

SDF-2-SDF: Highly Accurate 3D Object Reconstruction

Supplementary Material

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This document is organized as follows:

- Section 1 gives details about our 3D-printed object dataset.
- Section 2 contains tables with the average trajectory error metrics plotted in Figures 4 and 5 of the paper, in addition to the root-mean-squared, minimum and maximum translational errors, as well as the minimum and maximum angular errors for all methods.
- Section 3 summarizes the content of the accompanying video, which illustrates the functionality of our reconstruction pipeline.
- Section 4 juxtaposes outputs of the 3 evaluated reconstruction systems on the high quality depth data captured with an industrial device.
- Section 5 contains enlarged versions of some more figures from the main paper.
- Section 6 contains the derivations of important mathematical components of our algorithm.

1 Dataset Details

Table 1 specifies the dimensions of the 3D printed objects. The corresponding CAD models were also used for the synthetic rendering.

Table 1. Object dimensions

object	front width [mm]	side width [mm]	height [mm]	image
bunny	155.699	120.673	154.334	
teddy	170.200	160.300	200.000	
Kenny	110.980	93.040	122.000	
leopard	260.000	90.300	138.100	
tank	200.000	126.900	59.900	

Figure 1 displays the objects beside each other for relative size comparison.



Fig. 1. Dataset objects

Synthetic Sequences

The sequences rendered in *Blender* contain a single object around which a camera is moving in a circular (turntable-like) or sine-wave (handheld-like) trajectory. For each we will provide:

- 640×480 RGB images in PNG format;
- 640×480 depth images in EXR format;
- intrinsic camera parameters;
- groundtruth trajectories used for the rendering.



Industrial Sensor Sequences

These sequences were acquired with the object of interest put on a textured turntable, rotating in front of the fixed sensor. We will provide:

- 2040×1080 RGB images in BMP format;
- 2040×1080 depth images in BMP format;
- 2040×1080 binary object masks in PNG format;
- 2040×1080 binary table masks in PNG format;
- intrinsic camera parameters.



Kinect Sequences

For the Kinect datasets the object of interest was placed on a turntable with an attached markerboard. In case of a turntable trajectory, the turntable was rotating in front of a fixed Kinect. With the handheld trajectory the table was fixed, while the Kinect was moved around the object until loop closure. We will provide the following:

- 640×480 RGB images in PNG format;
- 640×480 depth images in PNG format;
- 640×480 binary object masks in PNG format;
- 640×480 binary table masks in PNG format;
- intrinsic camera parameters;
- trajectories estimated from the markerboard.



2 Detailed Experimental Evaluation

This section contains the tabulated results corresponding to the bar plots in the main paper. The following abbreviations are used to denote the different methods:

- *DVO*: dense visual odometry [1], as the tracking component of the reconstruction algorithm by Kehl *et al.* [2]; *DVO object* uses only the object for tracking, while *DVO full* also uses its textured support;
- *GICP*: indicates PCL’s implementation of Generalized-ICP [3,4];
- *KinFu*: indicates PCL’s implementation of KinectFusion [3,5,6];
- *FM-pt-SDF*: indicates the ROS package [7] for frame-to-model point-to-implicit registration [8,9];
- *FF-pt-SDF*: frame-to-frame point-to-implicit registration (our own implementation);
- *SDF-2-SDF*: our proposed pipeline.

2.1 Tracking on Synthetic Datasets

Table 2. Relative trajectory errors on synthetic data

object	traj.	method	drift [mm/frame]				angular error [°/frame]		
			RMS	avg	min	max	avg	min	max
	circle	DVO	3.332602	3.033579	0.853359	7.236036	0.315720	0.000000	0.773286
		GICP	16.524443	14.383451	3.884022	26.504988	1.782729	0.862294	3.031631
		KinFu	0.963244	0.777616	0.106514	3.339304	0.102260	0.000000	0.438794
	wave	FM-pt-SDF	5.083581	2.501978	0.057307	33.685467	0.339971	0.000000	4.096644
		FF-pt-SDF	0.608759	0.565256	0.129707	1.273190	0.031936	0.000000	0.142653
		proposed	0.250672	0.193492	0.004995	0.942823	0.009433	0.000000	0.125115
	circle	DVO	7.642210	5.055256	0.122611	38.634106	0.513349	0.000000	4.284211
		GICP	21.859379	18.304382	0.599215	47.136864	2.306236	0.301316	5.374302
		KinFu	1.869439	1.354203	0.140786	8.179884	0.197359	0.000000	1.070446
	wave	FM-pt-SDF	7.717026	4.767470	0.031675	27.817335	0.651115	0.000000	4.326036
		FF-pt-SDF	0.845739	0.635825	0.050713	5.327730	0.062028	0.000000	0.765146
		proposed	0.297115	0.206295	0.012617	1.292626	0.012808	0.000000	0.158259
	circle	DVO	2.817009	2.432231	0.091471	7.944780	0.303086	0.000000	0.882037
		GICP	5.834904	4.676374	0.795912	26.440723	0.615016	0.153233	2.985318
		KinFu	1.048660	0.787743	0.037250	4.466511	0.086353	0.000000	0.665582
	wave	FM-pt-SDF	2.173209	0.917534	0.017302	12.098502	0.097673	0.000000	1.300837
		FF-pt-SDF	0.492353	0.456525	0.097495	0.1060537	0.016931	0.000000	0.118694
		proposed	0.116955	0.101042	0.013273	0.379161	0.000332	0.000000	0.039565
	circle	DVO	4.394562	3.354639	0.639171	26.616692	0.388280	0.068528	3.067567
		GICP	26.145624	26.145111	0.5992638	26.473042	2.999256	2.999034	3.011684
		KinFu	2.507948	1.965686	0.100074	8.258312	0.246267	0.000000	0.993069
	wave	FM-pt-SDF	10.276282	4.371700	0.038599	51.252377	0.508174	0.000000	6.068182
		FF-pt-SDF	0.956355	0.801070	0.057985	8.328661	0.084134	0.000000	0.503577
		proposed	0.439260	0.357266	0.018586	1.415030	0.024849	0.000000	0.148037
	circle	DVO	12.231123	7.083187	0.879905	62.789932	0.797249	0.000000	7.436413
		GICP	31.578579	29.938622	11.721412	46.888008	3.508239	1.393786	5.373137
		KinFu	1.035179	2.469074	0.214728	7.758764	0.318556	0.039565	0.868625
	wave	FM-pt-SDF	13.337383	5.039370	0.026515	70.972321	0.581986	0.000000	8.306067
		FF-pt-SDF	1.040985	0.860335	0.119888	3.932851	0.089726	0.000000	0.503577
		proposed	0.468773	0.399137	0.072893	1.225283	0.031643	0.000000	0.142653

Table 3. Absolute trajectory errors on synthetic data

object	traj.	method	translational error [mm/pose]				angular error [°/pose]		
			RMS	avg	min	max	avg	min	max
bunny	circle	DVO	85.761810	81.987389	3.472104	116.159172	10.204186	0.326259	14.028675
		GICP	710.981201	643.967407	9.280423	976.151917	93.817205	1.203318	179.980286
		KinFu	5.888869	5.331917	0.406691	10.493214	0.779913	0.055953	1.278993
	wave	FM-pt-SDF	44.886726	31.800383	0.440060	117.284103	3.097882	0.000000	11.311511
		FF-pt-SDF	32.205364	28.392815	0.313109	46.909531	1.530576	0.055953	2.688132
		proposed	1.854068	1.656696	0.020598	4.008577	0.231607	0.000000	0.502020
teddy	circle	DVO	72.308990	69.543015	1.892460	103.403915	10.570494	0.227282	14.576346
		GICP	744.284426	666.105896	6.975756	1008.776917	98.952643	1.229698	179.734365
		KinFu	4.368211	3.760000	0.325695	11.473716	0.716599	0.000000	1.502427
	wave	FM-pt-SDF	41.709858	26.742332	0.433933	125.946510	3.039479	0.000000	14.757903
		FF-pt-SDF	33.895458	29.765867	0.561056	48.505302	2.390680	0.000000	3.998390
		proposed	3.779940	3.301488	0.148686	5.335198	0.489620	0.000000	0.802102
Kenny	circle	DVO	55.067028	50.237583	1.246483	93.420532	7.856947	0.163129	15.723247
		GICP	314.501312	273.966614	2.608954	488.988220	35.722948	0.395647	64.202127
		KinFu	4.771594	4.145760	0.352286	10.624366	0.467834	0.055953	1.222036
	wave	FM-pt-SDF	5.974824	5.433010	0.418685	20.088959	0.611397	0.000000	2.572671
		FF-pt-SDF	32.200302	27.713421	0.489138	52.462994	1.267628	0.000000	2.716518
		proposed	1.019222	0.807528	0.061403	2.031408	0.113451	0.000000	0.309010
leopard	circle	DVO	37.175110	35.227119	1.063431	50.916538	6.638618	0.303902	10.066598
		GICP	274.375671	234.350830	4.498727	456.344391	27.987116	0.539591	55.094839
		KinFu	4.422370	3.662355	0.200318	8.875053	0.426082	0.000000	1.135035
	wave	FM-pt-SDF	74.987526	48.269756	0.335898	141.760132	9.740253	0.000000	28.972846
		FF-pt-SDF	29.781687	26.028782	0.467877	45.965469	1.354977	0.000000	2.979806
		proposed	0.926383	0.749888	0.018285	1.923801	0.080152	0.000000	0.223812
tank	circle	DVO	63.281616	53.689896	5.203418	116.829712	9.165467	0.660861	16.718148
		GICP	700.295410	633.323425	25.759844	986.234009	90.862581	3.010644	179.991515
		KinFu	5.432887	5.024808	0.496254	12.169734	0.768561	0.167859	1.475088
	wave	FM-pt-SDF	72.163246	43.824753	1.219497	157.198563	5.321303	0.197823	18.164152
		FF-pt-SDF	35.780422	32.041111	1.304162	55.400394	1.937790	0.084694	4.777853
		proposed	3.574307	2.780642	0.576757	8.404356	0.330405	0.000000	1.023345
	circle	DVO	58.311875	55.547302	0.914004	85.340813	11.393007	0.155233	20.499283
		GICP	587.898222	561.490662	25.128435	739.109741	106.267320	3.072411	178.984654
		KinFu	7.013393	6.120502	0.638192	15.442928	0.780883	0.137056	1.663614
	wave	FM-pt-SDF	40.711937	23.699772	2.803717	144.059784	3.143829	0.349426	17.484797
		FF-pt-SDF	32.581696	29.177073	0.169971	50.232521	1.136346	0.055953	3.624155
		proposed	4.396399	3.371828	0.312573	8.719543	0.545319	0.039565	1.302040

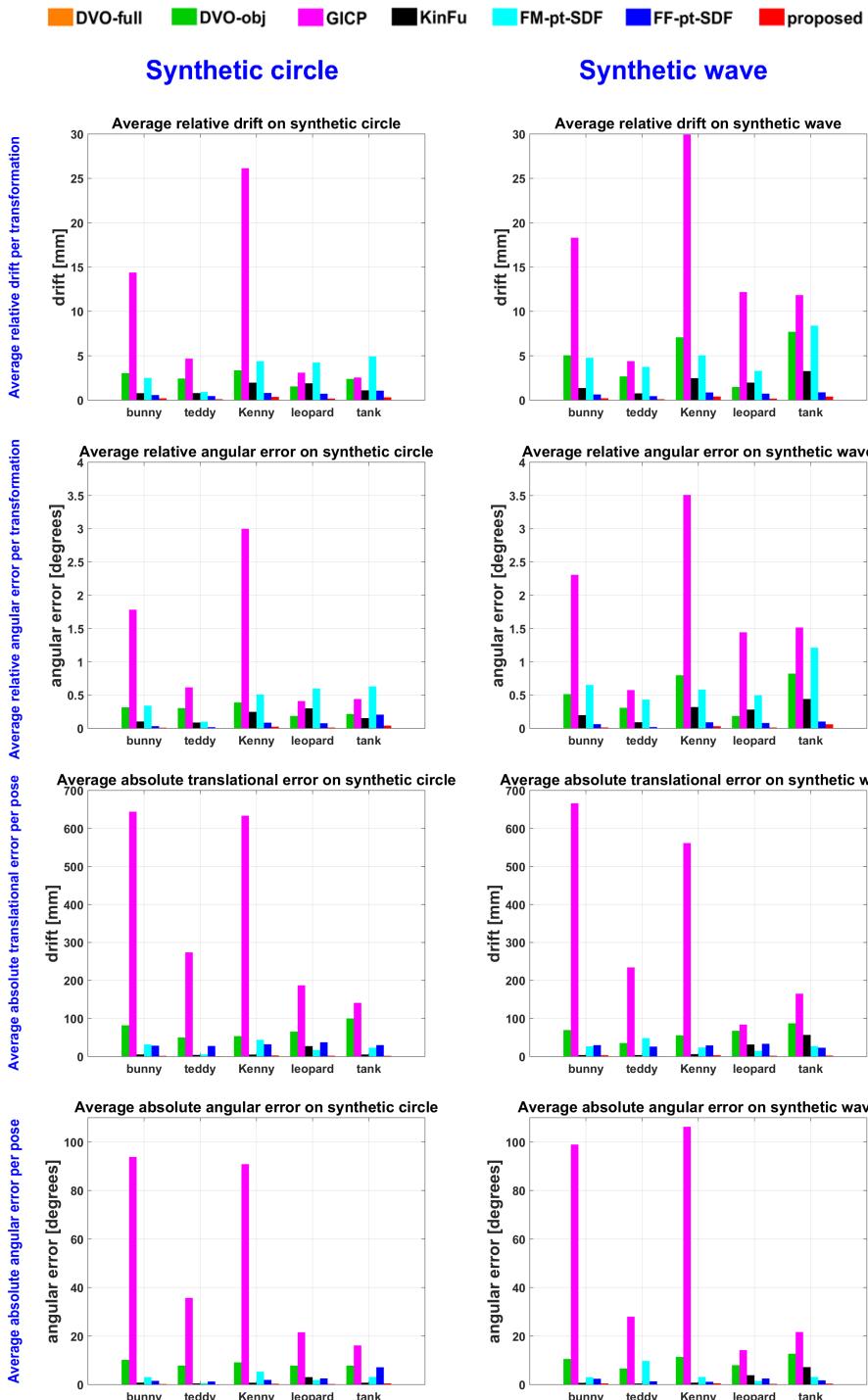


Fig. 2. Average tracking errors on synthetic sequences

2.2 Tracking on Kinect Datasets

Table 4. Relative trajectory errors on Kinect sequences

object	traj.	method	drift [mm/frame]				angular error [°/frame]		
			RMS	avg	min	max	avg	min	max
bunny	turntable	DVO full	3.222718	0.817717	0.055202	35.453266	0.060505	0.000000	2.982957
		DVO object	27.770582	19.002457	1.851878	180.269974	1.477170	0.131221	15.461468
		GICP	27.487379	26.812586	10.100257	43.081146	2.819611	1.120461	4.610063
		KinFu	10.082951	6.461852	0.344799	75.917824	0.664244	0.000000	8.681272
		FM-pt-SDF	18.571079	10.586092	0.488492	95.101913	1.157955	0.096913	10.902871
	handheld	FF-pt-SDF	5.210176	4.522889	0.119442	14.656347	0.483741	0.000000	1.380243
		proposed	4.189324	3.601685	0.305975	10.549968	0.388754	0.039565	1.433649
		DVO full	2.952505	1.911158	0.181382	21.353039	0.132800	0.000000	1.486190
		DVO object	49.141365	20.485128	0.524765	352.609741	1.919277	0.055953	47.177653
teddy	turntable	GICP	11.989499	10.489070	0.584330	48.613865	1.717062	0.069613	10.153879
		KinFu	8.969358	7.258654	0.577654	44.682060	0.173927	0.068528	10.278767
		FM-pt-SDF	8.502694	7.240862	0.864146	47.877308	0.757599	0.153233	7.731276
		FF-pt-SDF	11.375504	0.968094	0.658263	51.159912	1.366920	0.079129	16.807742
		proposed	7.897508	6.906138	0.709187	21.185940	0.738917	0.000000	2.087980
	handheld	DVO full	0.681674	0.583173	0.055879	2.138841	0.050226	0.000000	0.167859
		DVO object	10.913967	7.873542	0.991393	73.179123	0.706432	0.088469	7.058395
		GICP	32.686352	31.876904	6.366591	41.794418	2.921871	0.560927	3.890222
		KinFu	2.539919	2.014843	0.994084	8.263735	0.190168	0.000000	0.836493
Kenny	turntable	FM-pt-SDF	23.078222	10.916483	0.405778	127.847420	1.247797	0.068528	13.306624
		FF-pt-SDF	2.664747	2.304919	0.126625	7.065425	0.238076	0.055953	7.165485
		proposed	2.072518	1.829731	0.196472	4.696811	0.188983	0.000000	0.427958
		DVO full	14.887383	3.249595	0.123458	233.358902	0.125280	0.000000	11.405929
		DVO object	24.921490	10.196335	1.012551	224.997162	0.883732	0.039565	24.573428
	handheld	GICP	13.045246	10.950849	0.1090244	58.796944	1.503883	0.201741	6.586257
		KinFu	12.834058	7.591533	0.796786	107.114861	0.871317	0.039565	19.303974
		FM-pt-SDF	10.613819	8.163745	0.268875	72.020706	0.831365	0.055953	11.074999
		FF-pt-SDF	8.624208	7.453013	0.644877	24.527230	0.624547	0.000000	2.874171
		proposed	8.040944	6.777625	0.405095	31.326029	0.573862	0.104678	3.399926
leopard	turntable	DVO full	0.648363	0.536428	0.038173	2.379409	0.044182	0.000000	0.193827
		DVO object	43.447983	32.744400	1.647733	142.783371	0.627172	0.088469	14.296064
		GICP	34.433861	33.264874	13.285873	71.837746	3.022173	1.296618	5.973371
		KinFu	18.468212	14.734526	0.206238	43.388069	1.331296	0.055953	3.719454
		FM-pt-SDF	29.751539	24.961391	1.080843	67.298492	2.238250	0.172458	5.752471
	handheld	FF-pt-SDF	57.128792	14.955667	1.116388	607.982483	1.414353	0.000000	52.020824
		proposed	10.991909	8.220175	0.352939	39.456127	0.798359	0.000000	3.425616
		DVO full	1.322855	0.702395	0.017464	13.890581	0.034153	0.000000	0.939612
		DVO object	84.760872	43.771030	1.553089	547.170349	3.704117	0.039565	50.943177
tank	turntable	GICP	11.594671	10.707078	1.234116	30.151625	1.148131	0.181308	2.670603
		KinFu	88.766144	38.250023	0.554068	809.858215	2.908633	0.000000	55.264611
		FM-pt-SDF	10.812789	9.316893	0.876860	27.936213	0.949612	0.104678	2.500775
		FF-pt-SDF	14.869718	11.220050	0.637444	105.208069	1.548945	0.088469	35.022850
		proposed	76.915146	30.330130	0.714745	S21.734070	3.839594	0.163129	118.477634
	handheld	DVO full	3.998358	1.003003	0.175761	42.549683	0.080648	0.000000	3.338355
		DVO object	19.855284	13.092594	0.991910	98.539406	1.167292	0.039565	11.347770
		GICP	29.124208	26.824360	5.888054	46.508541	2.422137	0.555317	4.343734
		KinFu	39.860188	15.276608	0.223145	313.289373	1.255892	0.000000	26.381884
	turntable	FM-pt-SDF	21.049114	13.465719	0.471781	86.546371	1.350286	0.088469	10.895752
		FF-pt-SDF	5.882124	4.186366	0.279457	29.025558	0.475739	0.039565	4.262006
		proposed	3.317315	2.633779	0.199104	9.978995	0.256880	0.000000	1.173683
		DVO full	3.187790	1.771588	0.067484	28.228546	0.112453	0.000000	2.310766
bunny	handheld	DVO object	107.815599	47.014378	0.786685	787.579290	4.080174	0.000000	78.524299
		GICP	11.568313	9.632819	0.105198	43.989910	1.333333	0.088469	6.653216
		KinFu	52.995335	17.779074	0.454565	365.456177	1.931711	0.039565	43.023596
		FM-pt-SDF	12.527378	8.967976	0.636045	73.412666	0.858358	0.079129	6.956242
	turntable	FF-pt-SDF	11.045048	8.857202	0.587525	44.979191	0.841366	0.000000	3.838372
		proposed	8.108617	6.738611	0.649962	34.757378	0.649237	0.055953	3.742952
		DVO full	0.648054	0.557971	0.096277	1.579978	0.046443	0.000000	0.131221
		DVO object	13.389800	7.286947	0.795192	118.719200	0.536287	0.068528	10.449670
		GICP	35.288471	34.644783	19.338661	52.428825	3.139615	1.794441	4.786530
teddy	turntable	KinFu	6.681221	4.838645	0.490111	28.670773	0.428782	0.000000	2.723712
		FM-pt-SDF	6.013536	4.997223	0.133129	14.290857	0.459640	0.039565	1.689293
		FF-pt-SDF	3.837025	3.375415	0.361418	11.832083	0.303261	0.000000	1.285098
		proposed	3.086600	2.567249	0.313107	11.061914	0.256314	0.000000	0.882037
		DVO full	3.109319	1.854968	0.101436	18.332270	0.137100	0.000000	2.638462
	handheld	DVO object	28.253805	8.891199	0.241390	273.844269	0.713703	0.000000	20.057204
		GICP	11.997098	9.310331	0.441464	109.257233	1.432784	0.125115	11.633108
		KinFu	11.329130	7.843574	0.600309	81.003395	1.206707	0.000000	16.612198
		FM-pt-SDF	32.527649	17.369671	0.794782	213.906952	1.903111	0.111906	30.586153
		FF-pt-SDF	14.524949	10.051404	0.880819	64.981255	1.879210	0.000000	14.383840
		proposed	6.494926	5.548774	0.661384	25.016457	0.548744	0.000000	3.915095

Table 5. Absolute trajectory errors on Kinect sequences

object	traj.	method	translational error [mm/pose]				angular error [°/frame]		
			RMS	avg	min	max	avg	min	max
bunny	turn table	DVO full	33.928905	27.712349	0.345030	53.208721	3.417176	0.000000	6.086864
		DVO object	371.171997	331.667694	5.163693	639.950745	40.990257	0.484567	60.616325
		GICP	821.131958	735.490601	19.400297	1192.072754	86.104621	1.923289	178.58955
	hand held	KinFu	93.645958	80.757339	3.997274	183.253296	7.853780	0.494163	17.906920
		FM-pt-SDF	126.819611	84.353554	0.772393	374.100372	9.369270	0.601332	45.364953
		FF-pt-SDF proposed	88.354607	81.223457	1.504171	151.1808105	9.140825	0.318981	15.729487
teddy	turn table	DVO full	28.380400	25.406000	0.303766	50.206268	2.391614	0.000000	4.495539
		DVO object	564.247070	535.060059	8.443319	784.423983	101.416669	0.571981	144.442135
		GICP	505.332123	446.562469	3.459878	731.137024	84.804804	0.399584	179.643791
	hand held	KinFu	75.560539	59.147900	2.139833	170.833099	7.452401	0.414958	22.318996
		FM-pt-SDF	147.790115	119.573242	1.281658	261.855713	16.819570	0.362616	33.705965
		FF-pt-SDF proposed	134.876831	111.575729	3.137326	259.864288	21.958617	0.222087	47.997873
Kenny	turn table	DVO full	34.035957	27.005966	0.260590	62.448524	2.781908	0.000000	5.433274
		DVO object	167.901642	131.570190	1.181798	366.219299	12.394495	0.088469	27.325045
		GICP	902.025879	802.127380	6.365053	1315.675537	85.268592	0.560927	179.613445
	hand held	KinFu	43.904949	42.212215	4.383021	69.306740	3.734392	0.369035	5.777598
		FM-pt-SDF	209.852859	142.552185	2.731610	390.551514	21.689699	0.243893	57.173815
		FF-pt-SDF proposed	71.923714	65.631744	3.863447	96.309464	3.841092	0.349426	6.606440
leopard	turn table	DVO full	172.405991	129.935989	1.607449	251.371384	5.848975	0.096913	11.067283
		DVO object	566.585388	439.341705	3.481557	1056.536743	29.159164	0.039565	71.957793
		GICP	634.769409	578.830322	20.723282	921.179688	91.724382	2.185780	179.446693
	hand held	KinFu	70.441925	45.486603	1.126494	265.704010	5.590135	0.494163	32.433539
		FM-pt-SDF	153.281570	119.255440	4.024746	324.670807	10.176015	0.360452	35.882351
		FF-pt-SDF proposed	132.567200	122.002228	5.929694	244.887390	5.775285	0.296075	14.524783
tank	turn table	DVO full	36.705437	30.964493	0.235747	59.495354	2.919780	0.000000	5.187945
		DVO object	499.389648	455.564758	2.885160	756.796021	101.364233	0.228312	179.370827
		GICP	865.466187	785.741821	13.282857	1180.146362	94.496402	1.296618	179.309473
	hand held	KinFu	311.531097	279.263733	14.088740	514.703430	28.249626	1.270396	52.330459
		FM-pt-SDF	676.322693	511.410522	21.644049	1261.853882	59.334671	1.959974	179.896978
		FF-pt-SDF proposed	226.965179	188.209894	2.528077	448.067352	18.876184	1.234145	39.916784
bunny	turn table	DVO full	15.105408	14.005893	0.153245	22.619125	2.213895	0.000000	3.915095
		DVO object	793.046143	738.246643	4.711806	1271.999023	100.726428	0.654913	168.434617
		GICP	814.516602	736.681855	2.360406	1147.158680	94.350147	0.271242	179.477487
	hand held	KinFu	527.665894	458.603394	1.019482	802.491333	111.493312	0.104678	179.622440
		FM-pt-SDF	618.403931	479.840637	2.212128	1087.744385	68.929541	0.303902	179.972515
		FF-pt-SDF proposed	540.082031	466.242065	0.878977	748.750916	89.639398	0.227228	176.405769
teddy	turn table	DVO full	42.496383	36.152054	4.296674	863.777588	45.523151	0.433410	173.975081
		DVO object	534.076599	472.621338	1.716390	873.024841	39.104075	0.131221	174.321084
		GICP	914.406616	848.324219	11.603577	1178.810303	103.168753	0.130283	179.896318
	hand held	KinFu	351.326019	180.486450	21.488716	1135.789703	15.528135	1.224595	110.775163
		FM-pt-SDF	178.526337	134.085754	0.161490	296.258606	13.860103	0.137056	30.508799
		FF-pt-SDF proposed	149.819031	128.177139	1.814520	224.312805	10.606876	0.220287	16.763097
Kenny	turn table	DVO full	48.705437	40.150893	0.153245	62.448524	5.848975	0.096913	11.067283
		DVO object	566.585388	439.341705	3.481557	1056.536743	29.159164	0.039565	71.957793
		GICP	634.769409	578.830322	20.723282	921.179688	91.724382	2.185780	179.446693
	hand held	KinFu	70.441925	45.486603	1.126494	265.704010	5.590135	0.494163	32.433539
		FM-pt-SDF	153.281570	119.255440	4.024746	324.670807	10.176015	0.360452	35.882351
		FF-pt-SDF proposed	42.496383	36.152054	4.296674	863.777588	45.523151	0.433410	173.975081
leopard	turn table	DVO full	45.753986	33.997025	0.221306	100.051064	3.3232000	0.000000	8.173156
		DVO object	499.389648	455.564758	2.885160	756.796021	101.364233	0.228312	179.370827
		GICP	865.466187	785.741821	13.282857	1180.146362	94.496402	1.296618	179.309473
	hand held	KinFu	311.531097	279.263733	14.088740	514.703430	28.249626	1.270396	52.330459
		FM-pt-SDF	676.322693	511.410522	21.644049	1261.853882	59.334671	1.959974	179.896978
		FF-pt-SDF proposed	86.089172	78.885002	1.252629	129.455612	6.447838	0.079129	10.634574
bunny	turn table	DVO full	15.238122	13.959785	0.339947	34.741146	1.170635	0.000000	2.597500
		DVO object	1122.553054	956.133667	2.458684	1956.195801	64.399055	0.189746	173.290513
		GICP	598.021057	523.312866	3.585272	883.930725	87.912891	0.546795	179.518907
	hand held	KinFu	186.961929	95.153488	2.891815	630.442261	13.256021	0.104678	130.671260
		FM-pt-SDF	128.666992	73.992729	7.805862	480.484650	5.715068	0.772273	38.829481
		FF-pt-SDF proposed	124.927132	109.471481	3.444192	234.942047	13.366919	0.282548	21.813558
tank	turn table	DVO full	31.825539	25.973804	0.264588	55.138569	2.632574	0.000000	4.815394
		DVO object	118.359108	114.202049	9.273656	182.812302	5.388507	0.468136	7.772098
		GICP	863.893616	775.333252	17.718937	1235.005249	88.377310	2.128081	178.725756
	hand held	KinFu	51.355663	45.050194	6.772376	126.926216	4.322621	0.628071	12.353903
		FM-pt-SDF	86.818504	64.199203	2.174666	188.616577	5.965823	0.111906	18.070970
		FF-pt-SDF proposed	80.365967	64.029449	1.083399	174.732941	4.000227	0.189746	11.388043
teddy	turn table	DVO full	22.920689	20.615637	0.649209	40.4706638	5.102309	0.000000	8.758091
		DVO object	535.780273	473.147552	3.998750	807.867310	39.445538	0.282548	67.877130
		GICP	450.801025	401.273407	2.827571	701.370361	82.574964	0.414958	179.937097
	hand held	KinFu	74.610977	59.879650	1.147904	222.909119	7.307819	0.725234	31.961225
		FM-pt-SDF	233.492722	205.186630	5.127839	435.563080	31.431690	0.347179	71.045585
		FF-pt-SDF proposed	292.696777	257.175995	5.413389	478.673645	57.753292	0.506676	110.045511

DVO-full DVO-obj GICP KinFu FM-pt-SDF FF-pt-SDF proposed

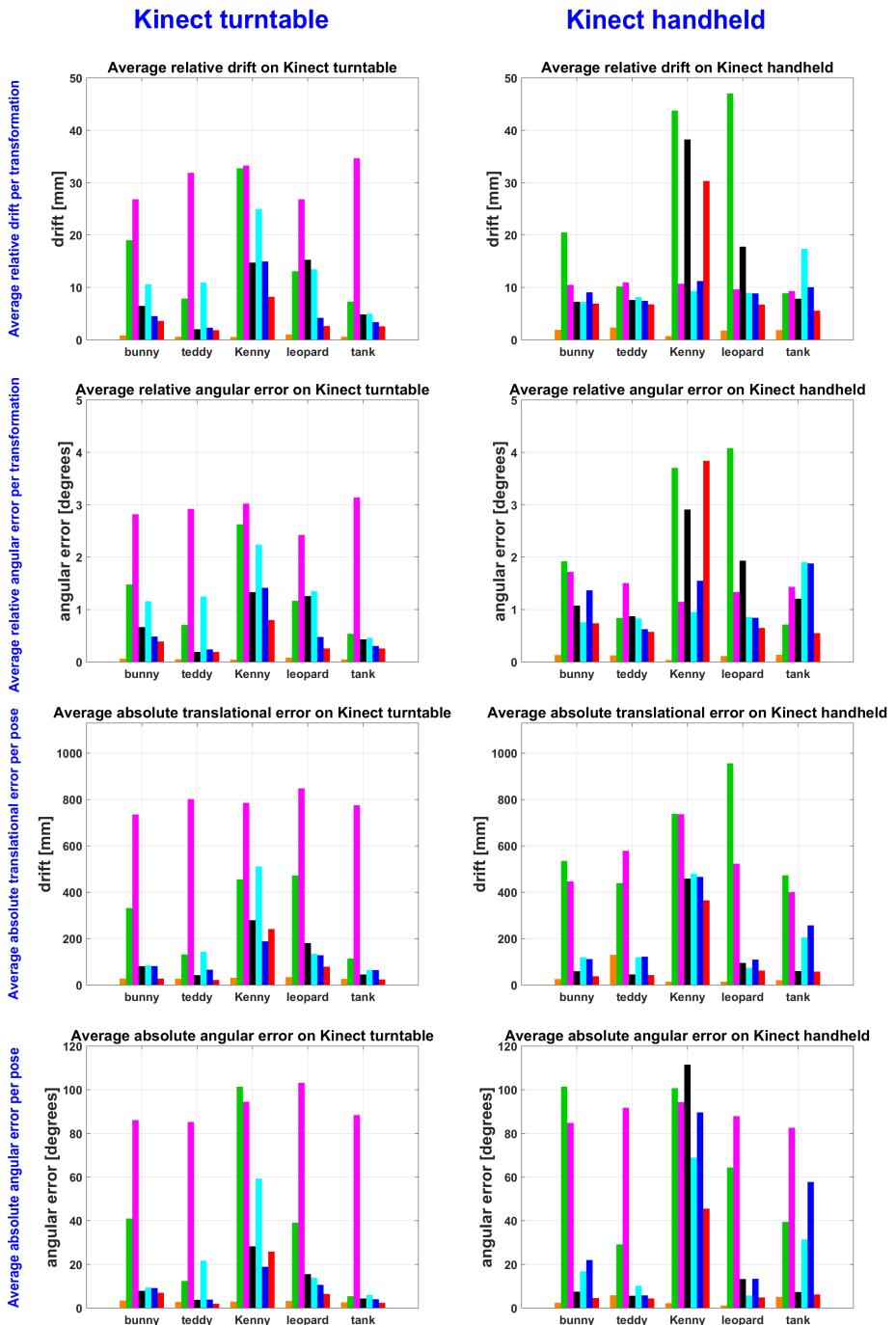


Fig. 3. Average tracking errors on Kinect sequences

2.3 Tracking on the TUM RGB-D Benchmark

Table 6. Relative pose errors on RGB-D benchmark [10]

sequence	method	drift [mm/frame]				angular error [°/frame]		
		RMS	avg	min	max	avg	min	max
fr1/plant	DVO	7.282877	5.792006	0.091372	37.988911	0.401266	0.000000	5.606332
	GICP	35.550060	20.600349	1.755276	796.881348	0.943883	0.055953	18.393562
	KinFu	29.956520	7.828046	0.333295	784.654175	0.897105	0.000000	63.796051
	FM-pt-SDF	28.436991	14.015480	0.587226	286.495239	1.264915	0.000000	22.258250
	FF-pt-SDF	6.747571	4.685713	0.286812	112.258728	0.518290	0.000000	8.724033
	proposed	8.505032	4.812376	0.257069	178.943863	0.525493	0.000000	9.074424
fr2/flower bouquet	DVO	2.988011	2.245177	0.129830	33.334740	0.205982	0.000000	2.354722
	GICP	51.701706	10.002730	0.420140	920.977417	0.420760	0.000000	15.866808
	KinFu	72.529808	18.513323	0.166472	1329.229980	1.373548	0.000000	115.369411
	FM-pt-SDF	4.903846	3.805674	0.090923	23.446049	0.346267	0.000000	1.756974
	FF-pt-SDF	10.608439	6.937403	0.232274	148.658875	0.433326	0.000000	8.129045
	proposed	2.591239	2.135890	0.118856	14.211413	0.262837	0.000000	1.280216
fr3/teddy	DVO	5.175436	4.063709	0.136940	48.679550	0.364938	0.000000	3.214843
	GICP	59.641399	19.115118	0.118683	1378.518066	1.086339	0.000000	79.820561
	KinFu	31.009665	4.920252	0.134037	940.139038	0.649807	0.000000	33.697436
	FM-pt-SDF	17.975712	10.215406	0.169401	184.999252	1.037215	0.000000	16.258346
	FF-pt-SDF	16.244909	4.068722	0.140474	460.743744	0.645698	0.000000	49.938365
	proposed	7.668943	3.232421	0.031339	232.944717	0.591318	0.000000	29.989766

Table 7. Absolute pose errors on RGB-D benchmark [10]

sequence	method	drift [mm/frame]				angular error [°/frame]		
		RMS	avg	min	max	avg	min	max
fr1/plant	DVO	265.212097	252.963959	7.706776	431.978424	25.089190	0.508218	49.238439
	GICP	1634.829346	1527.358276	36.871098	2723.447266	120.081491	1.684189	79.813826
	KinFu	883.577209	784.164856	1.745949	1316.959717	57.851438	0.240663	111.619809
	FM-pt-SDF	211.425079	124.463234	2.535587	778.685120	12.271404	0.167859	76.178245
	FF-pt-SDF	716.240051	621.478577	3.114061	1019.996399	30.984599	0.479697	59.811494
	proposed	130.432480	117.055527	2.731817	261.371216	9.973510	0.331022	24.153086
fr2/flower bouquet	DVO	1020.018677	900.273010	0.335561	1390.096191	60.006552	0.000000	99.930478
	GICP	2094.346191	1987.562134	2.362186	3165.697510	86.719919	0.111906	179.976050
	KinFu	996.424927	716.543518	1.020412	1764.560425	57.250750	0.111906	179.304635
	FM-pt-SDF	131.368195	123.198097	0.882893	228.602997	10.109181	0.104678	15.634462
	FF-pt-SDF	2104.010498	1934.969482	0.581525	3088.211426	110.464702	0.088469	179.941818
	proposed	205.243713	181.570419	1.040417	362.441559	13.035417	0.000000	26.335240
fr3/teddy	DVO	348.344391	303.327545	0.858319	673.209900	16.541975	0.000000	36.320585
	GICP	2601.178711	2013.626099	13.480266	5916.331055	101.366234	0.817565	179.898571
	KinFu	567.711548	265.846771	2.279144	1459.873047	6.36205	0.193827	69.852982
	FM-pt-SDF	1220.503784	1141.130249	1.301691	1858.237915	88.614109	0.000000	173.010515
	FF-pt-SDF	1060.396973	934.780090	1.414034	1751.351074	32.956456	0.111906	153.218310
	proposed	247.342026	227.097565	2.102742	495.531647	15.944466	0.088469	44.824430

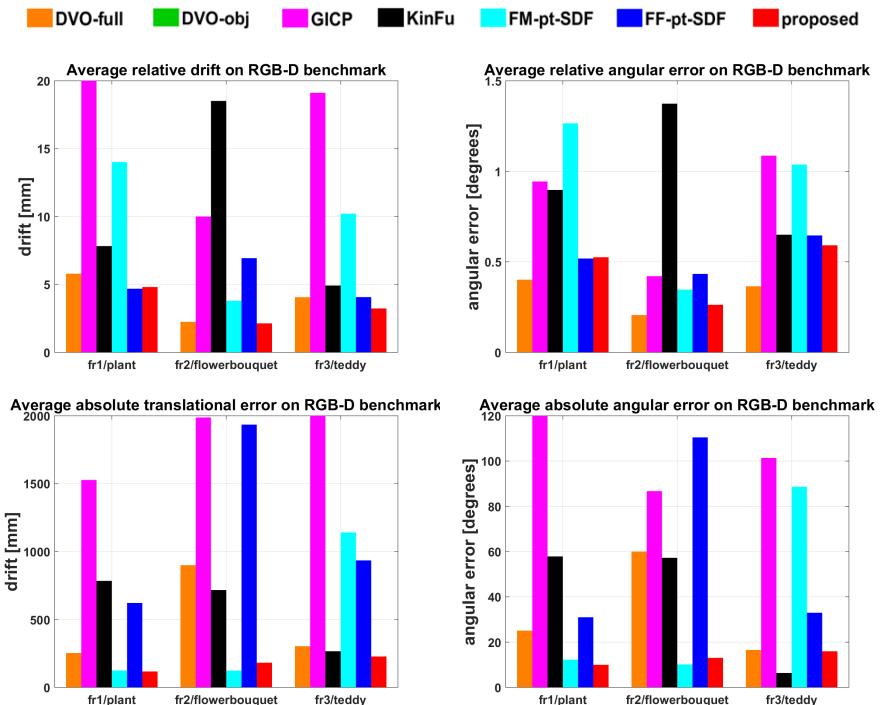


Fig. 4. Average tracking errors on RGB-D benchmark [10]

3 Video

The accompanying video shows qualitative results from our reconstruction pipeline. It follows our system as it tracks the camera motion on the *tank Kinect turntable* sequence. Next, the meshes before and after pose refinement are juxtaposed, zooming onto misalignment details that have been recovered during the optimization. Finally, we display results from the high quality industrial sensor.

4 Qualitative Comparisons on Industrial Quality Data

We display the outputs of the evaluated reconstruction systems on the sequences captured with the high-quality industrial scanner.¹ For fairness with *KinFu*, we display our meshes both without and with refinement. The method of Kehl *et al.* includes g²o pose graph optimization by default, and for each object we display the version with better reconstruction (*full* or *object*).

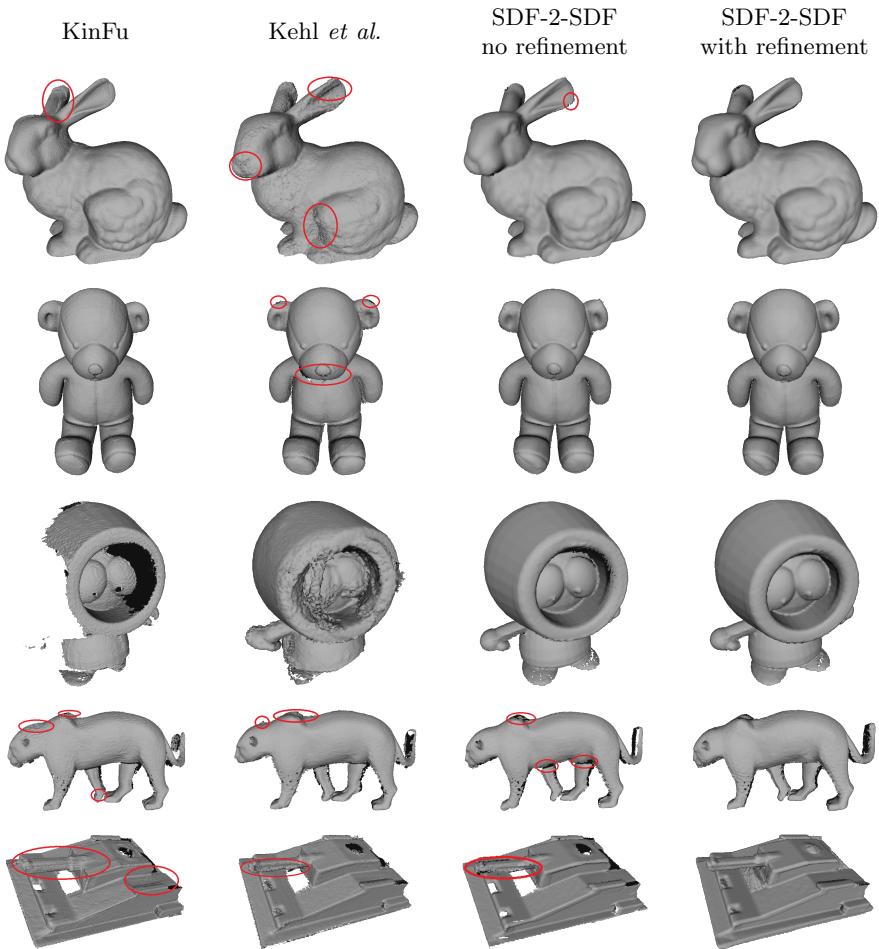


Fig. 5. Comparison of untextured reconstructions with high quality industrial sensor. Object poses might appear slightly different, since models yielded by different methods are non-identical. Fine structures cause related approaches to fail (on *Kenny*) or to exhibit misalignment errors (on *bunny*'s ears, *tank*'s gun, connection of *leopard*'s halves)

¹ Note: the holes on the leopard's tail and legs are not registration artifacts: they occur on regions of black color, where the used industrial sensor cannot capture data.

5 Magnified Figures

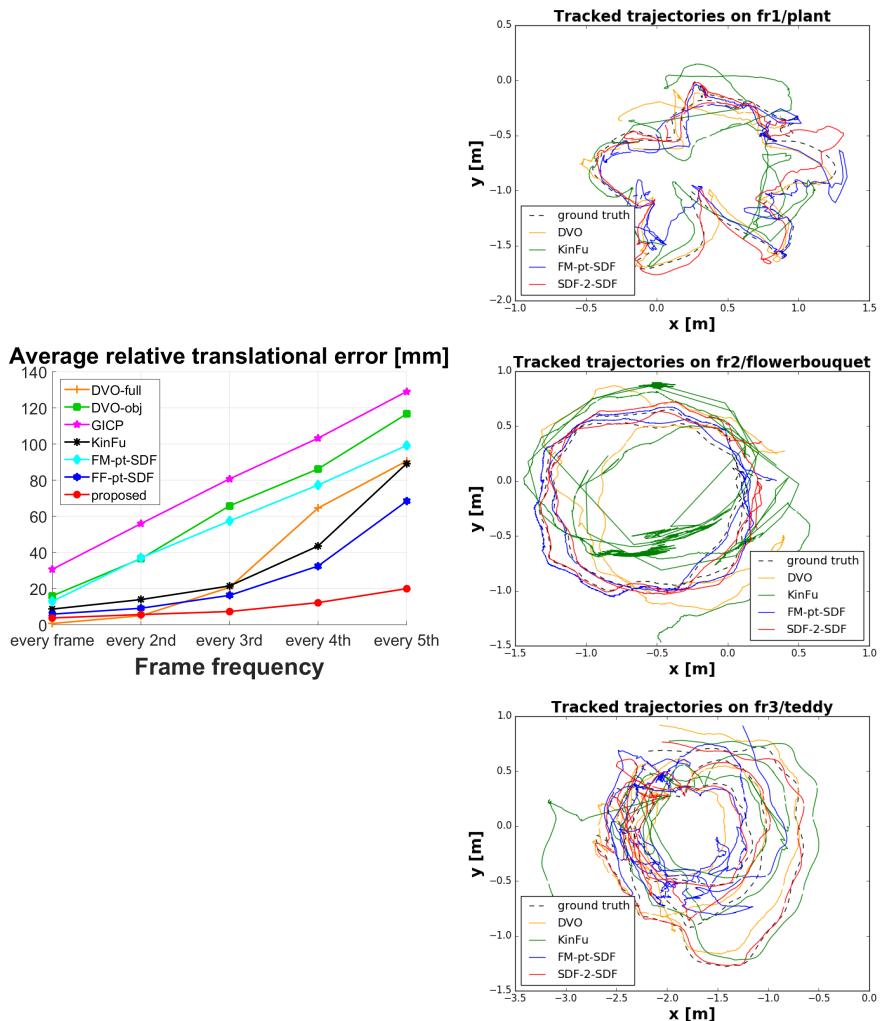


Fig. 6. Magnified version of Figure 4 from the main paper: convergence analysis (left) and estimated trajectories on the TUM RGB-D benchmark [10] (right)

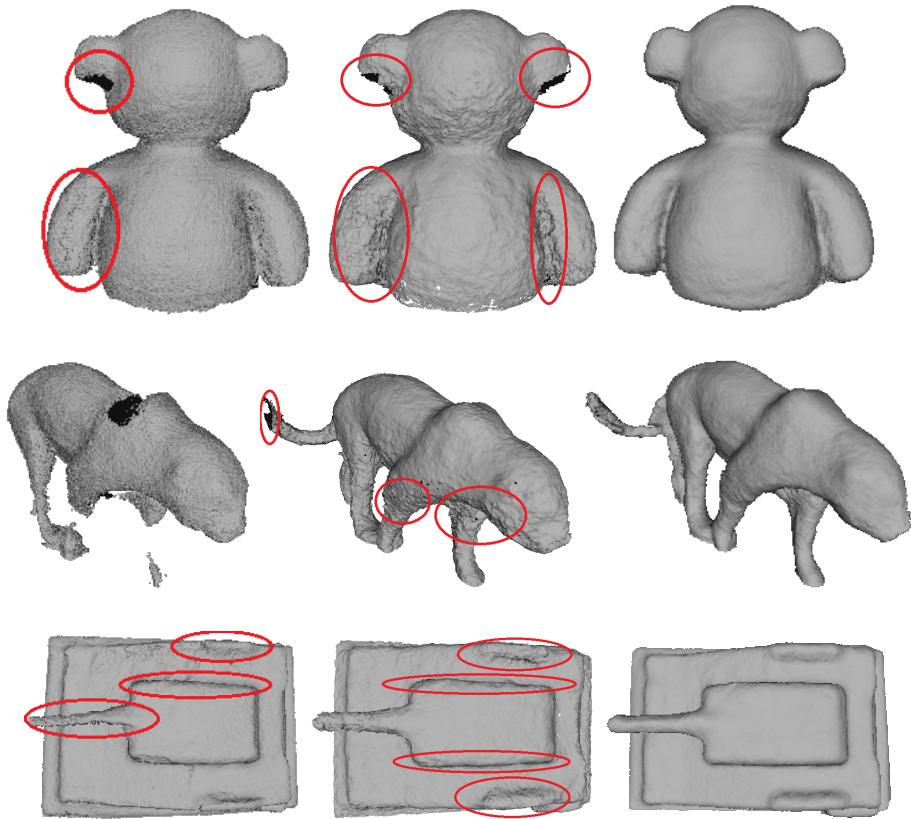


Fig. 7. Magnified version of the top row of Figure 5 from the main paper: qualitative comparisons on Kinect data

6 Mathematical Derivations

Derivation of **Eq. 13-17** (*Taylor expansion and linear system for camera tracking*):

$$\nabla_{\xi} \phi = \frac{d\phi}{d\xi} = \frac{d\phi}{d\mathbf{X}} \frac{d\mathbf{X}}{d\xi} = \nabla_{\mathbf{x}} \phi \begin{pmatrix} 1 & 0 & 0 & 0 & y_3 & -y_2 \\ 0 & 1 & 0 & -y_3 & 0 & y_1 \\ 0 & 0 & 1 & y_2 & -y_1 & 0 \end{pmatrix} = (\mathbf{I}_{3 \times 3} \mid -\mathbf{y}_x), \quad (1)$$

where $\mathbf{X} = \mathbf{y}(\xi)$ and $\mathbf{I}_{3 \times 3}$ is the 3×3 identity matrix.

$$\phi(\xi) = \phi(\xi^k) + \nabla_{\xi} \phi(\xi^k)(\xi - \xi^k) = \phi(\xi^k) - \nabla_{\xi} \phi(\xi^k)\xi^k + \nabla_{\xi} \phi(\xi^k)\xi \quad (2)$$

$$\begin{aligned} E_{geom}(\xi) &= \frac{1}{2} \sum_{voxels} (\phi_{ref} - \phi_{cur}(\xi))^2 = \\ &= \frac{1}{2} \sum_{voxels} (\phi_{ref} - \phi_{cur}(\xi^k) + \nabla_{\xi} \phi_{cur}(\xi^k)\xi^k - \nabla_{\xi} \phi_{cur}(\xi^k)\xi)^2 = \\ &= \frac{1}{2} \sum_{voxels} \left((\phi_{ref} - \phi_{cur}(\xi^k) + \nabla_{\xi} \phi_{cur}(\xi^k)\xi^k)^2 + \right. \\ &\quad \left. + \xi^\top \nabla_{\xi}^\top \phi_{cur}(\xi^k) \nabla_{\xi} \phi_{cur}(\xi^k) \xi - \right. \\ &\quad \left. - 2(\phi_{ref} - \phi_{cur}(\xi^k) + \nabla_{\xi} \phi_{cur}(\xi^k)\xi^k) \nabla_{\xi} \phi_{cur}(\xi^k)\xi \right) \end{aligned} \quad (3)$$

$$\begin{aligned} \frac{dE_{geom}}{d\xi} &= \frac{1}{2} \sum_{voxels} \left(0 + 2 \nabla_{\xi}^\top \phi_{cur}(\xi^k) \nabla_{\xi} \phi_{cur}(\xi^k) \xi - \right. \\ &\quad \left. - 2(\phi_{ref} - \phi_{cur}(\xi^k) + \nabla_{\xi} \phi_{cur}(\xi^k)\xi^k) \nabla_{\xi}^\top \phi_{cur}(\xi^k) \right) = \\ &= \sum_{voxels} \left(\nabla_{\xi}^\top \phi_{cur}(\xi^k) \nabla_{\xi} \phi_{cur}(\xi^k) \xi - \right. \\ &\quad \left. - (\phi_{ref} - \phi_{cur}(\xi^k) + \nabla_{\xi} \phi_{cur}(\xi^k)\xi^k) \nabla_{\xi}^\top \phi_{cur}(\xi^k) \right). \end{aligned} \quad (4)$$

$$\begin{aligned} \mathbf{A} &= \sum_{voxels} \left(\nabla_{\xi}^\top \phi_{cur}(\xi^k) \nabla_{\xi} \phi_{cur}(\xi^k) \right) \\ \mathbf{b} &= \sum_{voxels} \left((\phi_{ref} - \phi_{cur}(\xi^k) + \nabla_{\xi} \phi_{cur}(\xi^k)\xi^k) \nabla_{\xi}^\top \phi_{cur}(\xi^k) \right) \end{aligned} \quad (5)$$

$$\frac{dE_{geom}}{d\xi} = \mathbf{A}\xi - \mathbf{b}$$

$$\Rightarrow \xi^* = \mathbf{A}^{-1}\mathbf{b}$$

$$\xi^{k+1} = \xi^k + \beta(\xi^* - \xi^k)$$

Derivation of **Eq. 18** (*derivative of the normal vector energy term*):

$$\begin{aligned}
 \frac{dE_{norm}}{d\xi_j} &= \sum_{\substack{\text{surface} \\ \text{voxels}}} -\frac{d\bar{\mathbf{n}}_{ref}}{d\xi_j} \cdot \bar{\mathbf{n}}_{cur}(\xi) - \bar{\mathbf{n}}_{ref} \cdot \frac{d\bar{\mathbf{n}}_{cur}(\xi)}{d\xi_j} = \\
 &= \sum_{\substack{\text{surface} \\ \text{voxels}}} -\bar{\mathbf{n}}_{ref} \cdot \frac{d\bar{\mathbf{n}}_{cur}(\xi)}{d\xi_j} = \sum_{\substack{\text{surface} \\ \text{voxels}}} -\bar{\mathbf{n}}_{ref} \cdot \left(\frac{d\bar{\mathbf{n}}_{cur}(\xi)}{d\mathbf{V}} \frac{d\mathbf{V}}{d\xi_j} \right) = \\
 &= \sum_{\substack{\text{surface} \\ \text{voxels}}} -\bar{\mathbf{n}}_{ref} \cdot \left(\frac{d\bar{\mathbf{n}}_{cur}(\xi)}{d\mathbf{V}} \frac{d\mathbf{V}}{d\xi} \frac{d\xi}{d\xi_j} \right) = \\
 &= \sum_{\substack{\text{surface} \\ \text{voxels}}} -\bar{\mathbf{n}}_{ref} \cdot \left((\nabla_{\mathbf{x}} \bar{\mathbf{n}}_{cur}(\xi)) (\mathbf{I}_{3 \times 3} \mid -(\mathbf{V}(\xi^{-1})) \times) \delta_j \right),
 \end{aligned} \tag{6}$$

where δ_j is a 6-element vector of zeros with j^{th} component 1.

Derivation of **Eq. 19-20** (*gradient descent for pose optimization*):

$$\begin{aligned}
 \frac{dE_{geom}}{d\xi} &= \frac{1}{2} \sum_{\text{voxels}} 2(\phi_{avg} - \phi_{cur}(\xi)) \frac{d(-\phi_{cur}(\xi))}{d\xi} = \\
 &= \sum_{\text{voxels}} (\phi_{cur}(\xi) - \phi_{avg}) \frac{d\phi_{cur}(\xi)}{d\xi} = \\
 &= \sum_{\text{voxels}} (\phi_{cur}(\xi) - \phi_{avg}) \frac{d\phi_{cur}(\xi)}{d\mathbf{V}} \frac{d\mathbf{V}}{d\xi} = \\
 &= \sum_{\text{voxels}} (\phi_{cur}(\xi) - \phi_{avg}) \nabla_{\xi} \phi_{cur}(\xi)
 \end{aligned} \tag{7}$$

$$\xi_p^{k+1} = \xi_p^k - \alpha \sum_{\text{voxels}} (\phi_{cur}(\xi_p^k) - \phi_{avg}) \nabla_{\xi} \phi_{cur}(\xi_p^k), \quad \forall \text{ camera } p \neq 0. \tag{8}$$

References

1. Kerl, C., Sturm, J., Cremers, D.: Dense Visual SLAM for RGB-D Cameras. In: Proceedings of the International Conference on Intelligent Robot Systems (IROS). (2013)
2. Kehl, W., Navab, N., Ilic, S.: Coloured Signed Distance Fields for full 3D Object Reconstruction. In: Proceedings of the British Machine Vision Conference (BMVC). (2014)
3. PCL: Point Cloud Library. <http://pointclouds.org/> Last accessed: March 9, 2016.
4. Segal, A., Haehnel, D., Thrun, S.: Generalized-ICP. In: Proceesings of Robotics: Science and Systems (RSS). (2009)
5. : KinectFusion Implementation in the Point Cloud Library (PCL). <https://github.com/PointCloudLibrary/pcl/tree/master/gpu/kinfu> Last accessed: November 6, 2015.
6. Newcombe, R.A., Izadi, S., Hilliges, O., Molyneaux, D., Kim, D., Davison, A.J., Kohli, P., Shotton, J., Hodges, S., Fitzgibbon, A.: KinectFusion: Real-Time Dense Surface Mapping and Tracking. In: 10th International Symposium on Mixed and Augmented Reality (ISMAR). (2011)
7. Canelhas, D.: sdf_tracker - ROS Wiki. http://wiki.ros.org/sdf_tracker Last accessed: March 9, 2016.
8. Canelhas, D.R., Stoyanov, T., Lilienthal, A.J.: SDF Tracker: A Parallel Algorithm for On-line Pose Estimation and Scene Reconstruction from Depth Images. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). (2013)
9. Bylow, E., Sturm, J., Kerl, C., Kahl, F., Cremers, D.: Real-Time Camera Tracking and 3D Reconstruction Using Signed Distance Functions. In: Robotics: Science and Systems Conference (RSS). (2013)
10. Sturm, J., Engelhard, N., Endres, F., Burgard, W., Cremers, D.: A Benchmark for the Evaluation of RGB-D SLAM Systems. In: Proceedings of the International Conference on Intelligent Robot Systems (IROS). (2012)