Supplemental Material (4): Additional Synthetic Experiments

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1 Different noise levels

The accuracies of the comparison methods with different level of image noise are presented in Fig. 1. All the comparison methods are robust to image noises. It is observed that REPPnP performs very well with high level noise at moderate outlier rate, because REPPnP uses a dynamic threshold scheme. The rest comparison methods use a static threshold $\varepsilon = 10$ pixels instead. It is observed that our solution is more robust against image noise than the other methods when the noise levels are 4, 6, and 10 pixels. Surprisingly, the accuracy of our approach is not the highest when the noise level is 2 pixels. In our solution, soft weighting is used to leverage the points whose re-projection errors are higher than ε, and it tends to detect inliers which satisfy the condition $\epsilon_i \leq \varepsilon$ as much as possible. When the threshold $\varepsilon = 10$ pixels is too higher than the noise level of 2 pixels, some outliers that accidentally satisfy the condition $\epsilon_i \leq \varepsilon$ may be falsely counted as inliers, therefore damage the accuracy of our approach. This issue can be solved by decrease the threshold ε accordingly, for example, from 10 to 5 pixels.

2 RANSAC parameter p

The mean rotation error and average number of trials with different RANSAC parameter p are shown in Table 1. For classic RANSAC based methods (i.e. RSC($\cdot$) and RSC($\cdot$)+OGN series), the higher the p, the lower the mean $err_{\mathbf{R}}$ and the more the average n_{trials}. Following [3], p is set as 0.99 by default for classic RANSAC based methods to achieve accurate estimation as high as possible.

For the Ours($\cdot$) series, Ours(P3P) and Ours(RP4P) effectively decrease the mean $err_{\mathbf{R}}$ and the average n_{trials} comparing to their classic RANSAC counterparts. We find that, the proposed solution Ours is not sensitive to p, it achieves robust and accurate results even with $p = 0.7$, and higher p does not yield any benefit. Therefore, we set p as 0.7 for Ours by default in the experiments of this work.

3 Experiment for SQPnP

In this section, a comparative analysis is conducted against SQPnP [2]. Specifically, the OpenCV [1] SolvePnPRANSAC method was employed in the experiment, with its underlying solver flag configured to SOLVEPNP_SQPNP. For RANSAC parameterization, the confidence level was set to 0.99, and a high maximum iteration count of 100,000 was adopted to prevent premature termination under scenarios with high outlier rates. This implementation is referred to as RSC(SQPnP) hereafter. The results across various outlier rate levels are summarized in Table 2.

Under the Ordinary 3D case, RSC(SQPnP) achieved acceptable accuracy at a low outlier rate, with an average rotation error of 0.37 degrees at 5% outliers. However, its accuracy degraded sharply as the outlier rate increased: at 90% outliers, the rotation error jumped significantly to 4.33 degrees. In contrast, our method maintained consistently superior accuracy, achieving a much lower average rotation error of approximately 0.24 degrees across the same cases.

For the Planar case, RSC(SQPnP)'s limitations were even more pronounced. Even with a mere 5% outlier rate, its average rotation error reached 14.43 degrees. This result suggests that RSC(SQPnP) lacks the necessary robustness in planar cases. By comparison, our method maintained a significantly lower average rotation error of around 0.56 degrees, thereby showcasing both better accuracy and higher robustness in this configuration.

And then, we also conducted a comparative test between SQPnP and OPnP, as both methods are designed for outlier-free scenarios and are suitable for refining the pose after filtering out outliers. The results of the comparative experiment are as shown in Table 3, 4 and 5. Note: The postfix "+OGN" indicates the process of refining the pose by OPnP followed by Gauss-Newton optimization; similarly, the postfix "+SQGN" indicates the process of refining the pose by SQPnP followed by Gauss-Newton optimization.

From the experimental results, it can be seen that OPnP and SQPnP perform comparably. Moreover, if Gauss-Newton optimization is applied, the error can be further effectively reduced.

4 Noisy Camera Calibration

To address this question, we conducted supplementary experiments where standard Gaussian noise with a mean of 0 and a standard deviation of 1 was introduced

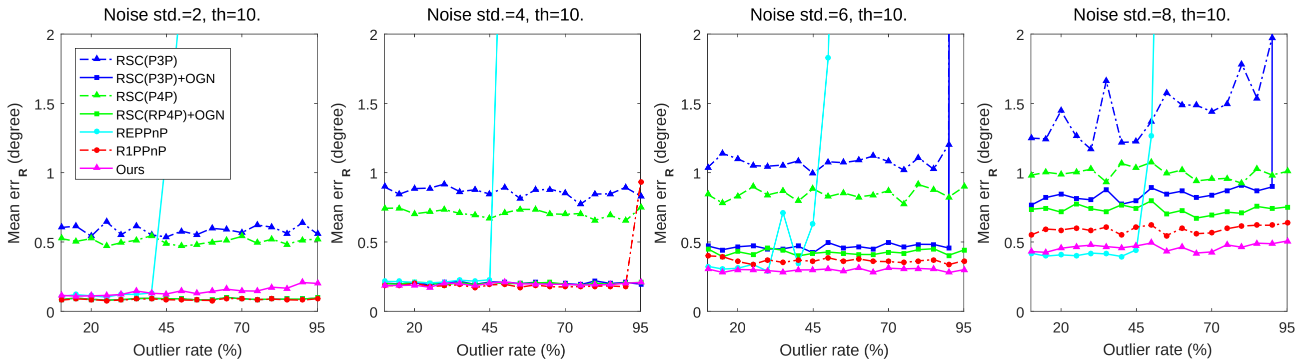

Figure 1: Mean rotation error of the comparison methods with different levels of image noise. The threshold ε of the comparison methods are set as 10 pixels. The experiment is evaluated in ordinary 3D case, and the number of inliers is 100.

Table 1: Mean rotation error and average number of trials with different RANSAC parameter p. In each cell, the values presented are mean $err_{\mathbf{R}}$ / average n_{trials}, and the postfix k denotes the unit thousand. The **bold font** denotes the result corresponding to the default setting of p in the experiments.

p	0.6	0.7	0.8	0.9	0.99
RSC(PST_Hough)	1.76°/0.11k	1.67°/0.13k	1.59°/0.16k	1.49°/0.20k	**1.34°/0.29*k***
RSC(PST_Hough)+OGN	0.43°/0.11k	0.41°/0.13k	0.39°/0.16k	0.38°/0.20k	**0.35°/0.29*k***
Ours	0.25°/0.04k	**0.25°/0.05*k***	0.25°/0.07k	0.25°/0.09k	0.25°/0.18k
RSC(P3P)	3.90°/2.00k	2.80°/2.35k	3.13°/2.94k	2.00°/3.83k	**1.86°/6.24*k***
RSC(P3P)+OGN	2.99°/2.00k	1.94°/2.35k	2.29°/2.94k	1.25°/3.83k	**1.20°/6.24*k***
Ours(P3P)	2.23°/1.40k	2.06°/1.68k	1.33°/1.89k	1.04°/2.55k	**0.72°/4.01*k***
RSC(RP4P)	2.01°/40.19k	1.04°/41.64k	0.93°/49.98k	0.88°/56.96k	**0.79°/62.33*k***
RSC(RP4P)+OGN	1.32°/40.19k	0.39°/41.64k	0.31°/49.98k	0.30°/56.96k	**0.30°/62.33*k***
Ours(RP4P)	0.81°/14.10k	0.48°/18.31k	0.40°/24.54k	0.25°/35.25k	**0.25°/57.83*k***

into the camera projection matrix K to simulate noisy calibration scenarios. The results of these experiments are presented in Table 6, 7 and 8. Note: A method name followed by an asterisk (e.g., Ours*) indicates the test results of that method under the condition of a noisy camera projection matrix.

It is observed that the random noise applied to the camera matrix K slightly increases the mean rotation estimation error of the compared methods; however, overall, the methods under comparison remain stable with respect to the noise.

References

[1] OpenCV Contributors. Perspective-n-point (pnp) pose computation. `https://docs.opencv.org/3.4/d5/d1f/calib3d_solvePnP.html`, 6 2025. Accessed: [Insert Access Date Here] (e.g., 2025-10-04); OpenCV Library Version 3.4 Documentation, Calib3d Module: solvePnP Function Reference.

[2] George Terzakis and Manolis Lourakis. A consistently fast and globally optimal solution to the perspective-n-point problem. In *Proceedings of the European Conference on Computer Vision (ECCV)*, pages 478–494. Springer, 2020.

[3] Haoyin Zhou, Tao Zhang, and Jayender Jagadeesan. Re-weighting and 1-point ransac-based pnp solution to handle outliers. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 41(12):3022–3033, 2019.

Table 2: Mean and Median Rotation Errors of the OpenCV Implementation for RSC(SQPnP)

Outerlier Rate	Ordinary3D		Quasi-singular		Planar	
	Mean	Median	Mean	Median	Mean	Median
5%	0.370	0.346	0.627	0.562	14.425	1.303
10%	0.362	0.338	0.670	0.603	16.549	1.356
15%	0.355	0.333	0.735	0.702	10.599	1.079
20%	0.343	0.326	0.709	0.652	8.964	1.127
25%	0.344	0.329	0.715	0.638	10.415	0.929
30%	0.348	0.358	0.683	0.631	6.817	1.084
35%	0.343	0.347	0.691	0.621	14.003	1.164
40%	0.340	0.313	0.645	0.544	12.591	1.262
45%	0.302	0.277	0.645	0.561	8.340	0.985
50%	0.346	0.325	0.655	0.625	9.487	1.450
55%	0.327	0.301	0.719	0.639	7.746	1.128
60%	0.348	0.317	0.699	0.624	15.111	1.335
65%	0.352	0.330	0.672	0.581	22.433	1.361
70%	0.369	0.362	0.679	0.617	28.632	1.368
75%	0.375	0.366	0.735	0.642	27.146	1.181
80%	0.378	0.346	0.698	0.638	28.943	1.681
85%	0.374	0.340	0.760	0.668	32.156	2.903
90%	4.331	2.580	1.968	1.567	48.974	19.625
95%	38.248	15.398	4.823	4.266	99.453	105.514

Table 3: Mean Rotation Error in Ordinary 3D Case for SQPnP

Outlier rate	RSC(RP4P)	RSC(RP4P) +OPnP	RSC(RP4P) +SQPnP	RSC(RP4P) +OGN	RSC(RP4P) +SQGN
5%	0.81578	0.40654	0.40667	0.3076	0.30838
10%	0.78004	0.41436	0.41402	0.31812	0.31513
15%	0.77959	0.37231	0.37222	0.29206	0.29362
20%	0.78178	0.38548	0.38555	0.28941	0.29541
25%	0.80397	0.39967	0.39985	0.30422	0.30507
30%	0.8024	0.38228	0.38205	0.29322	0.29385
35%	0.83472	0.39084	0.39089	0.29334	0.29763
40%	0.82779	0.38772	0.38795	0.28075	0.28157
45%	0.77531	0.38301	0.38278	0.283	0.28381
50%	0.7847	0.39201	0.39162	0.30862	0.31024
55%	0.82017	0.40935	0.40932	0.31101	0.31059
60%	0.81102	0.39935	0.39941	0.29844	0.2988
65%	0.78125	0.37788	0.37817	0.28923	0.2881
70%	0.78966	0.39709	0.39708	0.3052	0.31023
75%	0.76137	0.39556	0.39534	0.31818	0.31301
80%	0.79256	0.39895	0.39906	0.30096	0.3053
85%	0.8012	0.38358	0.38377	0.30473	0.30336
90%	0.82334	0.39018	0.39027	0.28588	0.28299
95%	1.0749	0.55406	0.55396	0.36341	0.36744

Table 4: Mean Rotation Error in Quasi-singular Case for SQPnP

Outlier rate	RSC(RP4P)	RSC(RP4P) +OPnP	RSC(RP4P) +SQPnP	RSC(RP4P) +OGN	RSC(RP4P) +SQGN
5%	1.4568	0.72785	0.7372	0.56549	0.56839
10%	1.3936	0.69915	0.70114	0.55774	0.56628
15%	1.5976	0.76763	0.77463	0.59612	0.58743
20%	1.4539	0.75199	0.75299	0.56941	0.5809
25%	1.4685	0.75474	0.76083	0.56471	0.60912
30%	1.468	0.72969	0.73439	0.57621	0.58726
35%	1.7057	0.76821	0.77927	0.56081	0.56847
40%	1.4898	0.76196	0.77245	0.59363	0.61581
45%	1.4076	0.6796	0.68515	0.53369	0.54478
50%	1.4952	0.77547	0.77751	0.58784	0.58892
55%	1.521	0.76554	0.77047	0.60248	0.61325
60%	1.5045	0.68282	0.67745	0.54647	0.54138
65%	1.5755	0.76642	0.7873	0.61106	0.62513
70%	1.57	0.76492	0.77831	0.5672	0.59122
75%	1.4901	0.75439	0.75488	0.58318	0.59575
80%	1.4796	0.77264	0.78211	0.61674	0.61699
85%	1.4191	0.72425	0.72975	0.60129	0.59365
90%	1.4111	0.7589	0.76475	0.61846	0.61237
95%	1.5118	0.77164	0.77668	0.64181	0.63856

Table 5: Mean Rotation Error in Planar Case for SQPnP

Outlier rate	RSC(RP4P)	RSC(RP4P) +OPnP	RSC(RP4P) +SQPnP	RSC(RP4P) +OGN	RSC(RP4P) +SQGN
5%	2.296	1.0089	1.0067	0.73474	0.71605
10%	2.142	1.1026	1.0893	0.75978	0.7626
15%	1.4873	0.7206	0.72924	0.57942	0.584
20%	1.7601	0.87496	0.8945	0.65308	0.67343
25%	1.4926	0.7299	0.72747	0.55507	0.54879
30%	2.133	0.97814	0.99865	0.72324	0.72395
35%	2.0317	0.96219	0.94992	0.6879	0.69443
40%	1.8858	0.92787	0.92999	0.71544	0.72107
45%	1.6205	0.86538	0.88111	0.72487	0.71544
50%	1.8021	0.8688	0.89462	0.62299	0.6339
55%	1.9574	1.0121	1.0179	0.79463	0.80686
60%	1.9536	0.99123	0.99544	0.71807	0.71176
65%	2.0453	0.97098	0.98889	0.71629	0.72284
70%	1.8717	0.91292	0.92238	0.70862	0.70785
75%	1.6258	0.79559	0.79999	0.5928	0.58479
80%	1.8765	0.95024	0.95732	0.75143	0.7361
85%	2.121	1.1063	1.1148	0.74172	0.75404
90%	1.796	0.92362	0.92707	0.72016	0.72316
95%	1.8974	0.9407	0.93846	0.68426	0.72324

Table 6: Mean Rotation Error in Ordinary 3D Case for Noisy Calibration

Outlier rate	REPPnP	REPPnP*	R1PPnP	R1PPnP*	Ours	Ours*
5%	0.25	0.27	0.29	0.30	0.25	0.26
10%	0.27	0.28	0.29	0.32	0.25	0.26
15%	0.27	0.29	0.29	0.31	0.25	0.27
20%	0.26	0.28	0.26	0.28	0.25	0.27
25%	0.27	0.29	0.27	0.29	0.26	0.28
30%	0.27	0.29	0.28	0.29	0.25	0.27
35%	0.56	0.57	0.26	0.27	0.26	0.26
40%	0.24	0.26	0.25	0.26	0.23	0.25
45%	1.14	1.15	0.27	0.27	0.25	0.25
50%	0.62	0.60	0.27	0.28	0.24	0.25
55%	7.19	7.21	0.25	0.27	0.24	0.25
60%	22.82	22.69	0.26	0.27	0.25	0.26
65%	47.59	46.64	0.24	0.25	0.23	0.24
70%	81.26	79.40	0.24	0.26	0.24	0.25
75%	81.12	80.74	0.26	0.26	0.26	0.26
80%	92.92	92.42	0.23	0.25	0.24	0.26
85%	100.65	99.31	0.25	0.27	0.25	0.26
90%	102.64	102.18	0.25	0.33	0.26	0.27
95%	106.85	106.96	0.26	0.27	0.23	0.26

Table 7: Mean Rotation Error in Quasi-singular Case for Noisy Calibration

Outlier rate	REPPnP	REPPnP*	R1PPnP	R1PPnP*	Ours	Ours*
5%	0.65	0.65	0.53	0.54	0.47	0.48
10%	2.46	2.46	0.57	0.57	0.50	0.51
15%	14.22	13.77	0.58	0.58	0.51	0.51
20%	47.31	47.16	0.56	0.57	0.54	0.54
25%	72.87	73.65	0.56	0.56	0.50	0.50
30%	75.77	75.56	0.55	0.57	0.49	0.52
35%	88.26	88.15	0.50	0.50	0.46	0.48
40%	92.81	90.60	0.53	0.55	0.52	0.53
45%	98.69	98.57	0.52	0.51	0.50	0.52
50%	98.49	97.57	0.56	0.57	0.49	0.50
55%	105.14	104.82	0.55	0.57	0.55	0.55
60%	100.57	100.05	0.56	0.57	0.54	0.54
65%	108.97	106.87	0.55	0.56	0.52	0.53
70%	102.99	102.86	0.59	0.58	0.53	0.53
75%	110.23	109.99	0.56	0.57	0.51	0.51
80%	112.01	112.83	0.63	0.63	0.54	0.55
85%	112.47	113.38	0.65	0.66	0.55	0.54
90%	109.92	108.82	0.73	0.74	0.52	0.54
95%	118.96	117.31	3.03	3.11	0.60	0.61

Table 8: Mean Rotation Error in Planar Case for Noisy Calibration

Outlier rate	REPPnP	REPPnP*	R1PPnP	R1PPnP*	Ours	Ours*
5%	0.63	0.63	24.34	23.73	0.63	0.64
10%	0.71	0.73	16.23	14.65	0.54	0.58
15%	0.47	0.48	23.24	23.18	0.45	0.48
20%	0.66	0.67	39.36	34.36	0.58	0.60
25%	0.48	0.48	32.34	29.83	0.42	0.42
30%	0.65	0.65	30.39	24.29	0.57	0.60
35%	0.64	0.65	24.41	26.84	0.53	0.54
40%	3.96	3.98	19.49	24.68	0.58	0.59
45%	3.63	3.64	28.84	25.71	0.56	0.56
50%	5.53	5.48	27.48	29.60	0.54	0.56
55%	25.69	24.19	24.15	23.47	0.65	0.69
60%	52.25	52.77	35.34	36.89	0.50	0.52
65%	75.03	75.14	21.57	25.10	0.60	0.60
70%	98.67	98.91	27.30	28.06	0.55	0.54
75%	99.11	100.64	44.64	36.10	0.50	0.51
80%	109.01	108.42	34.86	36.94	0.57	0.60
85%	107.37	108.53	30.73	30.41	0.64	0.65
90%	116.24	116.83	31.78	25.82	0.58	0.60
95%	112.66	111.89	44.35	43.01	0.58	0.58