Adaptive Color Structured Light for Calibration and Shape Reconstruction
- Supplementary Materials -

Xin Dong*
Southwest University

Haibin Ling†
Stony Brook University

Bingyao Huang‡
Southwest University

1 Introduction

In the supplementary materials, We provide more detailed experimental results and data. First, to analyze the methods of adaptive color SL and MAP more deeply, we conduct ablation studies and we will show more detailed experimental results in § 2. Then, to further verify the accuracy of the calibration, the reconstruction results are shown in § 3. Finally, we show the quantified results of the single-shot reconstruction in § 4. In addition to the presentation of the experimental results, we also briefly display different poses of the calibration board under the imaging setting and ambient light condition in Fig. 1 and Fig. 2. We will release the code and all data upon paper acceptance.

2 Ablation Studies

To verify the effectiveness of adaptive color SL and MAP more deeply, we come to the ablation experiment. In the ablation experiment, we conduct an experiment using Otsu [4] to perform color detection on the colors of the adaptive color SL, termed as **Ours w/o MAP**. Due to $\mathbf{Q}_{1:N}$ are obtained based on the generation process of adaptive color SL and MAP needs to use $\mathbf{Q}_{1:N}$, the fixed color SL does not have corresponding $\mathbf{Q}_{1:N}$ and MAP cannot be used to perform color detection on the colors of fixed color SL.

The comparisons of color detection and grid segmentation performance under different imaging settings and ambient light conditions for Huang [2], Ours w/o MAP and Ours are shown in Tab. 1 and Tab. 2.

Calibration RMS reprojection errors (pixels) of the camera, the projector and stereo under different imaging settings and ambient light conditions for Moreno & Taubin [3], Huang [2], Ours w/o MAP and Ours are shown in Tab. 3 and Tab. 4.

It should be noted that the performance of Ours w/o MAP varies greatly under different imaging settings and ambient light conditions. Otsu [4] relies on the characteristics of the color hue distribution, that is, when the intra-class variances of the hue distributions of different colors are very different, this can easily cause Otsu [4] to make mistakes, and please refer to [5] for detailed proof. The MAP no longer constrains the characteristics of the color hue distribution, as long as the color distinction of different colors is large.

3 Reconstruction

To further verify the accuracy of the calibration, the obtained calibration parameters of the four methods are also used to reconstruct point clouds for different real objects using Moreno & Taubin's [3] Gray-coded SL patterns.

The point cloud alignment errors (mm) of David (mm), girl (mm) and box (mm) for Moreno & Taubin [3], Huang [2], Ours w/o MAP and Ours under different imaging settings and ambient light conditions are shown in Tab. 5, Tab. 6, Tab. 7, Tab. 8, Tab. 9 and Tab. 10.

*e-mail: dongxin12345@email.swu.edu.cn
†e-mail: hling@cs.stonybrook.edu
‡e-mail: bhuang@swu.edu.cn. Corresponding author

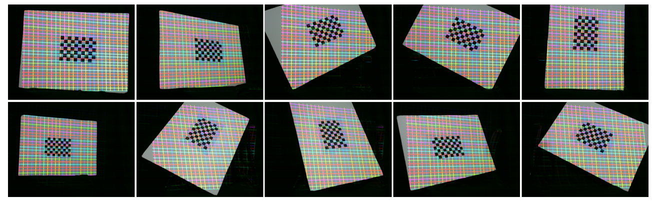

Figure 1: The different poses of the calibration board in Setting2.

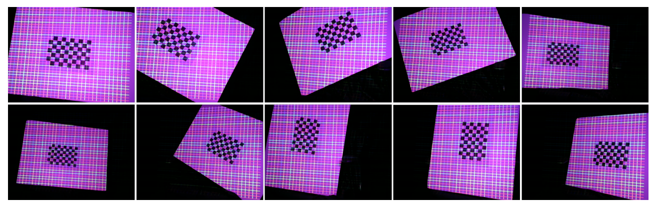

Figure 2: The different poses of the calibration board in Light2.

4 single-shot Reconstruction

The methods that are applied to scan the object from different views (about 7-12 shots) and merge the point clouds using ICP [1] are suffixed with **(merged)**. The number of reconstructed points and RMS point cloud alignment errors are shown in Tab. 11. Because Huang [2] and Ours w/o MAP has few points, the point cloud merge failed and is excluded from the table. Even, because the points reconstructed by Ours w/o MAP are too few, there is not enough point cloud information for point cloud alignment.

References

[1] P. J. Besl and N. D. McKay. Method for registration of 3-d shapes. In *Sensor Fusion IV: Control Paradigms and Data Structures*, vol. 1611, pp. 586–606. SPIE, 1992.
[2] B. Huang, Y. Tang, S. Ozdemir, and H. Ling. A fast and flexible projector-camera calibration system. *IEEE Transactions on Automation Science and Engineering*, 18(3):1049–1063, 2020.
[3] D. Moreno and G. Taubin. Simple, accurate, and robust projector-camera calibration. In *International Conference on 3d Imaging, Modeling, Processing, Visualization & Transmission*, pp. 464–471. IEEE, 2012.
[4] N. Otsu. A threshold selection method from gray-level histograms. *IEEE Transactions on Systems, Man, and Cybernetics*, 9(1):62–66, 1979.
[5] X. Xu, S. Xu, L. Jin, and E. Song. Characteristic analysis of otsu threshold and its applications. *Pattern Recognition Letters*, 32(7):956–961, 2011.

Table 1: Comparison of color detection accuracy, #extracted nodes and decoded nodes between Huang's [2] and our method in different imaging settings.

Setting	Accuracy↑			#Extr. nodes↑			#Deco. nodes↑		
	Huang	Ours w/o MAP	Ours	Huang	Ours w/o MAP	Ours	Huang	Ours w/o MAP	Ours
Setting1	0.9438	**0.9635**	0.9630	**3388**	3381	3381	**2255**	1992	1992
Setting2	0.8837	0.9371	**0.9522**	**3109**	3102	3102	1428	1883	**1889**
Setting3	0.8774	0.9535	**0.9546**	**3578**	3456	3456	1470	2104	**2108**
Setting4	0.8353	**0.9516**	0.9503	3814	5010	**5010**	1064	2609	**2609**
Setting5	**0.9265**	0.6996	0.9209	6788	8782	**8782**	3099	199	**4424**
Setting6	**0.9054**	0.6420	0.8563	9938	10254	**10254**	4477	383	**5147**
Setting7	0.7179	0.4793	**0.8882**	3916	4118	**4118**	771	286	**2043**

Table 2: Comparison of color detection accuracy, #extracted nodes and decoded nodes between Huang's [2] and our method under different ambient light conditions.

Light	Accuracy↑			#Extr. nodes↑			#Deco. nodes↑		
	Huang	Ours w/o MAP	Ours	Huang	Ours w/o MAP	Ours	Huang	Ours w/o MAP	Ours
Light1	0.7739	0.7221	**0.9230**	5498	5512	**5512**	1938	1016	**3170**
Light2	0.7905	0.6998	**0.8863**	5487	5505	**5505**	1701	686	**2950**
Light3	0.7938	0.6344	**0.8462**	5563	5571	**5571**	1993	571	**2923**
Light4	0.7842	0.7056	**0.8976**	5699	5674	**5674**	1327	731	**3034**
Light5	0.7198	0.4283	**0.8857**	**7021**	6993	6993	1077	96	**3596**
Light6	0.7752	0.3231	**0.8408**	8290	8888	**8888**	2526	118	**4549**

Table 3: Comparison of calibration reprojection errors between Moreno & Taubin [3], Huang [2] and Ours in different imaging settings. Note, MT stands for Moreno & Taubin [3] and '——' stands for the calibration failed due to failed optimization.

Setting	$RMSE^c$↓				$RMSE^p$↓				$RMSE^{stereo}$↓			
	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours
Setting1	**0.1542**	0.2403	0.2373	0.2373	0.6966	0.2614	0.2608	**0.2608**	0.5045	0.2511	0.2493	**0.2493**
Setting2	**0.1397**	0.2165	0.2171	0.2213	1.2378	**0.2201**	0.2028	0.2049	0.8808	0.2183	**0.2101**	0.2132
Setting3	**0.2251**	0.2428	0.2317	0.2322	0.8638	0.2271	**0.2126**	0.2129	0.6312	0.2351	**0.2224**	0.2228
Setting4	**0.1712**	0.2619	0.2348	0.2348	2.6071	0.1790	0.1615	**0.1615**	1.8475	0.2243	0.2015	**0.2015**
Setting5	0.4047	0.2487	——	**0.2309**	2.0323	0.1835	——	**0.1680**	1.4653	0.2185	——	**0.2019**
Setting6	0.4904	0.3387	44.8472	**0.2378**	2.0266	0.5322	117.6157	**0.2318**	1.4744	0.4461	89.0077	**0.2348**
Setting7	**0.1290**	12.4804	31.7189	0.2495	1.2099	13.5481	183.4021	**0.2222**	0.8603	13.0252	131.6100	**0.2363**

Table 4: Comparison of calibration reprojection errors between Moreno & Taubin [3], Huang [2] and Ours under different ambient light conditions. Note, MT stands for Moreno & Taubin [3] and '——' stands for the calibration failed due to failed optimization.

Light	$RMSE^c$↓				$RMSE^p$↓				$RMSE^{stereo}$↓			
	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours
Light1	**0.1639**	0.2381	33.2597	0.2349	2.0851	0.1880	76.1839	**0.1844**	1.4790	0.2145	58.7801	**0.2111**
Light2	**0.1545**	0.2352	29.0905	0.2353	1.9476	0.1884	82.7199	**0.1883**	1.3815	0.2131	62.0034	0.2131
Light3	**0.1764**	0.2573	31.4283	0.2417	1.9410	0.2223	137.0736	**0.1886**	1.3781	0.2405	99.4407	**0.2168**
Light4	**0.1732**	0.2291	101.4924	0.2243	2.1967	0.1920	64726.2026	**0.1775**	1.5582	0.2114	45768.3930	**0.2023**
Light5	**0.2181**	1.7906	19.5362	0.2371	1.0249	83.9224	451.2493	**0.1994**	0.7409	59.3556	319.3803	**0.2191**
Light6	**0.1554**	6.5740	——	0.2176	3.6754	7.6561	——	**0.1761**	2.6012	7.1356	——	**0.1979**

Table 5: Comparison of point cloud alignment errors (mm) of David (mm) for Moreno & Taubin [3], Huang [2] and Ours in different imaging settings. Note, MT stands for Moreno & Taubin [3] and '——' stands for the failed reconstruction due to failed calibration or failed iterative closest point (ICP) [1].

Setting	Mean				Median				Standard deviation			
	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours
Setting1	1.6517	1.5494	1.5404	**1.5404**	1.3724	1.3083	1.2983	**1.2983**	1.1786	1.0324	1.0278	**1.0278**
Setting2	2.0382	1.5818	**1.4402**	1.4403	1.6409	1.2971	1.1713	**1.1706**	1.5942	1.1160	**1.0192**	1.0226
Setting3	2.3749	1.6867	1.5806	**1.5802**	1.8226	1.4040	**1.3378**	1.3395	2.0222	1.1699	**1.0498**	1.0509
Setting4	3.0323	1.6874	1.2942	**1.2942**	2.6606	1.2952	1.0101	**1.0101**	2.1332	1.3245	0.9872	**0.9872**
Setting5	3.9359	1.5844	——	**1.4829**	3.3976	1.2710	——	**1.1891**	2.7709	1.1688	——	**1.0826**
Setting6	2.9209	1.6296	——	**1.5969**	2.4442	1.2877	——	**1.2674**	2.1369	1.2040	——	**1.1763**
Setting7	2.0357	13.1628	855.6479	**1.6916**	1.6413	10.8821	679.5693	**1.4161**	1.5116	10.9154	789.0774	**1.1792**

Table 6: Comparison of point cloud alignment errors (mm) of girl (mm) for Moreno & Taubin [3], Huang [2] and Ours in different imaging settings. Note, MT stands for Moreno & Taubin [3] and '——' stands for the failed reconstruction due to failed calibration or failed iterative closest point (ICP) [1].

Setting	Mean				Median				Standard deviation			
	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours
Setting1	1.8939	1.7343	1.7249	**1.7249**	1.5983	1.4761	1.4694	**1.4694**	1.2860	1.1532	1.1430	**1.1430**
Setting2	1.9852	1.6296	1.3889	**1.3885**	1.7065	1.2782	**1.0920**	1.0953	1.3591	1.2391	1.0769	**1.0731**
Setting3	2.0830	1.6476	1.5968	**1.5940**	1.7342	1.3653	1.3344	**1.3329**	1.4713	1.1237	1.0812	**1.0801**
Setting4	4.1105	**1.4405**	1.1552	1.1552	3.9930	1.1436	0.9477	**0.9477**	2.5090	1.0319	0.7712	**0.7712**
Setting5	3.4947	1.7000	——	**1.6081**	2.7953	1.4089	——	**1.3379**	2.7879	1.1746	——	**1.1013**
Setting6	2.6449	1.9418	——	**1.8981**	2.1459	1.5997	——	**1.5641**	2.0528	1.4746	——	**1.4289**
Setting7	1.5500	15.9355	445.6534	**1.5157**	1.3049	12.8186	358.8123	**1.2762**	1.0187	12.3660	405.7690	**0.9922**

Table 7: Comparison of point cloud alignment errors (mm) of box (mm) for Moreno & Taubin [3], Huang [2] and Ours in different imaging settings. Note, MT stands for Moreno & Taubin [3] and '——' stands for the failed reconstruction due to failed calibration or failed iterative closest point (ICP) [1].

Setting	Mean				Median				Standard deviation			
	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours
Setting1	1.2292	1.1846	1.1785	**1.1785**	1.0422	1.0289	1.0203	**1.0203**	0.7817	0.7099	0.7077	**0.7077**
Setting2	1.2147	**0.6707**	0.6871	0.6759	1.0839	0.6168	0.6198	**0.6135**	0.6882	**0.3371**	0.3635	0.3526
Setting3	1.6082	0.8201	0.7697	**0.7693**	1.2960	0.7262	0.6979	**0.6977**	1.1212	0.4546	**0.4003**	0.4004
Setting4	2.8470	0.7664	0.7058	**0.7058**	2.2536	0.6519	0.6291	**0.6291**	2.1430	0.4779	0.3858	**0.3858**
Setting5	3.4014	0.9937	——	**0.9227**	2.9549	0.8623	——	**0.8086**	2.2771	0.5783	——	**0.5195**
Setting6	1.7350	**0.9034**	——	0.9150	1.4350	**0.8042**	——	0.8130	1.1942	**0.4841**	——	0.4957
Setting7	0.8195	15.3093	479.3653	**0.7626**	0.7312	10.8761	448.4462	**0.7066**	0.4497	13.9267	365.8526	**0.3756**

Table 8: Comparison of point cloud alignment errors (mm) of David (mm) for Moreno & Taubin [3], Huang [2] and Ours under different ambient light conditions. Note, MT stands for Moreno & Taubin [3] and '——' stands for the reconstruction failed due to failed calibration.

Light	Mean				Median				Standard deviation			
	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours
Light1	2.8537	1.7245	19.9866	**1.6993**	2.3395	1.4508	16.3468	**1.4012**	2.1911	**1.1837**	15.9126	1.1997
Light2	2.5882	1.7112	18.8148	**1.6949**	2.1269	1.4088	12.8129	**1.4036**	1.9622	1.2079	18.9484	**1.1792**
Light3	2.5606	1.7474	41.5068	**1.6879**	2.1045	1.4695	36.0995	**1.3936**	1.9397	1.1959	28.8163	**1.1867**
Light4	1.8423	1.6323	23.1846	**1.5484**	1.4937	1.2924	18.0835	**1.2317**	1.4548	1.2113	19.3719	**1.1362**
Light5	2.4852	9.2549	317.3085	**1.6698**	2.0388	7.7165	57.0003	**1.3862**	1.9099	7.3835	1527.6116	**1.1737**
Light6	2.3856	24.0016	——	**1.4273**	1.9974	20.0156	——	**1.1259**	1.7649	18.4220	——	**1.0493**

Table 9: Comparison of point cloud alignment errors (mm) of girl (mm) for Moreno & Taubin [3], Huang [2] and Ours under different ambient light conditions. Note, MT stands for Moreno & Taubin [3] and '——' stands for the reconstruction failed due to failed calibration.

Light	Mean				Median				Standard deviation			
	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours
Light1	2.7717	1.5352	18.4845	**1.5339**	2.4223	1.2399	15.3412	**1.2325**	1.9680	**1.0974**	14.9082	1.1027
Light2	2.4978	**1.4904**	10.0544	1.5625	2.1560	**1.2026**	7.6564	1.2495	1.7804	**1.0641**	8.8892	1.1372
Light3	2.4932	**1.5210**	28.3107	1.5685	2.1467	**1.2180**	21.4328	1.2486	1.7762	**1.0966**	29.5077	1.1443
Light4	1.7747	1.3671	10.8638	**1.3648**	1.5069	1.1129	8.8445	**1.1125**	1.2078	0.9614	8.7018	**0.9583**
Light5	3.0365	11.8014	523.8869	**1.5965**	2.6889	8.4410	144.2638	**1.3026**	2.0501	11.3126	3338.8298	**1.1286**
Light6	2.2320	12.7706	——	**1.4002**	1.8849	8.2654	——	**1.1010**	1.6335	17.7579	——	**1.0309**

Table 10: Comparison of point cloud alignment errors (mm) of box (mm) for Moreno & Taubin [3], Huang [2] and Ours under different ambient light conditions. Note, MT stands for Moreno & Taubin [3] and '——' stands for the reconstruction failed due to failed calibration.

Light	Mean				Median				Standard deviation			
	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours	MT	Huang	Ours w/o MAP	Ours
Light1	2.0242	1.0994	7.8760	**0.9879**	1.7807	0.9466	6.8096	**0.8643**	1.2878	0.6523	6.0891	**0.5447**
Light2	1.8009	**0.9911**	4.0474	1.0166	1.5790	**0.8655**	3.3318	0.8825	1.1242	**0.5538**	3.0599	0.5742
Light3	1.7836	1.0317	22.0487	**1.0038**	1.5616	0.8936	18.8423	**0.8762**	1.1136	0.5902	17.0161	**0.5611**
Light4	1.1591	0.9322	23.4383	**0.8971**	1.0171	0.8011	20.1127	**0.7776**	0.6627	0.5572	16.4948	**0.5276**
Light5	2.0851	19.2273	374.8015	**0.8622**	1.8998	13.2914	104.2295	**0.7709**	1.2650	17.4184	2439.9482	**0.4599**
Light6	1.6624	6.7214	——	**0.7413**	1.3911	5.1888	——	**0.6662**	1.0883	5.3716	——	**0.3904**

Table 11: Comparison of the number of reconstructed points and RMS point cloud alignment errors (mm) among Huang [2], Ours and Ours (merged), in a **carefully tuned** imaging setting and an **extreme** imaging setting. Note, '——' stands for the iterative closest point (ICP) [1] failed due to too few points.

Method	David (mm)				Fan (mm)				Box (mm)			
	A carefully tuned setting											
	#Points↑	Mean↓	Median↓	Std.↓	#Points↑	Mean↓	Median↓	Std.↓	#Points↑	Mean↓	Median↓	Std.↓
Huang	500	**1.22**	**0.97**	**0.80**	310	1.04	0.83	0.73	192	**0.68**	**0.61**	**0.46**
Ours w/o MAP	14	——	——	——	93	——	——	——	42	——	——	——
Ours	1113	1.26	1.00	0.87	729	1.07	0.88	0.71	704	0.76	0.65	0.70
Ours (merged)	**2754**	2.18	1.53	2.00	**1314**	**0.99**	**0.80**	**0.70**	**1043**	0.75	0.62	0.48
	An extreme setting											
	#Points↑	Mean↓	Median↓	Std.↓	#Points↑	Mean↓	Median↓	Std.↓	#Points↑	Mean↓	Median↓	Std.↓
Huang	147	14.87	13.44	10.36	25	647.31	354.05	1038.08	91	22.85	19.17	16.58
Ours w/o MAP	7	——	——	——	5	——	——	——	1	——	——	——
Ours	887	**1.48**	**1.35**	**0.94**	689	1.39	1.22	**0.84**	559	0.92	0.78	**0.55**
Ours (merged)	**2630**	2.53	1.79	2.44	**1437**	**1.33**	**0.99**	1.02	**1064**	**0.90**	**0.75**	0.59