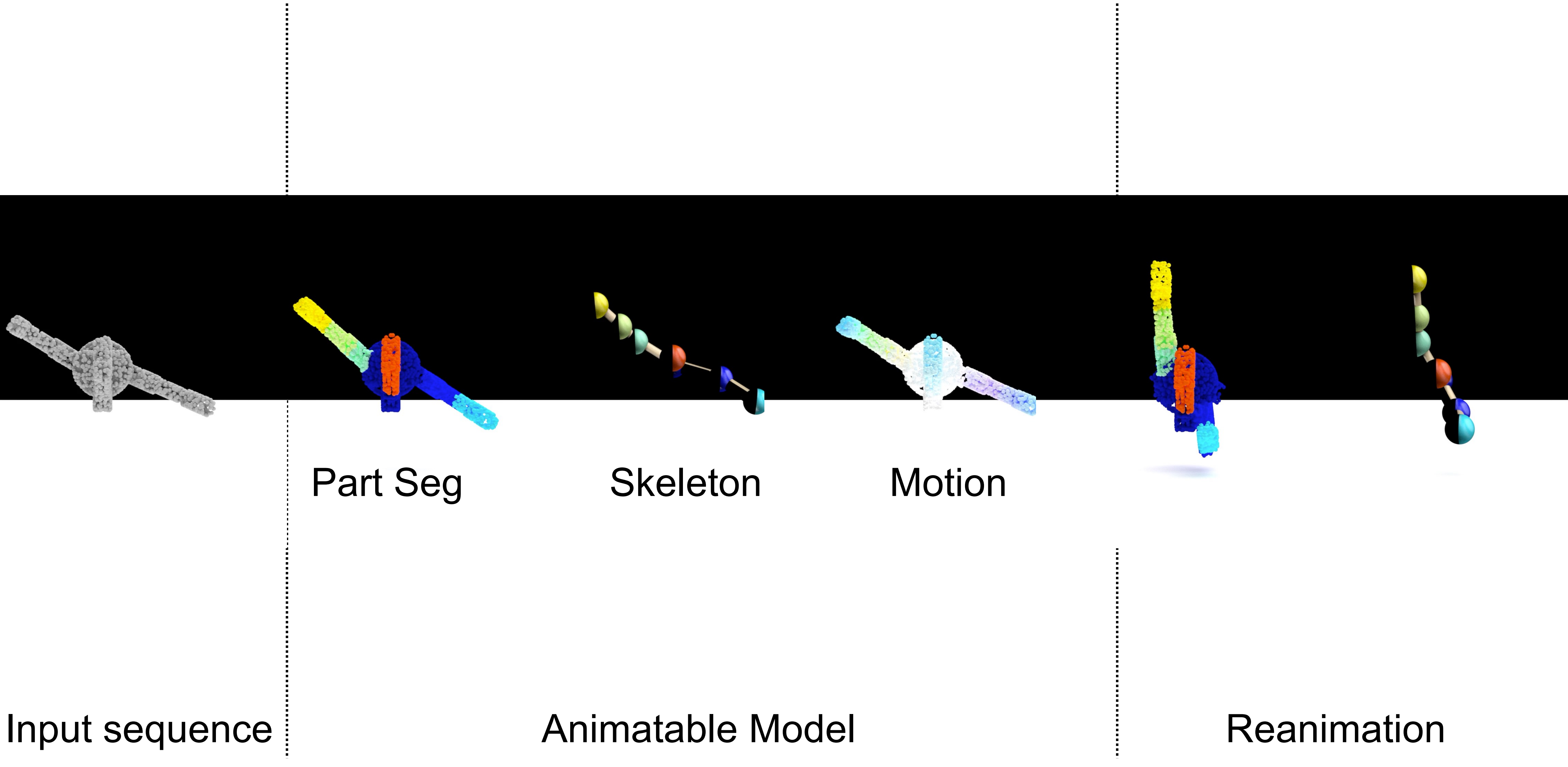
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Skeleton
Motion
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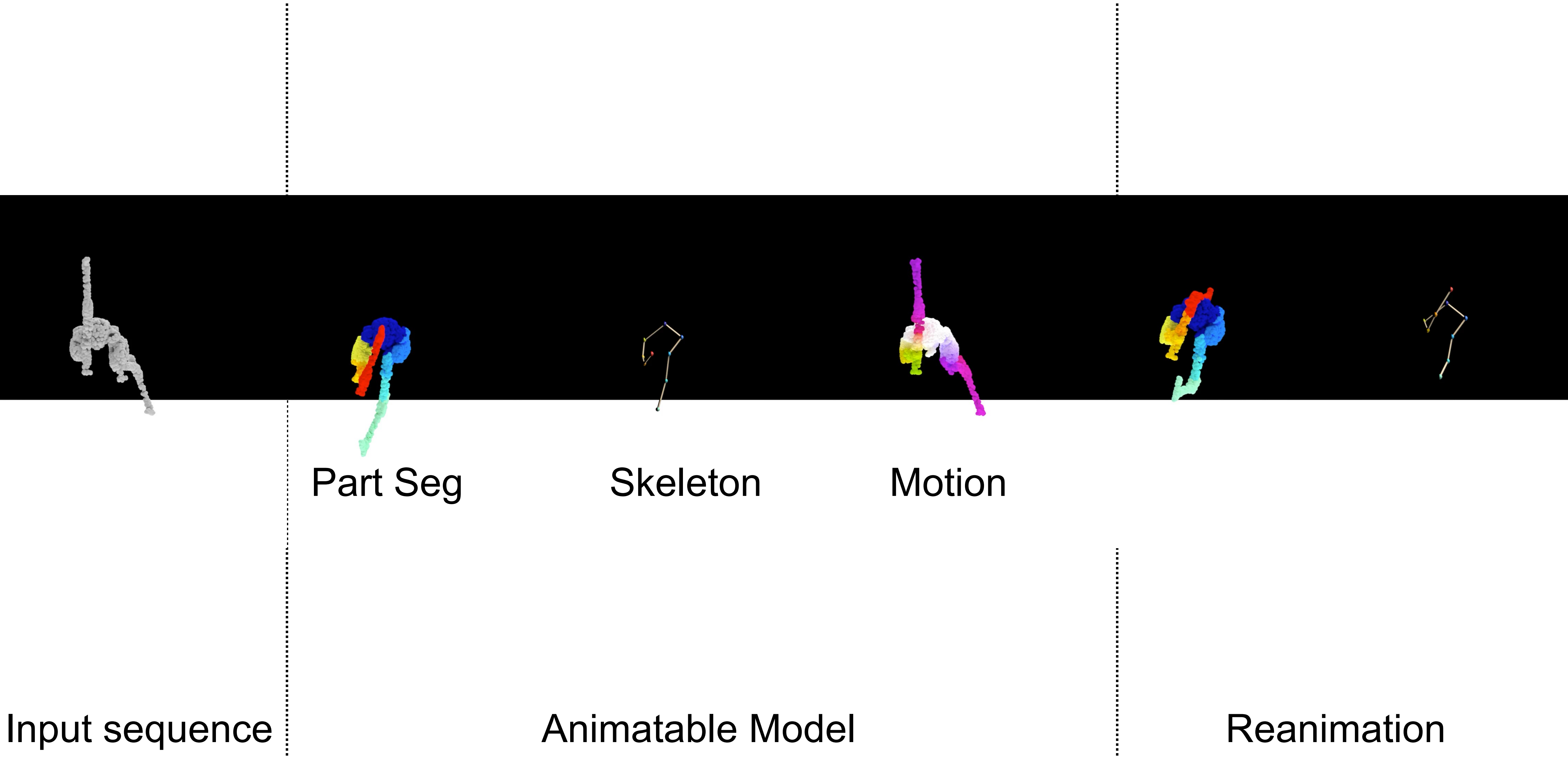
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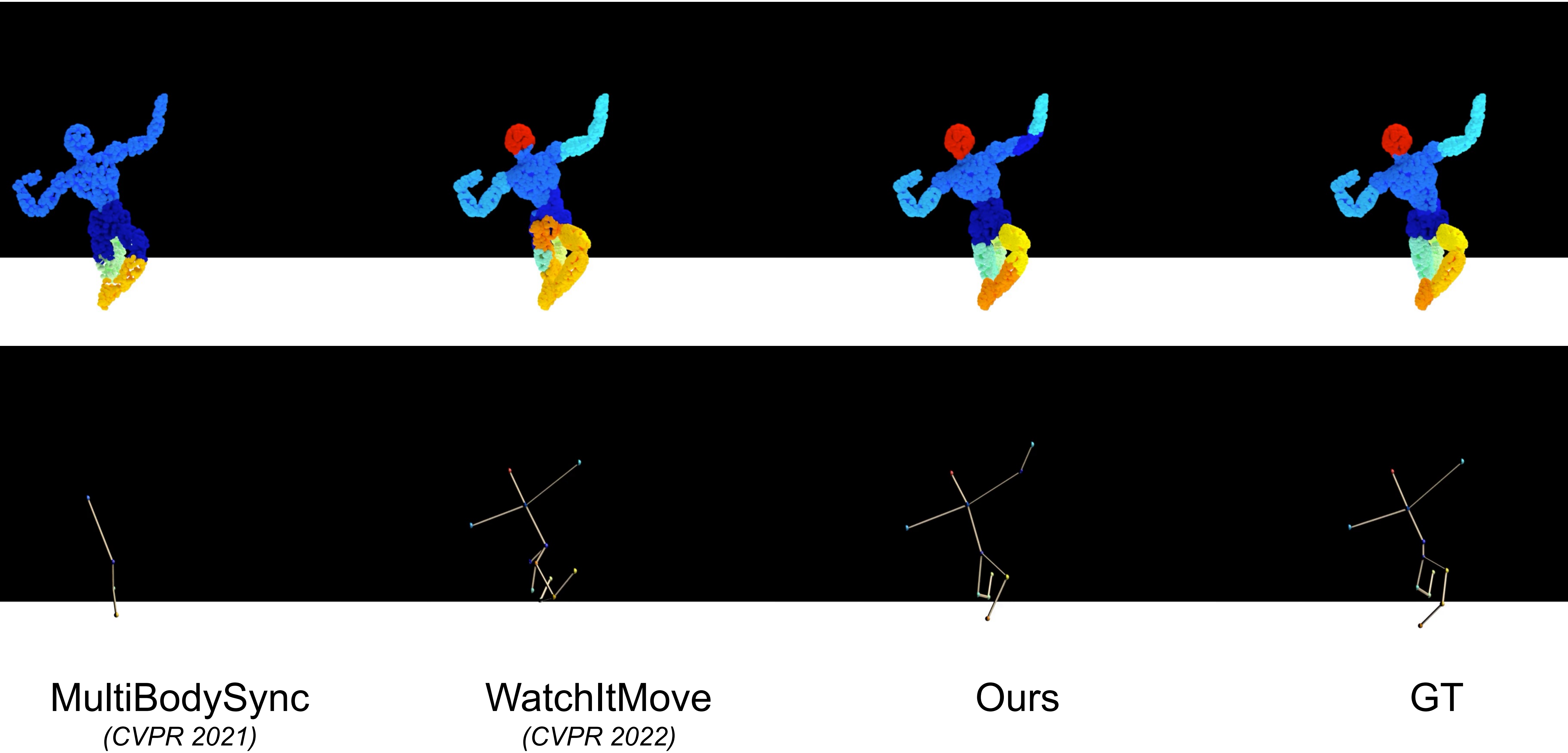
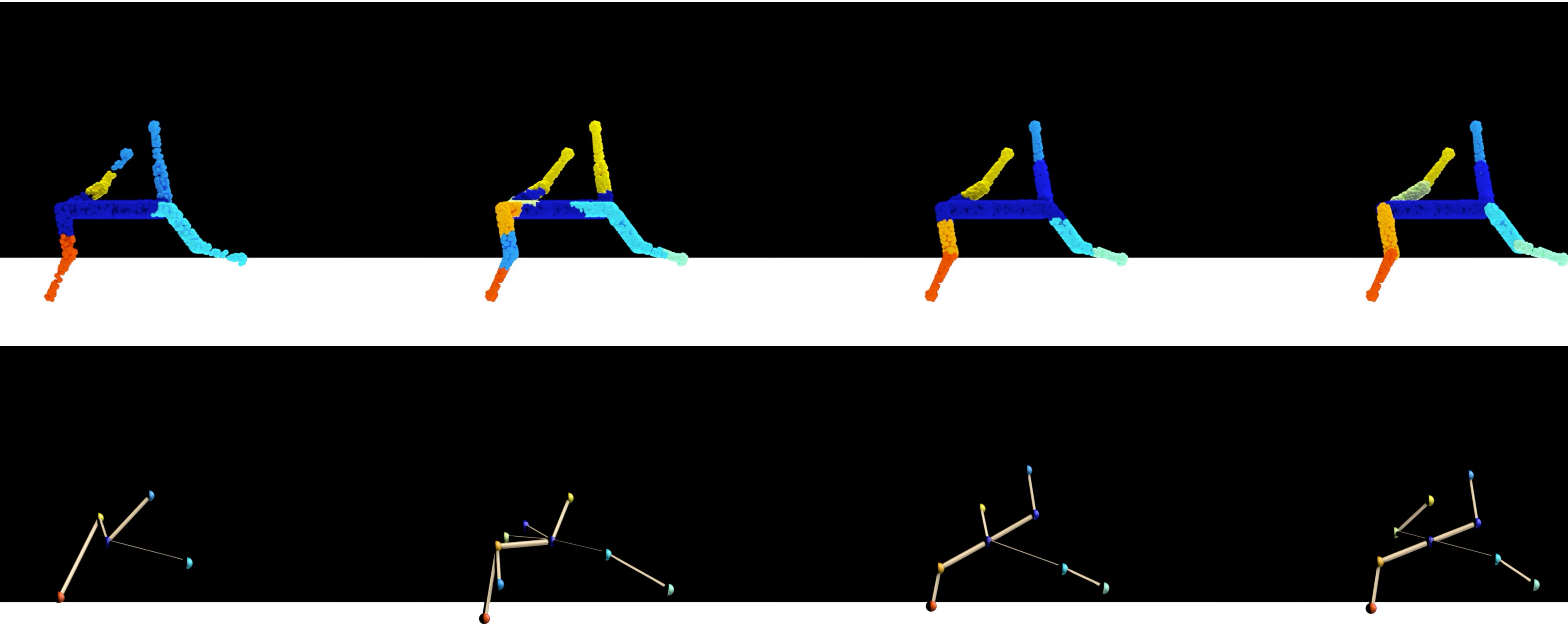
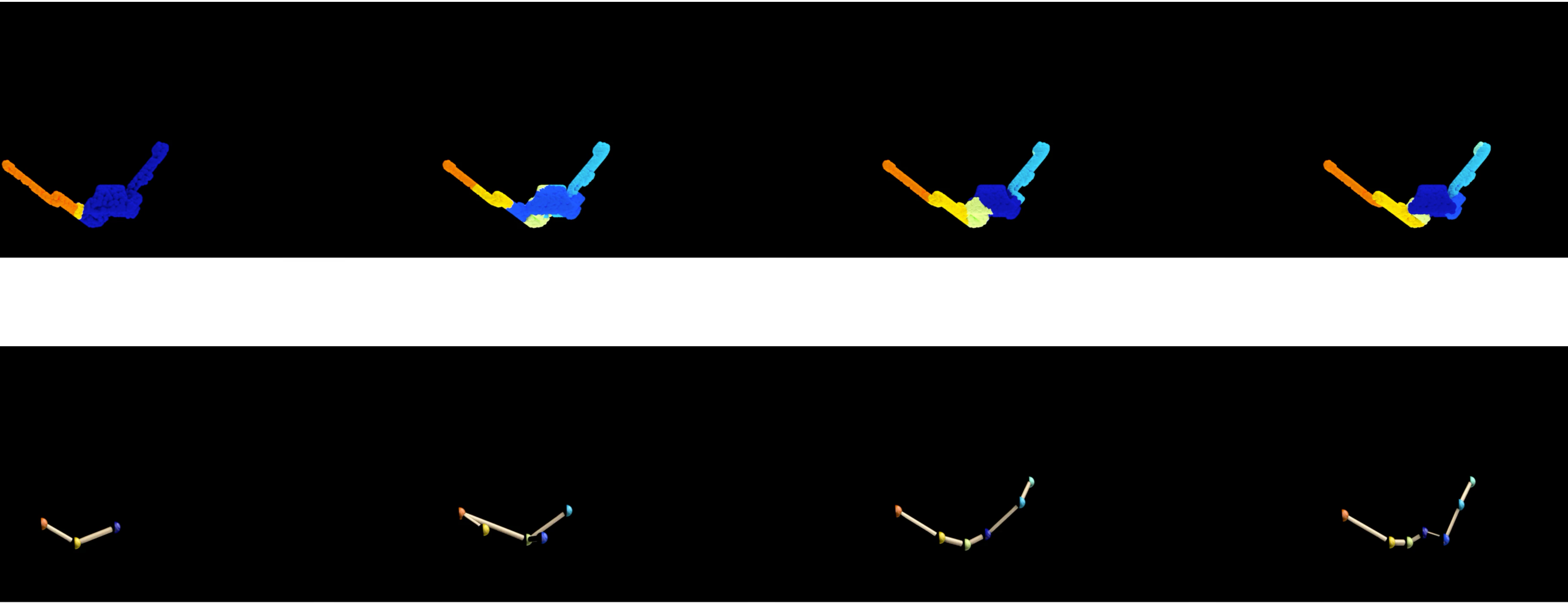
Qualitative Comparison

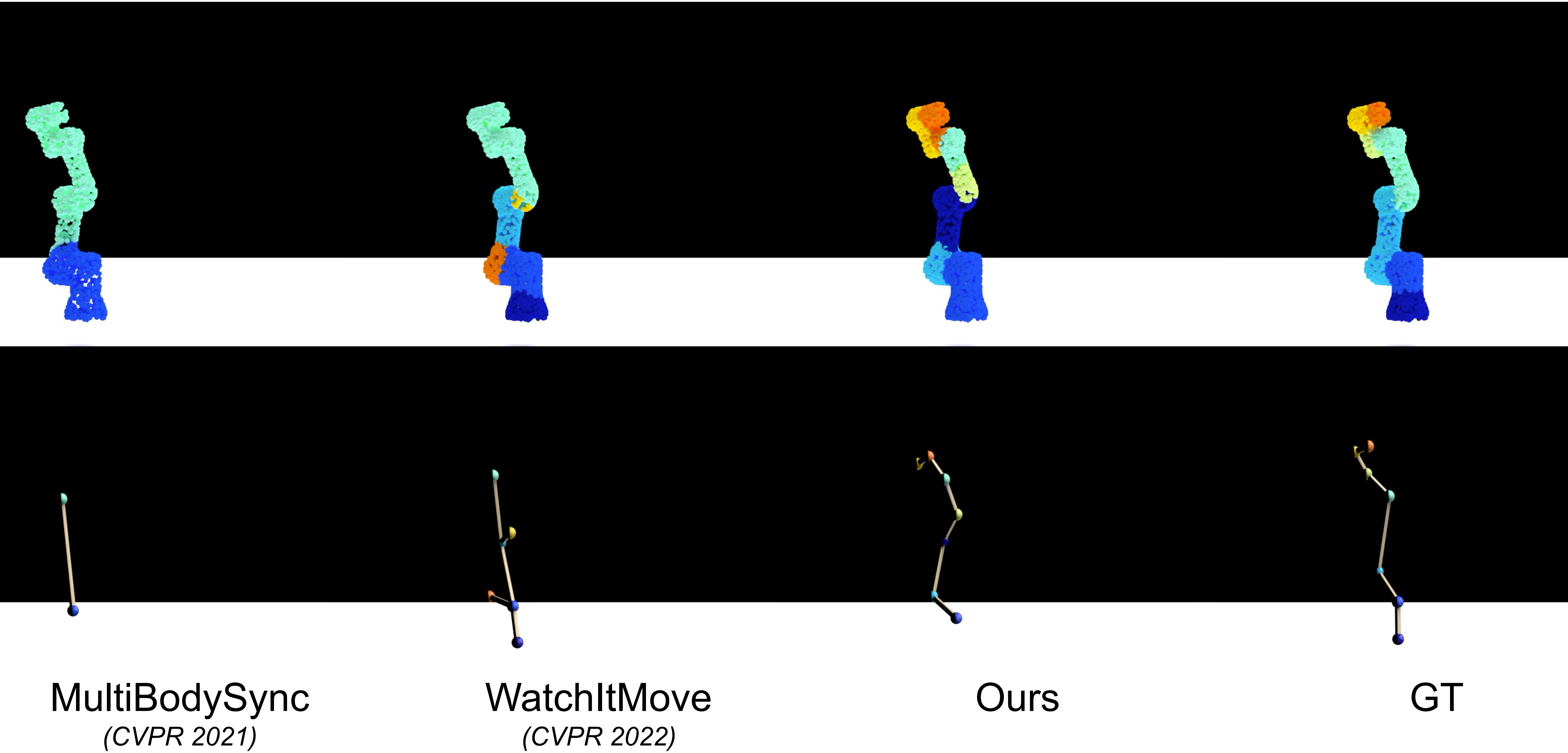

MultiBodySync
(CVPR 2021)
WatchItMove
(CVPR 2022)
Ours
GT



MultiBodySync *(CVPR 2021)* | WatchItMove *(CVPR 2022)* | Ours | GT



MultiBodySync *(CVPR 2021)* WatchItMove *(CVPR 2022)* Ours GT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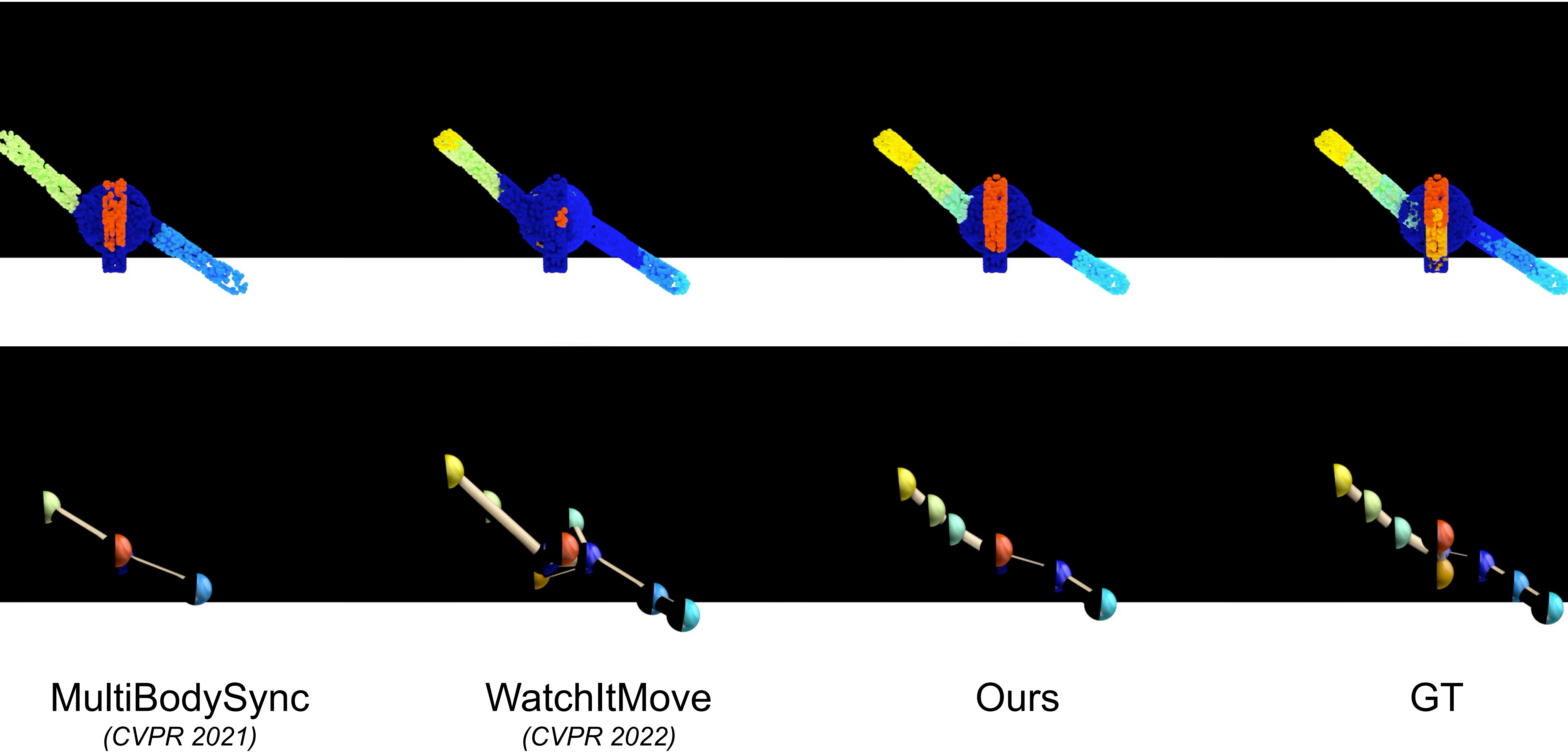
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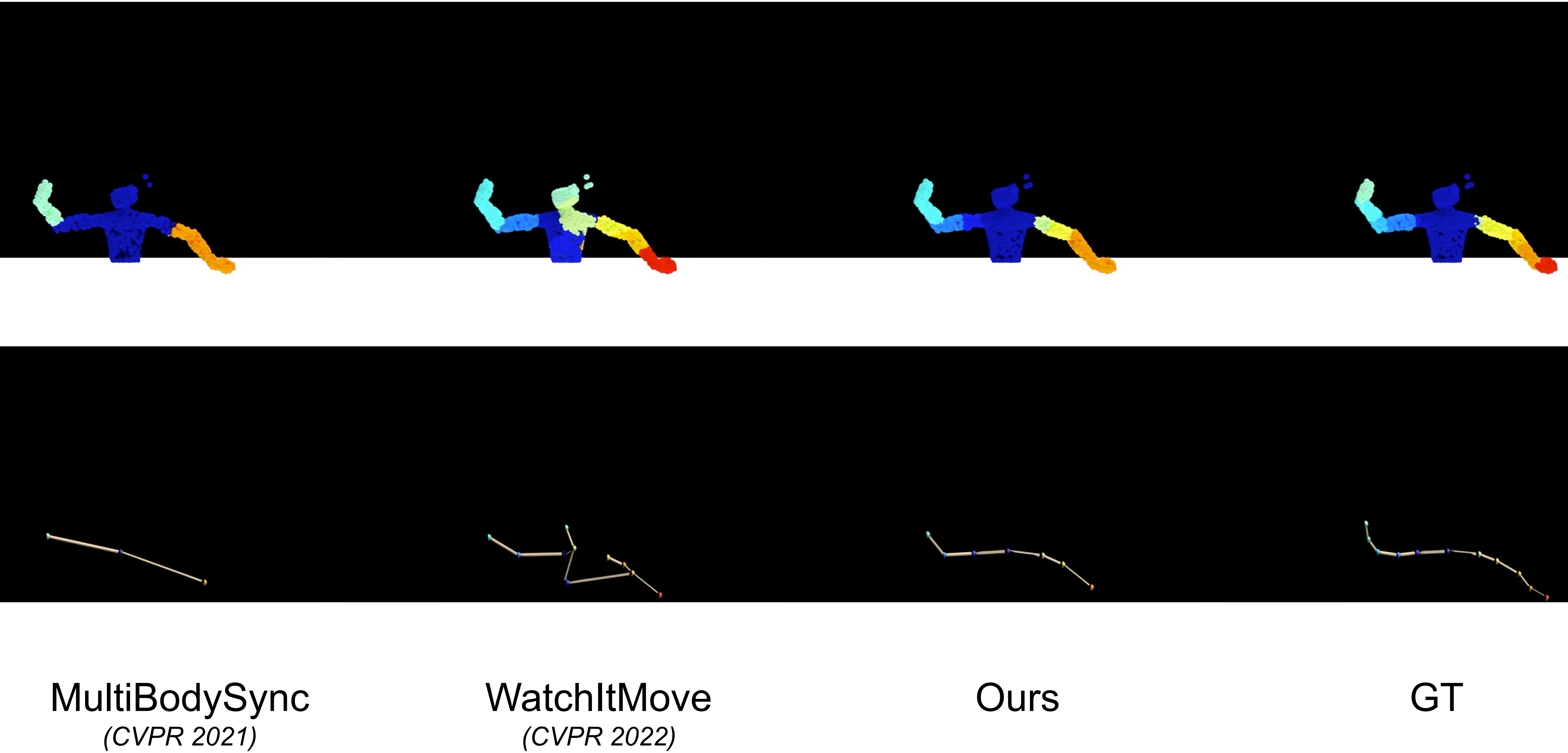
MultiBodySync
(CVPR 2021)
WatchItMove
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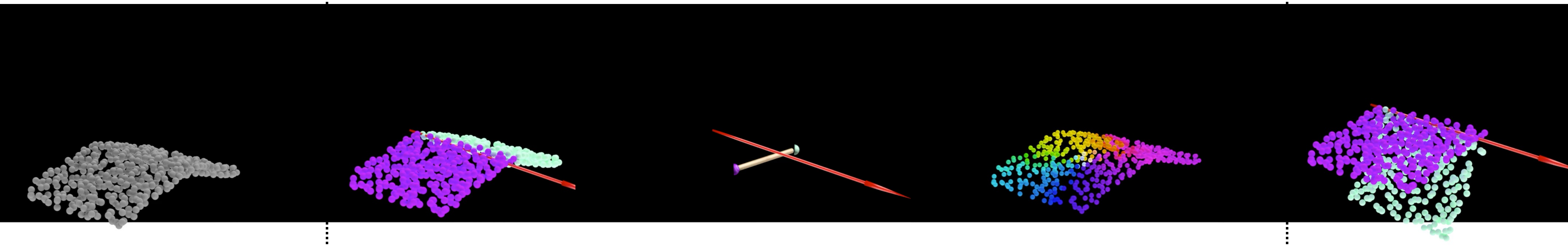
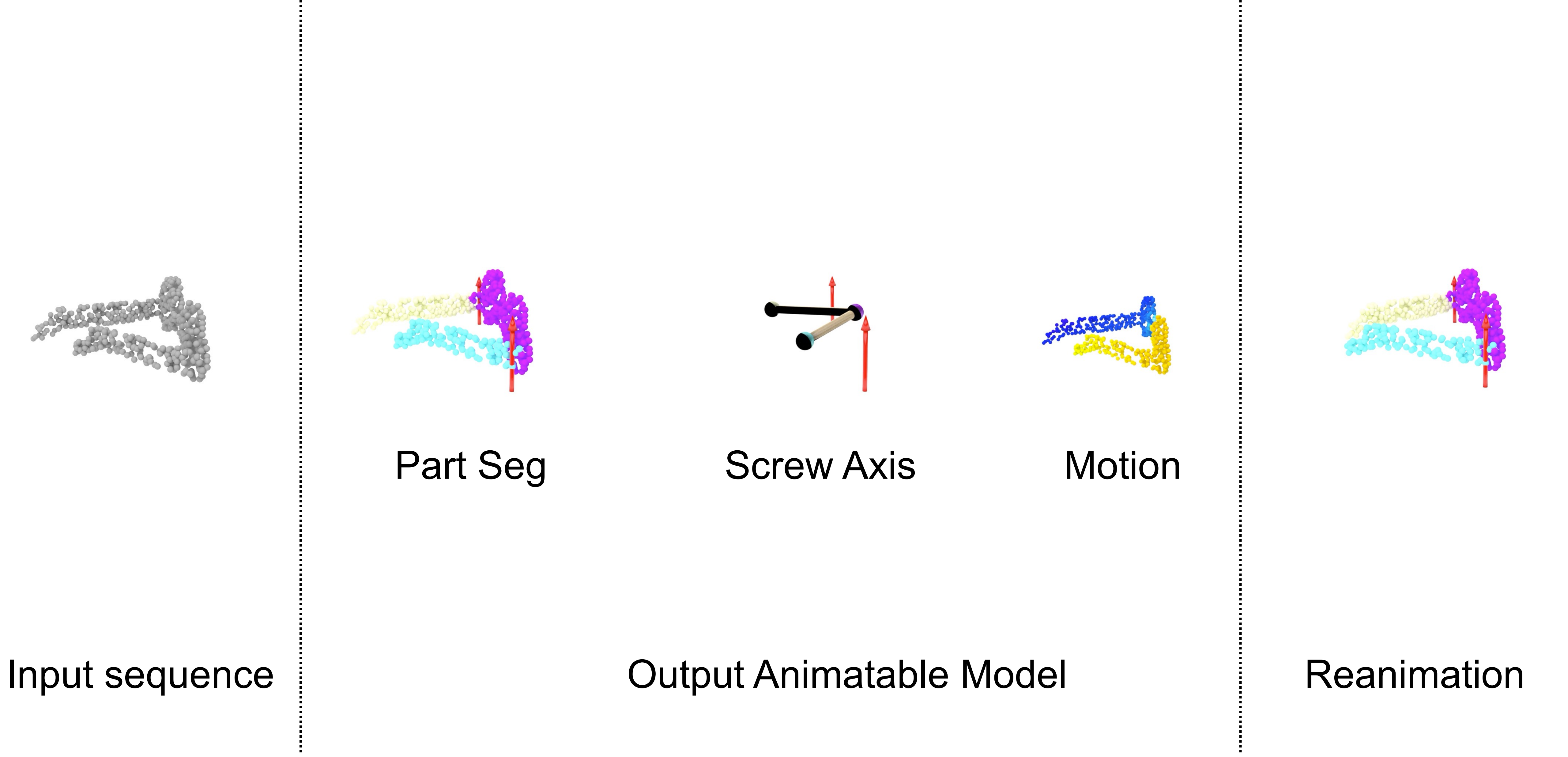
Ours
GT

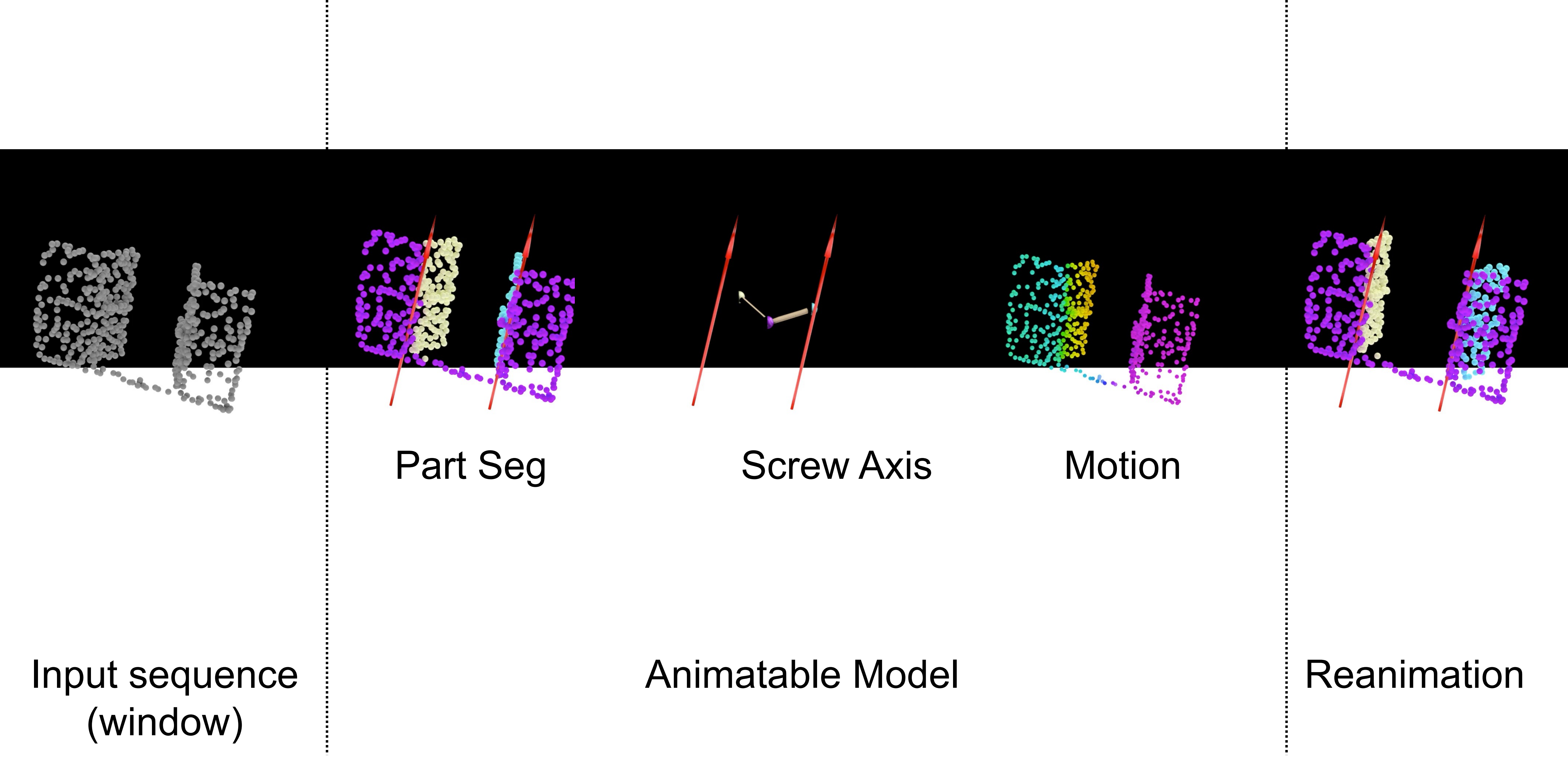
Experimental Results on daily objects

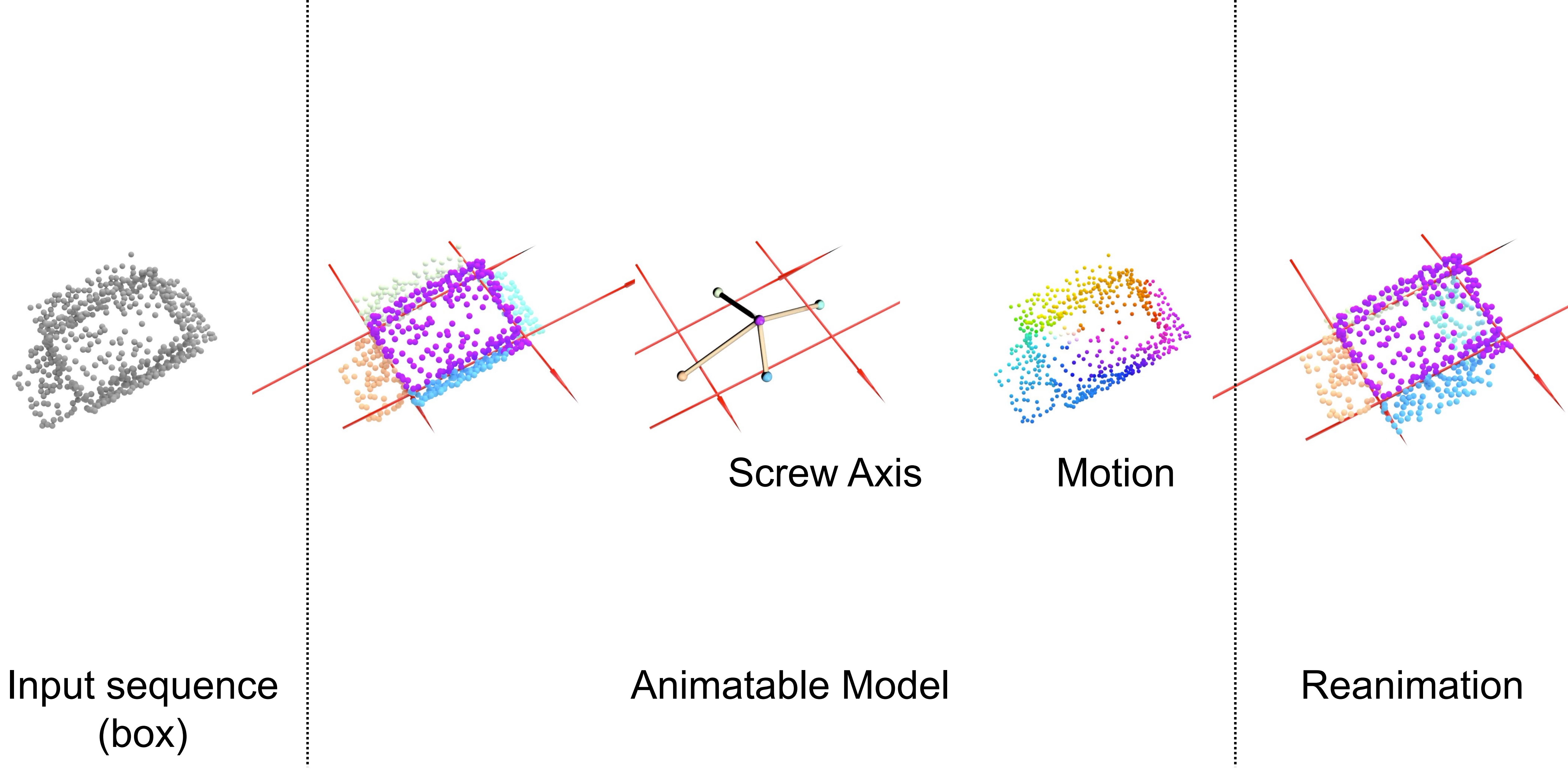


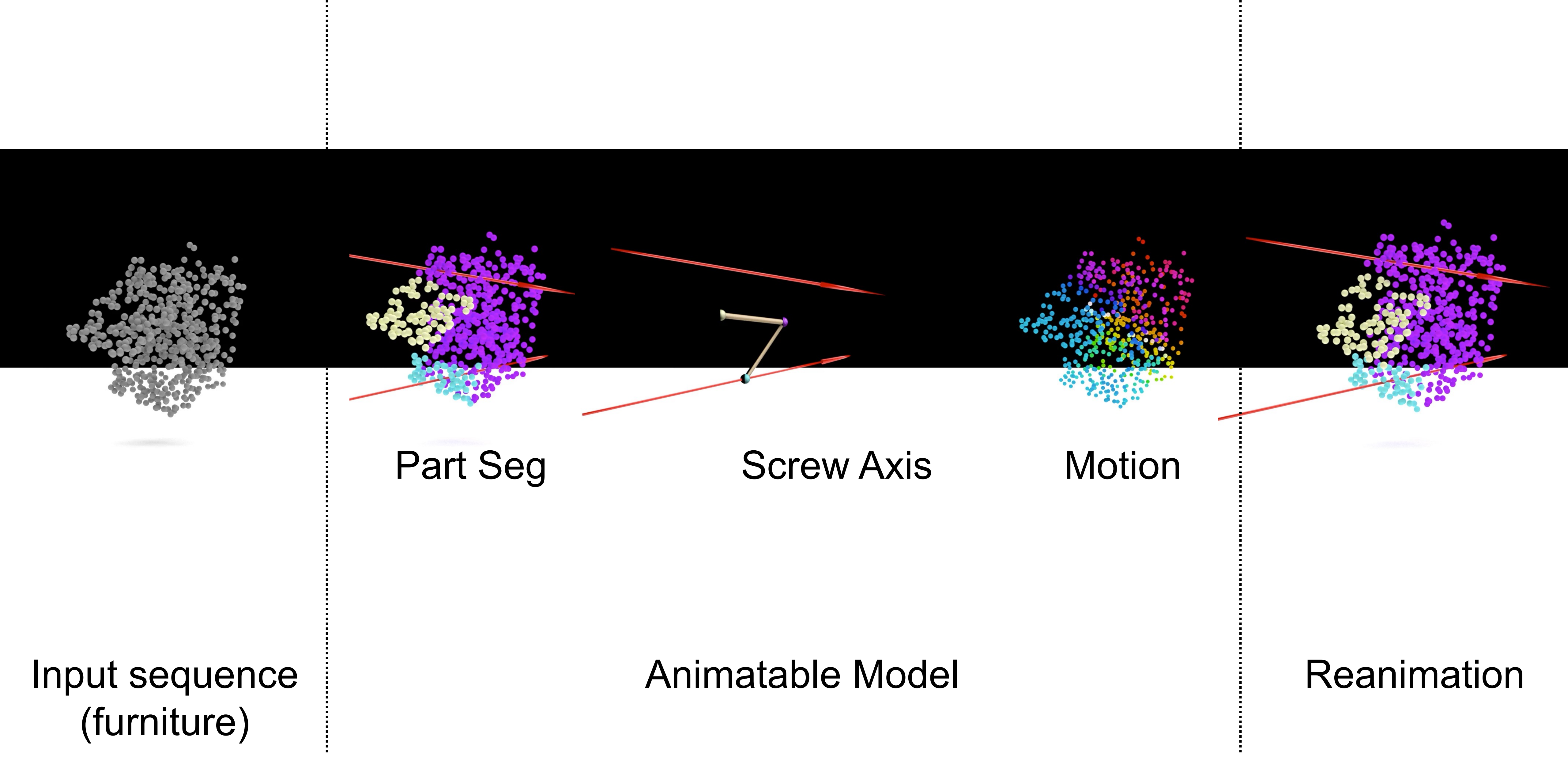
Part Seg | Screw Axis | Motion

Input sequence (laptop) | Animatable Model | Reanimation

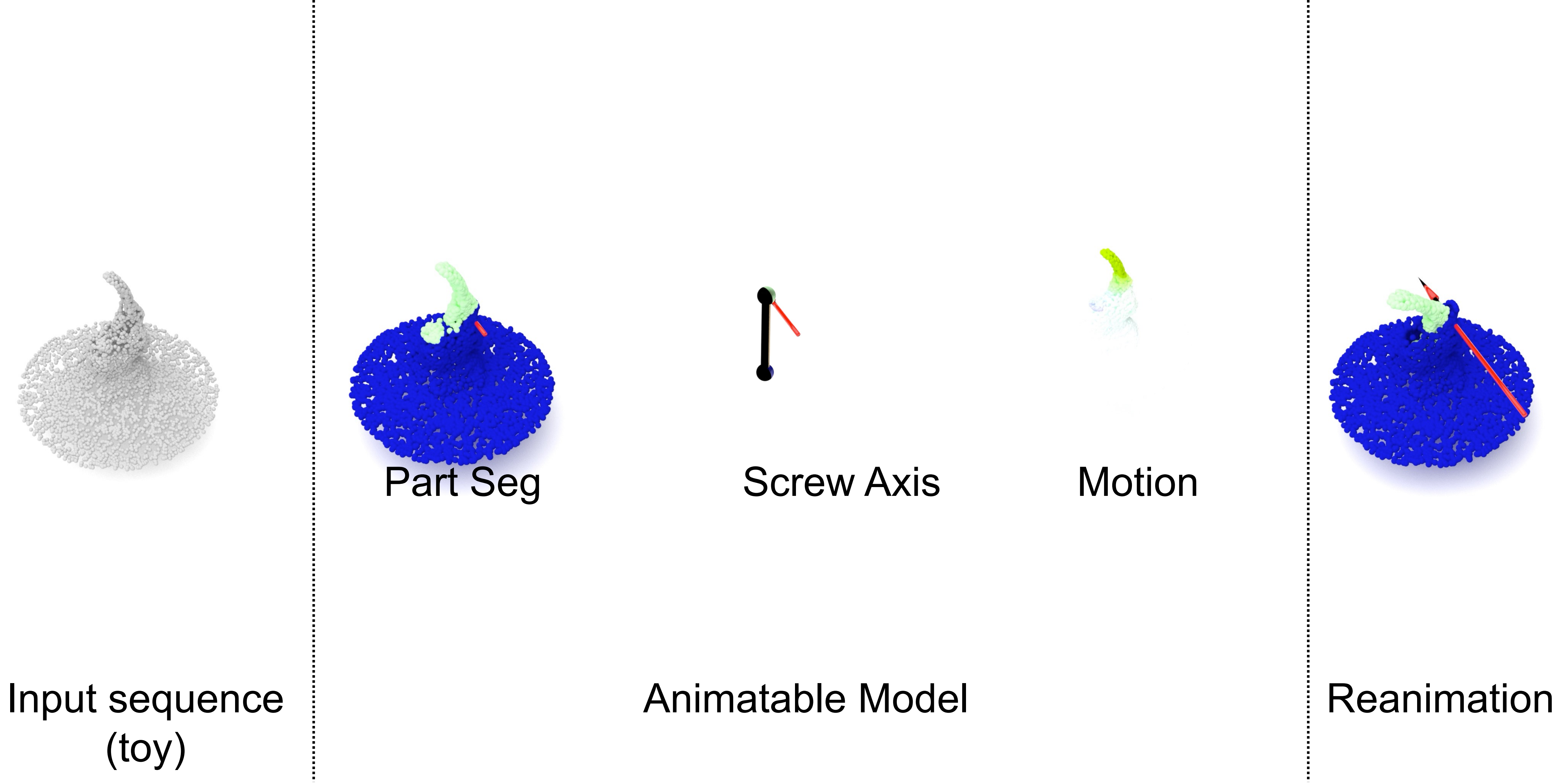

Part Seg
Screw Axis
Motion
Input sequence
Output Animatable Model
Reanimation

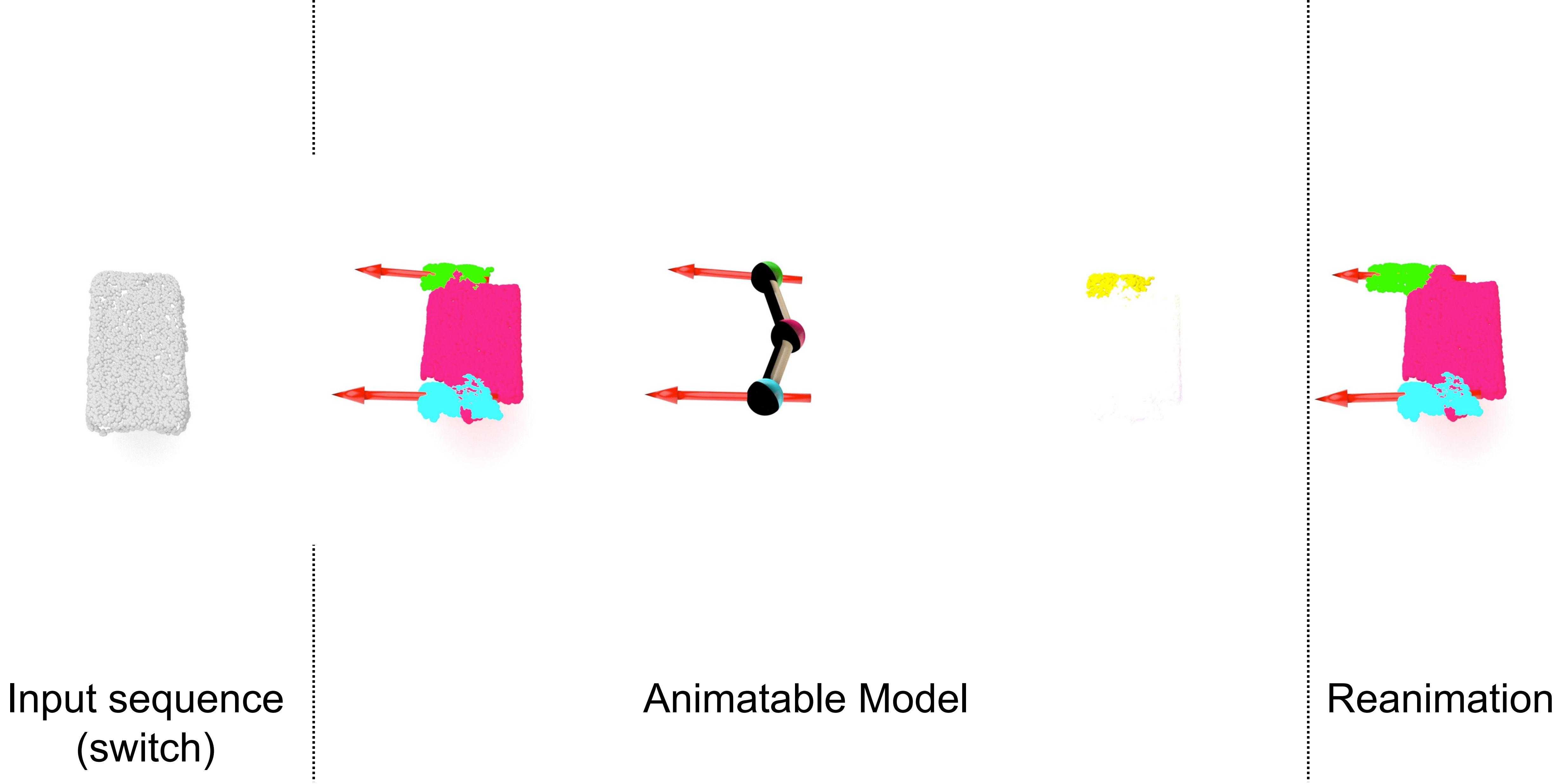

Part Seg
Screw Axis
Motion
Input sequence (window)
Animatable Model
Reanimation


Screw Axis
Motion
Input sequence
(box)
Animatable Model
Reanimation


Part Seg
Screw Axis
Motion
Input sequence
(furniture)
Animatable Model
Reanimation

Experimental Results on real objects


Part Seg
Screw Axis
Motion
Input sequence (toy)
Animatable Model
Reanimation


Input sequence
(switch)
Animatable Model
Reanimation

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JUNE 18-22, 2023 CVPR VANCOUVER, CANADA

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