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Learning Long-term Motion Embeddings for Efficient Kinematics Generation

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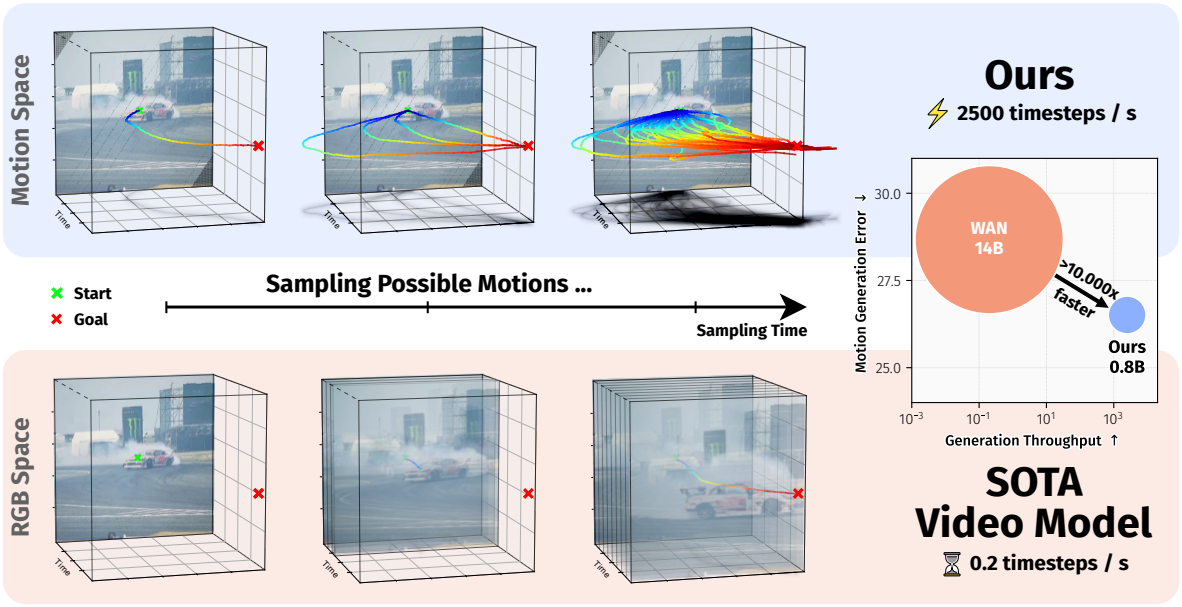


Figure 1. **Our approach enables extremely efficient, goal-conditioned kinematics generation and semantic motion reasoning.** We achieve this by learning a dense, temporally compressed motion space that allows goal-conditioned motion generation to be orders of magnitude faster than prior video models. While a video generative model has barely produced the first frame, our method can already generate multiple plausible motion trajectories connecting the start and goal, offering both speed and interpretability.

Abstract

Understanding and predicting motion is a fundamental component of visual intelligence. Although modern video models exhibit strong comprehension of scene dynamics, exploring multiple possible futures through full video synthesis remains prohibitively inefficient. We model scene dynamics orders of magnitude more efficiently by directly operating on a ***long-term motion embedding*** *that is learned from large-scale trajectories obtained from tracker models. This enables efficient generation of long, realistic motions that fulfill goals specified via text prompts or spatial pokes. To achieve this, we first learn a highly compressed motion embedding with a temporal compression factor of* $64\times$*. In this space, we train a conditional flow-matching model to generate motion latents conditioned on task descriptions. The resulting motion distributions outperform those of both state-of-the-art video models and specialized task-specific approaches.*

1. Introduction

Understanding and predicting motion is a fundamental trait of visual intelligence, yet current learning-based approaches with the goal of understanding and generating motion either focus on low-level motion information (optical flow or spatially sparse tracks) or conflate motion with appearance in video generative models, ultimately having to model per-pixel changes over time and requiring large amounts of compute to model this high-dimensional signal. In this paper, we propose to address these limitations by learning a long-term *motion embedding*: a compact, semantic latent

* Equal Contribution
Experimentation, including use of pre-trained models, was completed by university collaborators

representation that aggregates global kinematic structure, integrates information across trajectories, and models how motion evolves over extended time horizons. Unlike flow, which describes only instantaneous displacements, or tracks, which record sparse point correspondences, our embedding learns a continuous, scene-level representation of motion dynamics that generalizes beyond the observed samples and supports reasoning and generation in a unified latent space.

Our approach is rooted in two insights. First, learning useful motion representations requires more than tracking what moves: it demands reasoning about how things *can* move, how motions aggregate across objects, and forecasting what complex future behaviors are plausible in a given scene. Second, while direct modeling of video [13, 43, 48] or flow [30, 34] provides access to rich visual signals, these representations are high-dimensional and computationally intensive, and they cannot be strongly temporally compressed without significant information loss. In contrast, trajectories (tracks) are far more compact and interpretable, but lack the ability to generalize or aggregate motion contextually, and remain limited to the specific points sampled by the tracker.

To address these limitations, we introduce a two-stage framework that learns and predicts in a motion space for long-term kinematics. As the first step, we train a model to map sets of sparse tracker-derived motion samples into a continuous latent embedding. Unlike raw tracks, our latent motion space can be queried at any spatial position, enabling dense, context-aware motion predictions that go far beyond the tracker inputs. Secondly, we leverage the learned motion space for higher-order generative reasoning: a conditional flow matching model operates directly in the motion space, generating plausible, goal-directed motion under complex prompts such as text or spatial queries.

Our motion space thus sits at a new level of abstraction: longer than flow, richer than tracks, and far more efficient than video. It aggregates global kinematic context, supports reasoning about motion beyond observed samples, and provides a standardized interface for downstream models. By focusing on kinematics, i.e., how things *can* move, not just what happens frame-to-frame, we enable new forms of motion reasoning and generative modeling not possible with prior representations.

We demonstrate that our approach delivers substantial efficiency and reasoning gains across diverse motion tasks, outperforming raw tracks and enabling controllable motion generation with orders of magnitude greater compression than video models. Our framework thus establishes motion spaces as a powerful substrate for both large-scale motion understanding and semantic kinematics generation.

Contributions:

1. We propose a long-term motion embedding that captures the essential motion patterns of a scene from a single image, avoiding the overhead of full video generation.
2. We develop a goal-conditioned motion generator trained via flow matching on open-set data for efficient generative motion reasoning, operating entirely on the learned motion embedding.
3. We show that strong temporal compression improves learning, yielding better motion quality, more coherent dynamics, and faster training and inference.
4. Through extensive evaluations on open-set internet videos and robotics benchmarks, we show that our approach outperforms specialized trajectory predictors and video-based baselines while being substantially more efficient.

2. Related Work

Motion Representations Learning compact representations of motion has been studied from several perspectives, ranging from classical trajectory modeling to modern autoencoder-based approaches. Early works such as *An Uncertain Future* [42] explored stochastic VAEs for predicting future motion conditioned on a single image. More recent efforts adopt masked autoencoding or vector quantization to reconstruct trajectories or motion fields. Examples include trajectory autoencoders for anomaly detection or policy learning [2, 11], and two-stage models such as WHN [9] that encode dense grid trajectories and generate in latent space without temporal compression.

In contrast, our goal is to learn a *semantic and structured motion space* that captures generic kinematics to enable open-domain planning.

Motion in Video Models Most modern generative video models implicitly learn motion alongside appearance synthesis. Large-scale diffusion architectures such as Wan [43], Veo 3 [13] and others [1, 8, 17, 48] predict future frames without an explicit notion of motion. While such models excel at visual fidelity, the learned motion is entangled with texture and lighting, making kinematic reasoning and control difficult. Moreover, latent video autoencoders typically employ modest compression ratios (typically $4\times$–$8\times$), as stronger compression severely degrades visual detail. These modest compression ratios imply that large compute budgets are often needed to learn useful video generative models. Recent works have also explored world modeling in pre-trained feature spaces rather than RGB pixels, for example, by predicting the temporal evolution of DINO [31] features [3, 22, 53]. These approaches demonstrate that dynamics can be learned efficiently in a latent representation space, yet they do not provide an explicit notion of motion or kinematic structure. Their dense feature dynamics remain entangled with appearance and lack the interpretability and controllability of explicit trajectory-based motion representations. In contrast, our method models motion directly

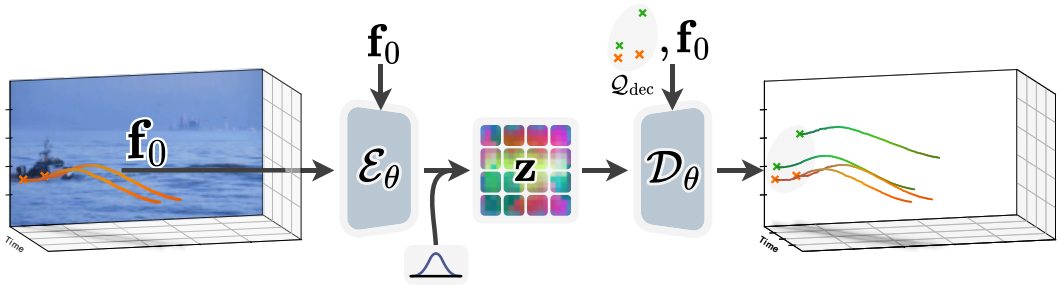


Figure 2. **Our approach to learn a dense motion space.** Sparse tracker trajectories and the start frame are encoded into a latent motion grid, which enables dense reconstruction at arbitrary spatial query points. The model jointly attends over trajectory tokens and frame features, producing temporally consistent, spatially dense motion predictions.

through sparse trajectories in a dedicated latent space, yielding a compact and semantically structured representation of kinematics.

Motion-conditioned Video Generation A separate line of work explicitly models motion as an intermediate representation before video synthesis. Motion I2V [34], MoVideo [25], and MOFA [30] first generates optical flow or depth maps that guide subsequent frame generation. VideoJam [10] combines motion and appearance branches through joint diffusion, while dragging-based methods [7, 15, 35, 36, 46] manipulate motion vectors interactively to steer local frame changes, provide intuitive spatial or semantic control over motion dynamics. Although these models explicitly handle motion, it remains defined at the pixel level and tied to visual rendering. In contrast, our framework models motion itself as the generative domain by learning a dedicated latent motion space, which can later drive downstream synthesis or reasoning tasks without relying on pixel data.

Goal-Conditioned Motion Generation Controllable motion generation has received increasing attention in both vision and robotics. Trajectory-based models such as ATM [45], Traj-MoE [47], and Track2Act [6] predict trajectories conditioned on high-level cues like start frames or language, often for action policy learning. Similarly, Vision-Language-Action (VLA) [24, 50, 51] use trajectory prediction as a means of grounding vision-language models in physical actions. Our method builds on this idea of controllable generation but operates fully within the latent motion space learned by our autoencoder. The second stage employs a conditional flow matching model that generates motion latents conditioned on text or spatial pokes, enabling efficient and interpretable motion synthesis. Unlike prior approaches that predict explicit trajectories for downstream control or learn motion implicitly through appearance, our model unifies both perspectives by learning a generative motion prior in latent space that is compact and semantically grounded.

3. Method

We aim to first learn a compact and dense latent representation of trajectories obtained from off-the-shelf trackers that we can later use to model and manipulate kinematics.

We represent a track as a sequence of x, y coordinates in a normalized grid, i.e. $x, y \in [-1, 1]$. We denote a single track as $\mathbf{x}_i = ([x_0, y_0], ..., [x_t, y_t], ..., [x_{T-1}, y_{T-1}])$, with t being the timestep, representing the motion of a tracked point across time within a normalized image coordinate system.

3.1. Learning Motion Spaces

Overview To compress trajectories into a compact latent representation, we train a variational autoencoder [23] $\mathcal{F}_\theta = (\mathcal{E}_\theta, \mathcal{D}_\theta)$ that maps sets of sparse, partially masked trajectories to a latent grid and reconstructs them from it. The encoder $\mathcal{E}_\theta$ processes a set of trajectories $\mathbf{X} = \{\mathbf{x}_0, \dots, \mathbf{x}_{N-1}\}$, where each trajectory $\mathbf{x}_i = (\mathbf{x}_{i,0}, \dots, \mathbf{x}_{i,T-1})$ contains spatial coordinates $\mathbf{x}_{i,t} = [x_{i,t}, y_{i,t}]$, together with an embedding of the first video frame $\mathbf{f_0}$ (e.g., a DINO [53] feature map). The encoder produces a latent representation

$$\mathcal{E}_\theta : \underbrace{\left(\left\{(\mathbf{x}_{i,t})_{t\in\mathbf{t}}\right\}_{i\in\mathcal{I}}}_{\text{trajectories}}, \underbrace{\mathbf{f}_0}_{\text{frame}}\right) \mapsto \underbrace{\mathbf{z}}_{\text{latent}}, \tag{1}$$

with $\mathbf{z} \in \mathbb{R}^{H\times W\times D}$ where H, W denote the spatial grid size and D the number of latent channels.

The latent grid acts as a compact *motion space*, summarizing the kinematic content of all trajectories in a video. The decoder $\mathcal{D}_\theta$ reconstructs future motion at arbitrary spatial locations and time indices through a set of query tokens,

$$\mathcal{D}_\theta : \underbrace{\left(\left\{\mathbf{x}_{j,0}\right\}_{j\in\mathcal{J}}}_{\text{query points } \mathcal{Q}_{\text{dec}}}, \mathbf{z}, \mathbf{f}_0\right) \mapsto \underbrace{\left\{(\hat{\mathbf{x}}_{j,t})_{t\in\mathbf{t}}\right\}_{j\in\mathcal{J}}}_{\text{trajectories}}, \tag{2}$$

where $\mathcal{Q}_{\text{dec}} = \{\mathbf{x}_{j,0}\}_{j\in\mathcal{J}}$ denotes query points in normalized coordinates. Importantly, query points are not restricted to those used during encoding. While the autoencoder is

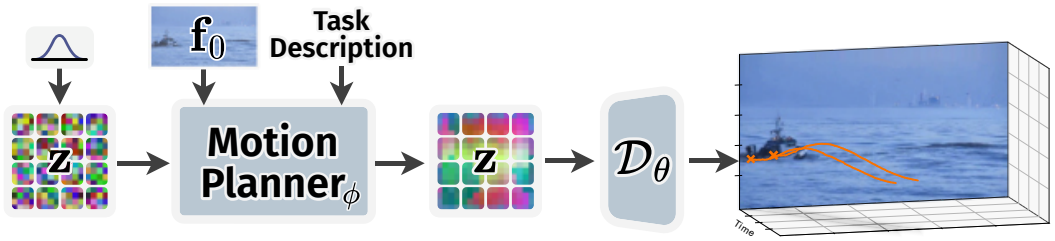


Figure 3. **Model architecture to generate motion space.** We train a conditional flow matching model that learns a vector field over latent motion grids. We condition on either pokes [7] or text prompts, enabling controllable and semantically coherent motion synthesis in the learned motion space. The frame $\mathbf{f}_0$ provides context over the scene.

trained with sparse trajectories, the learned latent representation allows decoding motion at any position on the start frame, effectively enabling dense motion reconstruction.

Encoder Each individual trajectory sample $\mathbf{x}_{i,t}$ is Fourier-embedded using random frequencies drawn from a Gaussian distribution [38]. Temporal and trajectory identity information are encoded using a 3D rotary positional embedding (RoPE) [37]. It jointly encodes each sample's time index t and the start position $[x_{i,0}, y_{i,0}]$, which anchors the trajectory's identity. Token values and positional embeddings are thus computed as follows:

$$\mathrm{tok}(\mathbf{x}_{i,t}) = \mathrm{MLP}([\mathcal{F}(x_t) \mid \mathcal{F}(y_t)]) \quad \triangleright \text{ Encoding} \tag{3}$$

$$\mathrm{PE}(\mathbf{x}_{i,t}) = [\overbrace{\underbrace{\mathbf{R}(x_0)}_{d_k/4} \mid \underbrace{\mathbf{R}(y_0)}_{d_k/4}}^{\text{start position}} \mid \overbrace{\underbrace{\mathbf{R}(t)}_{d_k/4}}^{\text{time}} \mid \overbrace{\underbrace{\mathbf{1}}_{d_k/4}}^{\text{empty}}] \quad \triangleright \text{ RoPE} \tag{4}$$

The latent grid $\mathbf{z}$ is initialized as a learnable embedding broadcasted to the desired latent grid size $H \times W$. We differentiate between individual tokens of the latent grid using RoPE:

$$\mathrm{PE}(\mathbf{z}) = [\overbrace{\underbrace{\mathbf{R}(h)}_{d_k/4} \mid \underbrace{\mathbf{R}(w)}_{d_k/4}}^{\text{spatial position}} \mid \overbrace{\underbrace{\mathbf{1}}_{d_k/2}}^{\text{empty}}] \quad \triangleright \text{ RoPE} \tag{5}$$

We follow [4, 12] and only apply RoPE partially to encourage the model to rely more on semantic information instead of only positional information. In total, this yields $N \cdot T$ trajectory tokens jointly processed with the tokens of the latent grid $\mathbf{z}$. All tokens interact through global self-attention [41] with interleaved cross-attention to the start-frame features $\mathbf{f_0}$. The encoder outputs the mean and log-variance of a Gaussian posterior

$$q_\theta(\mathbf{z} \mid \mathbf{X}, \mathbf{f_0}) = \mathcal{N}\big(\boldsymbol{\mu}_\theta(\mathbf{X}, \mathbf{f_0}),\, \mathrm{diag}\big(\boldsymbol{\sigma}^2_\theta(\mathbf{X}, \mathbf{f_0})\big)\big)\,. \tag{6}$$

Decoder The decoder follows a masked-autoencoder (MAE) [18] design. Each query token encodes its temporal index t_q and start position $(x_{q,0}, y_{q,0})$ using RoPE similar to the encoder, and attends to the latent grid $\mathbf{z}$ and the start-frame features $\mathbf{f_0}$ via cross-attention. The decoded query tokens are projected to (x, y) coordinates through a small MLP, yielding motion predictions at the specified query positions.

Training follows a β-VAE objective [19] combining an L1 reconstruction loss and a KL regularization term:

$$\mathcal{L} = \underbrace{\frac{1}{|\mathcal{I}|}\sum_{i\in\mathcal{I}} \big\|\mathcal{D}_\theta\big(\mathbf{x}_{i,0}; \mathbf{z}, \mathbf{f}_0\big) - \mathbf{x}_i\big\|_1}_{\text{reconstruction}} \tag{7}$$

$$+ \underbrace{\frac{1}{|\mathcal{J}_{\text{mae}}|}\sum_{j\in\mathcal{J}_{\text{mae}}} \big\|\mathcal{D}_\theta\big(\mathbf{x}_{j,0}; \mathbf{z}, \mathbf{f}_0\big) - \mathbf{x}_j\big\|_1}_{\text{masked reconstruction: } \mathcal{J}_{\text{mae}} \cap \mathcal{I} = \varnothing} \tag{8}$$

$$+ \underbrace{\beta\, D_{KL}[q_\theta(\mathbf{z} \mid \{(\mathbf{x}_{i,t})_{t\in\mathbf{t}}\}_{i\in\mathcal{I}}, \mathbf{f}_0) \parallel p(\mathbf{z})]}_{\text{latent regularization}} \tag{9}$$

where $\{\mathbf{x}_{i,0}\}_{i\in\mathcal{I}}$ are the query points corresponding to encoded trajectories (autoencoding loss) and $\{\mathbf{x}_{j,0}\}_{j\in\mathcal{J}_{\text{mae}}}$ are randomly held-out points not seen by the encoder (masked reconstruction loss). β controls the strength of the KL term.

This stage learns a semantic and structured motion bottleneck. The latent grid $\mathbf{z}$ captures the essential kinematics while enabling motion reconstruction at arbitrary spatial locations. Because trajectories are inherently low-dimensional and disentangled from appearance, the encoder achieves strong temporal compression without sacrificing semantic coherence. The resulting latent space provides a compact and interpretable *motion space*, forming the foundation for the subsequent flow-matching generation stage.

3.2. Reasoning in Motion Spaces

We train a conditional flow matching model that operates directly in the latent motion space learned by the first stage. The goal is to model a distribution over motion latents $\mathbf{z}$ that captures the diversity of plausible trajectories while allowing for flexible conditioning on, e.g., text prompts or pokes [7].

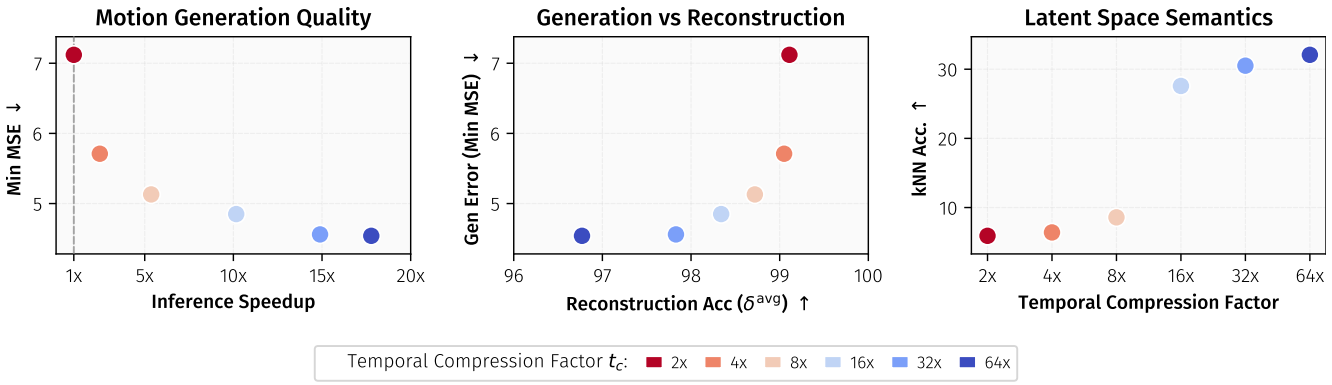


Figure 4. Temporal compression enables our model to generate plausible motions more efficiently. Under a fixed compute budget, both motion generation quality and inference throughput improve substantially with stronger compression (left), with only a minor reduction in reconstruction fidelity (middle). We attribute these gains to the reduced token count, which improves training efficiency, and to an increasingly semantic latent structure, as evidenced by higher kNN retrieval accuracy (right).

Given that the first stage already produces a compact and semantic motion embedding, learning to generate in this space becomes efficient.

Formally, we train a neural vector field $\mathbf{v}_\phi(\mathbf{z}_t, \mathbf{c}, t)$ to predict the instantaneous flow of a sample $\mathbf{z}_t$ along a continuous trajectory from a prior distribution $p_0(\mathbf{z}) = \mathcal{N}(0, I)$ to the empirical data distribution $p_1(\mathbf{z})$ of encoded motion latents. The conditioning variable $\mathbf{c}$ includes the start-frame embedding $\mathbf{f_0}$ and optionally additional control signals (language, pokes). The flow matching objective follows the continuous formulation of [26]:

$$\mathcal{L}_{\mathrm{FM}}(\phi) = \mathbb{E}_{t\sim\mathcal{U}(0,1)}\, \mathbb{E}_{\mathbf{z}_0,\mathbf{z}_1\sim p_0,\, p_1} [\|\mathbf{v}_\phi(\mathbf{z}_t, \mathbf{c}, t) - \mathbf{v}_t^*(\mathbf{z}_0, \mathbf{z}_1)\|_2^2], \quad (10)$$

where $\mathbf{z}_t = (1-t)\mathbf{z}_0 + t\mathbf{z}_1$ is the linear interpolation between noise and data, and $\mathbf{v}_t^* = \mathbf{z}_1 - \mathbf{z}_0$ is the target flow field driving samples toward the data manifold. In practice, $\mathbf{v}_\phi$ is implemented as a transformer-based denoiser that takes as input the noisy latent $\mathbf{z}_t$, the scalar timestep t, and conditioning features $\mathbf{c}$. Both the poke and the text conditional model use cross attention to integrate the conditioning signal. In the poke-conditional setting, we Fourier-embed the target poke positions and the target timestep, similar to Eq. (3). The pokes' start positions are encoded using RoPE (Eq. (4)). This design allows flexible conditioning on a variable number of pokes overall, as well as a variable number of pokes per trajectory, which can be placed arbitrarily throughout the temporal horizon.

4. Experiments

We evaluate our model's ability to compress motion and generate high-quality kinematics. First, we test our hypothesis that strong temporal compression enables efficient and accurate modeling of plausible motions. Second, we evaluate generative reasoning in this compressed motion space on both a closed-domain robotics setting and an open-domain general video setting. These experiments assess how well the model reasons about scene dynamics and plans trajectories that achieve goals specified through either text or poke.

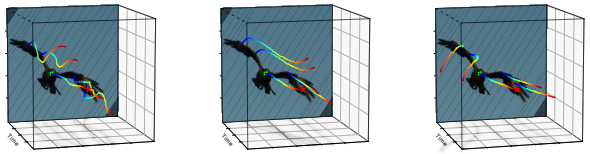


Figure 5. Example of multiple plausible motion hypotheses for the flight of an eagle, generated by our model from a single start frame. Our model produces diverse, physically coherent motions even in complex natural scenes, illustrating the expressiveness of the learned motion space.

Implementation Details The model used in all experiments has a latent grid with spatial dimensions of 16×16 and a temporal compression of $64\times$. Both VAE and Motion Planner are implemented as transformers, generally following LLaMA [39], with 340M and 530M parameters respectively. The goal conditioning is realized by cross-attending to either pokes for the open-domain setting or BERT [14] text embeddings, as is usual for LIBERO [45, 47]. For training, the models optimize their respective objective using AdamW [28] with $(0.9.0.95)$ betas. We provide additional implementation details of our model in Sec. B and Tab. F.

Datasets We consider both an open-domain and a closed-domain setting. For the open-domain setting, we train our models on KOALA-36M [44], aiming to capture broad world

Method	Modality	Speed	1 Poke			2 Pokes			4 Pokes			8 Pokes			Dense		
		timesteps/s ↑	Min ↓	Mean ↓	EPE ↓	Min ↓	Mean ↓	EPE ↓	Min ↓	Mean↓	EPE ↓	Min ↓	Mean ↓	EPE ↓	Min ↓	Mean ↓	EPE ↓
Motion-I2V [34]	Flow	21	135.7	429.7	19.7	106.5	336.2	17.1	87.4	245.7	14.4	54.5	121.7	11.2	46.9	71.7	8.8
Track2Act [6]	Tracks	180	-	-	-	-	-	-	-	-	-	-	-	-	138.7	156.1	20.9
Ours	Latent	**2500**	**41.0**	**57.9**	**0.5**	**40.9**	**57.2**	**0.5**	**35.8**	**53.9**	**0.4**	**34.8**	**48.7**	**0.7**	**30.4**	**44.1**	**1.1**

Table 1. **Poked Motion Generation.** We compare against other methods that were trained on general video data and predict an explicit motion representation for multiple time steps. We report metrics for different conditioning densities to assess how well these models perform under varying levels of uncertainty. Track2Act [6] is end frame conditional, which is why we only report numbers for the dense case. Our approach outperforms other models while also being significantly faster.

knowledge and diverse motion patterns. The source video clips are up to eight seconds long, and we downsample them by skipping every other frame, resulting in frame rates between 12 and 15 fps. Training supervision is provided by pseudo ground-truth trajectories obtained using TapNext [52]. We filter out uncertain tracks as indicated by TapNext and train on tracks with 64 timesteps. We then evaluate on a subset of stock videos from Pexels [40], selected for scenes with a static camera that show complex motions and interactions, as introduced in [5]. See Sec. E for an ablation on tracker choice.

In the closed-domain setting, we train and evaluate on CoTracker3 [21] tracks obtained from the LIBERO benchmark [27], which focuses on structured robotic interaction scenarios. Together, these datasets allow us to assess how well the learned motion spaces generalize across domains and motion regimes.

Metrics We evaluate generated motions in terms of plausibility, diversity, and distributional fidelity. Our goal is to measure how well a model captures physically and semantically plausible motions in a scene. Since real-world data typically provides only a single ground-truth motion per video, evaluation must capture distributional quality despite the lack of a ground-truth distribution. To that end, we adopt metrics from prior work, primarily WHN [9], focusing on measuring fidelity, plausibility, and diversity.

To measure fidelity, we compute the minimum mean squared error (Min MSE), which measures the minimum distance between the ground truth (GT) motion and the distribution of generated samples. This metric correlates with the likelihood of the GT motion under the model's distribution, as high-likelihood regions are sampled more densely, reducing the minimum MSE. Motion diversity is measured with the mean squared error to the GT averaged over all samples (Mean MSE). A Mean MSE close to the Min can be seen as evidence for a collapsed motion distribution whereas a very high Mean MSE indicates potential implausible motion and outliers. Since our model is trained on open-set videos, the distribution of possible motions is highly multimodal, with many possible motions being plausible under the model. Metrics assuming unimodal (ie, deterministic) correspondence are therefore unsuitable. In cases where we condition models on pokes, we additionally measure conditioning adherence with the endpoint error (EPE). While no single metric independently guarantees meaningful motion generation, jointly considering Min MSE, Mean MSE, and EPE serves as a strong proxy for motion quality. All metrics are computed with tracks scaled to $[0, 128]$.

In the closed domain robotics setting, we measure the quality of generated motion embeddings by predicting a corresponding action sequence and executing it in simulation, allowing us to report success rates.

4.1. Semantic Motion Compression

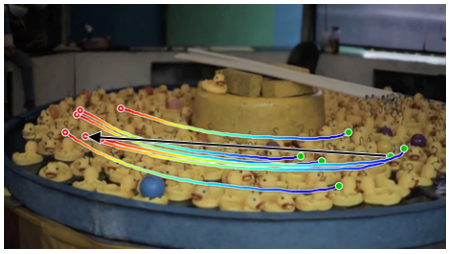
We analyze the effectiveness of compressing motion across time using compression factors $t_c \in \{2, 4, 8, 16, 32, 64\}$. A compression factor of t_c means that t_c consecutive frames are aggregated into a single latent representation with no temporal dimension. Temporal compression enables the model to represent long-term scene dynamics more efficiently while reducing computational cost. We train models with varying temporal compression factors using a fixed compute budget. We evaluate the resulting motion generation quality in Fig. 4. Results clearly demonstrate that high temporal compression consistently improves motion generation quality while also significantly increasing inference efficiency. Increasing temporal compression also enhances the semantic structure of the motion space. This is reflected in a monotonically increasing kNN accuracy on a subset of SSv2 [16], shown in Fig. 4. Higher kNN accuracies indicate that semantically similar motions are grouped more closely in the latent space. We hypothesize that the improved motion generation quality under high temporal compression can be attributed to both the reduced token count, which increases training and inference efficiency, and a more semantically structured latent space. Additional results comparing performance over the course of training are provided in Fig. M, including two compute-matching schemes: matching either step time or batch size across models.

4.2. Motion Reasoning and Planning

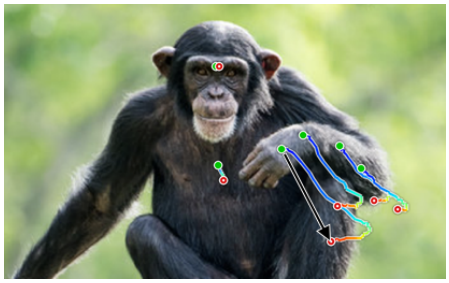
We compare models in their ability to reason about physically plausible motions and plan trajectories that achieve desired goal states specified by prompts or end pokes.



(a) Path finding



(b) Rotational Motion



(c) Joint Reasoning

Figure 6. Qualitative examples demonstrating diverse motion reasoning capabilities. These results highlight that the model captures semantic motion structure and generalizes to varied motion regimes.

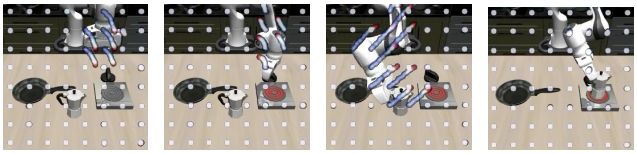
4.2.1. Trajectory Prediction

To comprehensively assess motion reasoning and planning, we conduct experiments in both a closed-domain robotics setting and an open-domain video setting.

In the open-domain setting, we investigate whether models trained on large-scale, open-set data have acquired transferable knowledge about how objects move and interact in the world. This evaluation tests each model's ability to generate physically plausible, goal-conditioned motions across diverse, unconstrained scenes. We compare models that directly predict motion, either as trajectories or optical flow. Evaluation is performed in a conditional setup, where the model is given a start frame and either a set of n target pokes or an end frame. The task is to generate plausible motions that transform the initial state into an end state consistent with the conditioning signals. To assess how well models handle different levels of conditioning sparsity and therefore uncertainty, we vary the strength of the conditioning signal by using $n \in \{1, 2, 4, 8\}$ pokes, along with a dense setting that uses the strongest conditioning signal supported by each method. Sparse conditioning provides more flexibility but can lead to more implausible motions, whereas dense conditioning offers stronger guidance but increases the challenge of reconciling all conditionings into a consistent motion. As shown in Tab. 1, our model consistently outperforms both flow-based and trajectory-based baselines across all conditioning sparsities. Qualitative results in Figs. 5 and 6 further demonstrate that our approach produces diverse, coherent, and physically plausible real-world motions. We show further results on DAVIS [32] and PhysicsIQ [29] in Sec. G.

In the closed-domain setting, we evaluate our model's ability to generate trajectories from high-level text instructions on the LIBERO robotics dataset [27]. Given a start frame and task description, the model predicts how the robot arm and surrounding objects should move to achieve the described goal, effectively performing motion planning from visual and linguistic input. Task descriptions in LIBERO are abstract (see Fig. 7), requiring the model to reason about both the current scene state and the specified goal to produce physically plausible and goal-directed trajectories. Results and evaluation details are presented in Sec. A.

(a) *Turn on the stove and put the moka pot on it*



(b) *Put the yellow-and-white mug in the microwave and close it*

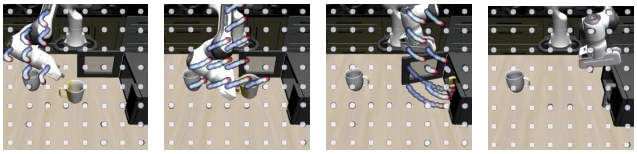


Figure 7. **LIBERO rollout samples.** Our track predictor forecasts tracks 16 steps ahead (visualized), enabling long-horizon planning. A policy head conditions on these predictions to select the next actions, with predictions updated after every new observation.

Model	LIBERO succ. rates ↑					
	10	90	Spatial	Goal	Object	Avg.
ATM [45]	39.3	48.4	68.5	**77.8**	68.0	60.4
Ours	**68.0**	**62.9**	**93.0**	75.3	**99.0**	**79.6**
Tra-MoE [47]	28.5	–	62.5	81.0	73.5	61.4
Ours	**63.0**	–	**83.3**	**84.0**	**91.0**	**80.3**

Table 2. Success rates on LIBERO tasks following the respective training and evaluation setup of ATM [45] (top) and of Tra-MoE [47] (bottom). Policy heads are trained to predict robot actions conditioned on generated task-conditional motion embeddings.

4.2.2. Action Prediction

The LIBERO robotics setting allows us to rigorously evaluate generated motion embeddings by predicting corresponding robot actions, executing them in simulation and measuring

task success. Following ATM [45] and Tra-MoE [47], we train a policy head that predicts robot actions from our generated conditional motion embeddings. Our model maintains a rolling motion plan over a horizon of T steps, updated at each timestep with new observations. At timestep t, it predicts a motion embedding encoding future motion for $\tilde{t} \in [t, t+T]$ (see Fig. 7), from which the policy head predicts the action at $t+1$. After executing this action, the model replans over the next horizon given the new observation. Since the policy head receives only the generated motion embeddings as input, it learns a mapping from motion embeddings to actions, effectively acting as an *inverse dynamics module*. This clear split ensures that the actual task-conditional reasoning and planning is done by the motion planner, not the policy head. We follow the evaluation setup of both baselines and report results in Tab. 2. Our model significantly outperforms both baselines across tasks, indicating superior understanding of scene dynamics. Further details are provided in Sec. A.

4.3. Comparison to Generative Video Models

To assess the effectiveness of modeling motion directly in our learned trajectory space, as opposed to modeling individual frames, we compare against state-of-the-art generative video models that also aim to learn world dynamics. The key distinction is that video models must jointly synthesize both appearance and motion, while our approach focuses exclusively on kinematics. Since we are interested in goal-directed motion rather than arbitrary dynamics, we focus on video models that can be conditioned on both a start frame and an end frame. This setup aligns with our conditioning scheme, where the model receives a start-frame embedding and a motion goal specified by pokes.

A direct comparison between our method and video models is challenging because videos do not provide explicit motion trajectories or any other motion representations. To obtain a comparable representation, we track the generated videos using CoTracker3 [21] (see Sec. F for TapNext), producing estimated trajectories $\text{tracks}_{\text{gen}} \in \mathbb{R}^{N \times T \times 2}$. However, tracking generated videos can introduce several sources of error, such as losing correspondences over time, resulting in incomplete or inconsistent motion estimates. In contrast, our method directly generates motion embeddings, providing globally consistent motion information without the risk of tracker drift or loss.

All methods are evaluated on a subset of Pexels [40] videos, which contain diverse and visually distinct motions. While this subset was held-out for our models, we cannot guarantee that this was also the case for the video models. For each video, we extract ground-truth trajectories by initializing trackers on the start frame and tracking them across time until the end frame, retaining only moving tracks that remain visible throughout. This yields a ground-truth trajectory set $\text{tracks}_{\text{gt}} \in \mathbb{R}^{N \times T \times 2}$. Our model is conditioned on $N = 40$ pokes $\mathbf{p}_{0 \to T} \in \mathbb{R}^{N \times 2}$, each specifying the intended displacement from the start to the end frame, while video baselines are conditioned on the same start frame and the ground-truth end frame.

Model	Time ↓	Min MSE ↓	Mean MSE ↓	EPE ↓
Wan [43]	1h	28.67	57.02	4.68
Veo 3 [13]	?	36.18	94.00	6.21
Ours	**1s**	**27.08**	**39.53**	**1.17**

Table 3. **Samples Matched:** We sample $k = 8$ times from each model and track the generated videos to report our distributional metrics as well as conditioning adherence with EPE. This is an unfavorable setting for us, as our model is much smaller. Still, we outperform the video while being orders of magnitude faster.

Model	Samples ↑	Min MSE ↓	Mean MSE ↓	EPE ↓
Wan [43]	1	64.20	64.20	5.23
Veo 3 [13]	1	65.99	65.99	5.84
Ours	**> 10k**	**21.29**	**40.33**	**1.17**

Table 4. **Time Matched:** Setup similar to Tab. 3 but now matching wall clock time for sampling. Our performance lead increases drastically due to the efficiency of our approach.

We report quantitative results using our proposed motion metrics. Because sampling from video diffusion models is computationally expensive, we consider two evaluation regimes: (i) *Sample Matched* where both methods generate the same number of samples, and (ii) *Time Matched* where the wall-clock time for sampling is held constant, based on the average time required to generate a single video sample from the baseline. In the *Sample Matched* regime, we outperform Wan, with a larger gap for Veo. We hypothesize that this is because Veo tends to generate very high magnitude motions, which yields high errors if the ground truth video has more moderate motion.

5. Conclusion

We have introduced a framework that enables highly efficient modeling of scene dynamics by operating on a learned motion embedding. By leveraging large-scale tracker-derived trajectories, our approach captures long-term kinematic structure while heavily compressing temporal information by $64\times$. Operating on these motion embeddings, our conditional flow matching model efficiently generates realistic, long-horizon motions that fulfill goals specified via text prompts or spatial pokes. We empirically show that heavy temporal compression aids learning kinematics and enables our model to reason efficiently over long time. Across multiple benchmarks, our generated motion distributions significantly outperform those of both modern video models and task-specific approaches, demonstrating that our motion embeddings provide a compact, expressive, and flexible representation for modeling kinematics.

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