Temporal-controlled Frame Swap for Generating High-Fidelity Stereo Driving Data for Autonomy Analysis

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Motivation

Stereo vision data is critical for up-to-scale visual SLAM tasks. Synthetic data from research simulators offers a scalable solution to data scarcity, but **the realism of dedicated research simulators is not on par with state-of-the-art commercial games. Meanwhile, commerical games like GTA V lack native stereo support** and restrict multiple viewport rendering, severely limiting our access to high quality stereo data.

- **The goal is to develop a novel method to overcome the single viewport limitation and enable dynamic stereo data collection from commercial games.**

Method

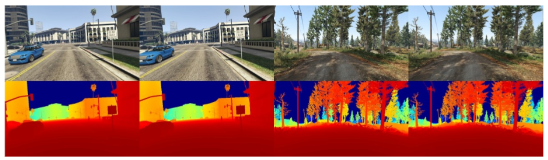
We present **Temporal-controlled Frame Swap (TeFS)**, a novel method that enables precise control over the passage of time during stereo capture process.

- Develops a customizable stereo camera setup attached to the ego vehicle.
- Leverages a single-thread architecture for precise temporal control rather than a client-server model.
- Implements a pseudo-pause function to halt the temporal state for stereo capture while keeping the rendering engine active.
- Swaps between left and right cameras at controlled moments during pseudo-pauses.
- Minimizes temporal disparity between left and right cameras from 16.7ms to 0.2-0.3ms.

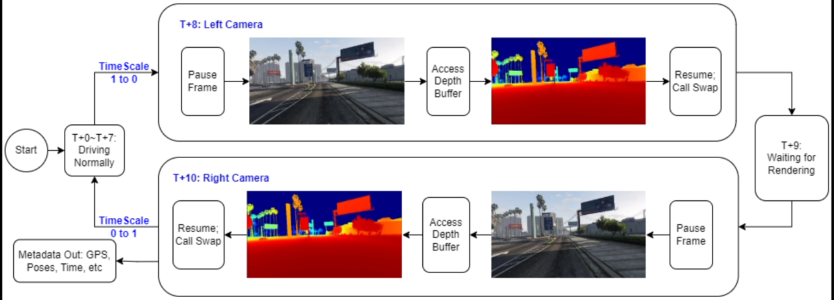
To demonstrate its generalizability, we implmented TeFS in both GTA V and CARLA. Given that CARLA is research focused and has native stereo support, it serves as a benchmark for validating TeFS Stereo.

GTAV-TeFS Dataset

We present GTAV_TeFS dataset, the first large-scale stereo driving dataset based on the high-fidelity video game, GTA V, which includes **88000 high-resolution stereo RGB image pairs, temporal information, GPS coordinates, camera poses, full-resolution dense depth maps, and challenging-case comparison groups,** facilitating up-to-scale stereo odometry tasks in a realistic commercial game environment



TeFS Stereo and Depth Capture Pipeline

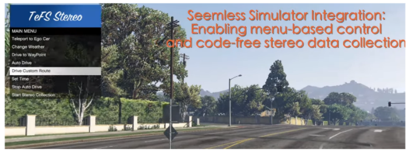


Depth and Camera fps

$$Depth = \frac{Map_{uv}}{NDC + Map_{uv} \times \frac{nc_z}{2 \times fc_z}}$$

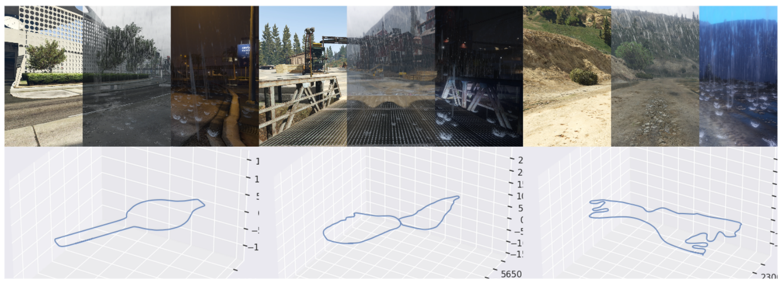
$$f_{\text{cam}} = \frac{1}{T_g \times \left(\frac{Dr}{86400}\right)}$$

Menu-based Interface



TeFS vs Native Stereo vs Simple Swap

Challenging-case Comparison Group



Experiment Results

- Validate TeFS Stereo using CARLA with ORBSLAM 3 Stereo Odometry

Map	Trajectory Distance (m)	Method	Evaluate Metrics		
			APE(m) ↓	APE(%) ↓	RPE(m) ↓
Town 03	954.41	Native	1.67±0.59	0.17%±0.06%	0.39±0.14
		TeFS	**1.82±0.65**	**0.19%±0.06%**	**0.39±0.14**
Town 06	957.97	Native	4.22±3.17	0.44%±0.33%	0.31±0.25
		TeFS	**2.30±1.67**	**0.24%±0.17%**	**0.31±0.25**
Town 10	950.05	Native	0.98±0.64	0.10%±0.07%	0.27±0.22
		TeFS	**1.01±0.63**	**0.10%±0.07%**	**0.27±0.22**

- GTAV-TeFS Stereo Odometry Eval on Feature-based vSLAM Models

Scene	Length(m)	Weather	Model	Metrics			
				APE(m)↓	APE(%)↓	RPE(m)↓	Loop Detected
City 04	760.0	Extra Sunny	ORBSLAM3	3.20±0.85	0.42±0.11	2.78±0.16	✓
			OV²SLAM	**2.53±1.21**	**0.33±0.16**	**0.06±0.09**	✓
			VINS Fusion	2.95±1.36	0.39±0.18	0.09±0.26	✓
		Cloudy with Rain	ORBSLAM3	**2.13±1.19**	**0.28±0.16**	**0.03±0.04**	✓
			OV²SLAM	21.01±9.33	2.77±1.23	0.29±2.28	✓
			VINS Fusion	3.63±2.00	0.48±0.26	0.21±0.48	✓
		Night Thunderstorm	ORBSLAM3	Lost track of the map			
			OV²SLAM	**54.19±48.40**	**7.11±6.35**	**0.59±4.15**	
			VINS Fusion	Map range unreachable			
Offroad 01	1206.0	Extra Sunny	ORBSLAM3	**3.16±1.65**	**0.26±0.14**	**0.11±0.12**	✓
			OV²SLAM	4.81±2.21	0.39±0.18	0.21±0.19	
			VINS Fusion	4.27±1.73	0.35±0.14	0.16±0.25	✓
		Cloudy with Rain	ORBSLAM3	**4.19±2.39**	**0.35±0.20**	**0.07±0.40**	✓
			OV²SLAM	6.60±4.19	0.54±0.34	0.20±0.25	
			VINS Fusion	49.75±32.98	4.12±2.73	0.38±4.73	✓
		Night Thunderstorm	ORBSLAM3	Lost track of the map			
			OV²SLAM	**91.90±45.50**	**7.57±3.79**	**0.29±2.31**	
			VINS Fusion	Map range unreachable			
Offroad 02	3230.0	Extra Sunny	ORBSLAM3	**8.19±3.95**	**0.25±0.12**	**0.39±0.26**	✓
			OV²SLAM	15.47±12.69	0.48±0.39	0.36±2.07	✓
			VINS Fusion	15.44±8.99	0.48±0.39	0.16±0.21	✓
		Cloudy with Rain	ORBSLAM3	**9.45±2.77**	**0.29±0.09**	**0.16±0.14**	
			OV²SLAM	85.62±65.35	2.65±2.03	0.14±0.21	
			VINS Fusion	72.47±61.96	2.26±1.93	0.22±0.70	
		Night Thunderstorm	ORBSLAM3	Lost track of the map			
			OV²SLAM	**160.33±82.39**	**4.97±2.49**	**0.34±3.54**	
			VINS Fusion	Map range unreachable			

- GTAV-TeFS Stereo and RGB-D Eval on Learning-basd DROIDSLAM

Scene	Weather	Input Mode	Metrics(Corrected)			Metrics(Raw)
			APE(m)↓	APE(%)↓	RPE(m)↓	APE(m)↓
City 04	Extra Sunny	Stereo	1.27±0.58	0.23±0.12	0.63±0.14	73.69±33.71
		RGBD	**0.86±0.45**	**0.11±0.06**	**0.63±0.10**	**15.77±6.79**
	Cloudy with Rain	Stereo	**1.73±0.95**	**0.23±0.12**	0.63±0.14	73.75±33.65
		RGBD	2.99±1.19	0.39±0.16	**0.62±0.10**	**13.16±5.48**
	Night Thunderstorm	Stereo	6.42±2.09	0.84±0.27	0.63±0.20	74.61±33.79
		RGBD	**4.91±2.39**	**0.64±0.31**	**0.62±0.15**	**10.29±4.77**
Offroad 01	Extra Sunny	Stereo	3.61±1.15	0.30±0.10	0.58±0.19	98.68±49.18
		RGBD	**1.35±0.54**	**0.11±0.04**	**0.58±0.18**	**19.72±9.85**
	Cloudy with Rain	Stereo	6.23±3.66	0.51±0.30	0.59±0.18	99.44±49.29
		RGBD	**2.64±1.13**	**0.22±0.09**	**0.58±0.18**	**18.59±9.23**
	Night Thunderstorm	Stereo	18.24±6.11	1.50±0.50	0.62±0.31	100.32±50.09
		RGBD	**6.68±4.42**	**0.55±0.35**	**0.62±0.19**	**21.48±12.89**

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