

Geometric Accuracy of 3D Reality Mesh Utilization for BIM-Based Earthwork Quantity Estimation Workflows

Paulius Kavaliauskas *, Daumantas Židanavičius and Andrius Jurelionis

Faculty of Civil Engineering and Architecture, Kaunas University of Technology, 44249 Kaunas,

Lithuania; daumantas.zidanavicius@ktu.edu (D.Ž.); andrius.jurelionis@ktu.lt (A.J.)

* Correspondence: pa.kavaliauskas@ktu.edu

Tables S1-S6 illustrate the coordinates of the control points obtained from the reality mesh models and processed using different configurations. Table S7 presents the GCPs and CHPs RMSE values using the main PPK and GCPs-based methods. Tables S8-S11 show the differences in vertical reference points obtained using ground level manual GNSS and UAV-based methods. Figures S1-S3 show the examples of the boundaries used for stockpiles volume comparison.

Table S1. Control points measurement information. UAV-based PPK method.

CP No	PPK 74 m Height			PPK 100 m Height		
	Northing, (Meters)	Easting, (Meters)	Elevation, (Meters)	Northing, (Meters)	Easting, (Meters)	Elevation, (Meters)
1	6050236.696	556234.219	162.697	6050236.752	556234.249	162.724
2	6050043.456	555982.113	159.573	6050043.478	555982.139	159.579
3	6049904.378	555953.411	159.510	6049904.373	555953.436	159.460
4	6050013.165	556105.786	157.799	6050013.171	556105.800	157.762
5	6049966.746	556230.242	156.084	6049966.726	556230.275	156.055
6	6049781.309	556206.621	155.860	6049781.303	556206.684	155.842
7	6049821.211	556140.154	152.685	6049821.197	556140.191	152.668
8	6049656.276	556080.618	157.861	6049656.275	556080.672	157.910
9	6049755.714	556125.178	157.182	6049755.711	556125.228	157.192
10	6049807.233	556330.654	158.182	6049807.213	556330.702	158.179
11	6049985.560	556330.067	155.380	6049985.523	556330.130	155.386

Table S2. Control points measurement information. UAV 5 GCPs-based method.

CP No	5 GCPs-Based 74 m Height			5 GCPs-Based 100 m Height		
	Northing, (Meters)	Easting, (Meters)	Elevation, (Meters)	Northing, (Meters)	Easting, (Meters)	Elevation, (Meters)
1	6050236.701	556234.259	162.677	6050236.703	556234.255	162.695
2	6050043.431	555982.135	159.570	6050043.445	555982.142	159.573
3	6049904.347	555953.455	160.203	6049904.398	555953.411	159.576
4	6050013.147	556105.792	157.605	6050013.142	556105.785	158.040
5	6049966.716	556230.287	156.121	6049966.718	556230.279	156.137
6	6049781.295	556206.677	155.624	6049781.339	556206.672	155.742
7	6049821.185	556140.202	152.521	6049821.195	556140.210	152.157
8	6049656.238	556080.624	158.929	6049656.314	556080.621	157.359
9	6049755.709	556125.182	157.224	6049755.715	556125.199	157.216
10	6049807.246	556330.677	158.159	6049807.246	556330.668	158.172
11	6049985.544	556330.127	155.877	6049985.514	556330.097	155.030

Table S3. Control points measurement information. UAV 6 GCPs-based method.

CP No	6 GCPs-Based 74 m Height			6 GCPs-Based 100 m Height		
	Northing, (Meters)	Easting, (Meters)	Elevation, (Meters)	Northing, (Meters)	Easting, (Meters)	Elevation, (Meters)
1	6050236.703	556234.257	162.682	6050236.702	556234.258	162.662
2	6050043.401	555982.133	159.564	6050043.416	555982.138	159.568
3	6049904.338	555953.413	159.466	6049904.337	555953.408	159.470
4	6050013.119	556105.788	157.800	6050013.141	556105.774	157.859
5	6049966.712	556230.288	156.132	6049966.716	556230.277	156.127
6	6049781.313	556206.672	155.885	6049781.325	556206.649	155.884
7	6049821.194	556140.204	152.703	6049821.186	556140.210	152.710
8	6049656.282	556080.681	157.989	6049656.304	556080.611	157.780
9	6049755.708	556125.191	157.224	6049755.716	556125.198	157.207
10	6049807.247	556330.669	158.166	6049807.246	556330.669	158.156
11	6049985.528	556330.110	155.434	6049985.526	556330.097	155.432

Table S4. Control points measurement information. UAV 8 GCPs-based method.

CP No	8 GCPs-Based 74 m Height			8 GCPs-Based 100 m Height		
	Northing, (Meters)	Easting, (Meters)	Elevation, (Meters)	Northing, (Meters)	Easting, (Meters)	Elevation, (Meters)
1	6050236.699	556234.258	162.679	6050236.704	556234.254	162.675
2	6050043.434	555982.142	159.577	6050043.441	555982.154	159.579
3	6049904.342	555953.412	159.458	6049904.349	555953.422	159.472
4	6050013.147	556105.800	157.815	6050013.139	556105.798	157.828
5	6049966.713	556230.268	156.177	6049966.717	556230.265	156.117
6	6049781.310	556206.653	155.912	6049781.311	556206.665	155.880
7	6049821.187	556140.182	152.685	6049821.183	556140.187	152.702
8	6049656.300	556080.641	157.841	6049656.298	556080.604	157.816
9	6049755.698	556125.177	157.328	6049755.715	556125.197	157.209
10	6049807.246	556330.677	158.165	6049807.248	556330.670	158.170
11	6049985.536	556330.092	155.433	6049985.525	556330.099	155.437

Table S5. Control points measurement information. UAV GCPs-based RTK method.

CP No	3 GCPs-Based RTK 100 m Height			5 GCPs-Based RTK 100 m Height		
	Northing, (Meters)	Easting, (Meters)	Elevation, (Meters)	Northing, (Meters)	Easting, (Meters)	Elevation, (Meters)
1	6050236.690	556234.246	162.669	6050236.694	556234.252	162.662
2	6050043.439	555982.150	159.571	6050043.437	555982.150	159.567
3	6049904.355	555953.417	159.453	6049904.367	555953.425	159.474
4	6050013.145	556105.796	157.833	6050013.153	556105.805	157.832
5	6049966.687	556230.258	156.091	6049966.733	556230.267	156.106
7	6049821.181	556140.163	152.662	6049821.191	556140.180	152.691
10	6049807.179	556330.666	158.162	6049807.236	556330.617	158.256
11	6049985.532	556330.113	155.412	6049985.539	556330.116	155.421

Table S6. Control points measurement information for smaller-scale PPK survey. Separate measurements were obtained using GNSS receiver.

CP No	GNSS Receiver Ground Level			PPK 100 m Height		
	Northing, (Meters)	Easting, (Meters)	Elevation, (Meters)	Northing, (Meters)	Easting, (Meters)	Elevation, (Meters)
1	6050066.107	556169.741	156.523	6050066.145	556169.744	156.482
2	6049871.842	556259.675	154.222	6049871.845	556259.67	154.190
3	6049722.953	556182.283	156.363	6049722.97	556182.271	156.348
4	6049730.563	556176.176	155.965	6049730.576	556176.162	155.978
5	6049910.055	556146.170	152.203	6049910.095	556146.167	152.187

Table S7. RMSE values for 11 control points.

Method	Ground Control Points			Check Points		
	X (m)	Y (m)	Z (m)	X (m)	Y (m)	Z (m)
1 known point PPK 74 m	0.013	0.016	0.000	0.023	0.029	0.028
1 known point PPK 100 m	0.019	0.002	0.037	0.027	0.025	0.038
6 GCPs-based GPS 74 m	0.04	0.09	0.018	0.026	0.028	0.071
6 GCPs-based GPS 100 m	0.01	0.07	0.012	0.022	0.020	0.043
5 GCPs-based GPS 74 m	0.008	0.018	0.237	0.023	0.017	0.547
5 GCPs-based GPS 100 m	0.004	0.003	0.022	0.035	0.015	0.346
8 GCPs-based GPS 74 m	0.005	0.008	0.016	0.018	0.014	0.085
8 GCPs-based GPS 100 m	0.007	0.009	0.023	0.016	0.008	0.014

Table S8. Vertical reference point differences obtained through manual GNSS and UAV-based PPK methods.

CP No	Vertical Datum Measurements in Meters Obtained Through Manual GNSS and UAV-based PPK Methods.				
	GNSS Receiver		PPK		PPK
	Ground Level	74 m Height	Difference from Ground Level	100 m Height	Difference from Ground Level
1	162.661	162.697	-0.036	162.724	-0.063
2	159.556	159.573	-0.017	159.579	-0.023
3	159.463	159.510	-0.047	159.460	0.003
4	157.799	157.799	0	157.762	0.037
5	156.111	156.084	0.027	156.055	0.056
6	155.857	155.860	-0.003	155.842	0.015
7	152.670	152.685	-0.015	152.668	0.002
8	157.837	157.861	-0.024	157.910	-0.073
9	157.208	157.182	0.026	157.192	0.016
10	158.154	158.182	-0.028	158.179	-0.025
11	155.408	155.380	0.028	155.386	0.022

Table S9. Differences in vertical reference points obtained using ground level manual GNSS and 74 m UAV GCPs-based methods.

CP No	Vertical Datum Measurements in Meters Obtained Through Manual GNSS and UAV GCPs-Based Methods.						
	GNSS	5 GCPs-Based		6 GCPs-Based		8 GCPs-Based	
	Ground Level	74 m Height	Difference from Ground Level	74 m Height	Difference from Ground Level	74 m Height	Difference from Ground Level
1	162.661	162.677	-0.016	162.682	-0.021	162.679	-0.018
2	159.556	159.570	-0.014	159.564	-0.008	159.577	-0.021
3	159.463	160.203	-0.740	159.466	-0.003	159.458	0.005
4	157.799	157.605	0.194	157.800	-0.001	157.815	-0.016
5	156.111	156.121	-0.010	156.132	-0.021	156.177	-0.066
6	155.857	155.624	0.233	155.885	-0.028	155.912	-0.055
7	152.670	152.521	0.149	152.703	-0.033	152.685	-0.015
8	157.837	158.929	-1.092	157.989	-0.152	157.841	-0.004
9	157.208	157.224	-0.016	157.224	-0.016	157.328	-0.120
10	158.154	158.159	-0.005	158.166	-0.012	158.165	-0.011
11	155.408	155.877	-0.469	155.434	-0.026	155.433	-0.025

Table S10. Differences in vertical reference points obtained using ground level manual GNSS and 100 m UAV GCPs-based methods.

CP No	Vertical Datum Measurements in Meters Obtained Through Manual GNSS and UAV GCPs-Based Methods.						
	GNSS	5 GCPs-Based		6 GCPs-Based		8 GCPs-Based	
	Ground Level	100 m Height	Difference from Ground Level	100 m Height	Difference from Ground Level	100 m Height	Difference from Ground Level
1	162.661	162.695	-0.034	162.662	-0.001	162.675	-0.014
2	159.556	159.573	-0.017	159.568	-0.012	159.579	-0.023
3	159.463	159.576	-0.113	159.470	-0.007	159.472	-0.009
4	157.799	158.040	-0.241	157.859	-0.060	157.828	-0.029
5	156.111	156.137	-0.026	156.127	-0.016	156.117	-0.006
6	155.857	155.742	0.115	155.884	-0.027	155.880	-0.023
7	152.670	152.157	0.513	152.710	-0.040	152.702	-0.032
8	157.837	157.359	0.478	157.780	0.057	157.816	0.021
9	157.208	157.216	-0.008	157.207	0.001	157.209	-0.001
10	158.154	158.172	-0.018	158.156	-0.002	158.170	-0.016
11	155.408	155.030	0.378	155.432	-0.024	155.437	-0.029

Table S11. Vertical reference point differences in smaller-scale RTK/PPK surveys.

CP No	Vertical Datum Measurements in Meters Obtained Through Manual GNSS and UAV RTK/PPK Methods.						
	GNSS	3 GCPs-Based RTK		5 GCPs-Based RTK		PPK	
	Ground Level	100 m Height	Difference from Ground Level	100 m Height	Difference from Ground Level	100 m Height	Difference from Ground Level
1	162.661	162.669	-0.008	162.662	-0.001	-	-
2	159.556	159.571	-0.015	159.567	-0.011	-	-
3	159.463	159.453	0.010	159.474	-0.011	-	-
4	157.799	157.833	-0.034	157.832	-0.033	-	-
5	156.111	156.091	0.020	156.106	0.005	-	-
7	152.670	152.662	0.008	152.691	-0.021	-	-
10	158.154	158.162	-0.008	158.256	-0.102	-	-
11	155.408	155.412	-0.004	155.421	-0.013	-	-
1*	156.523	-	-	-	-	156.482	0.041
2*	154.222	-	-	-	-	154.190	0.032
3*	156.363	-	-	-	-	156.348	0.015
4*	155.965	-	-	-	-	155.978	-0.013
5*	152.203	-	-	-	-	152.187	0.016

*Separately measured control points.



(a)



(b)

Figure S1. Example of the boundaries used for stockpiles volume comparison. Stockpile number 3: (a) the view in Trimble Stratus and (b) the view in ContextCapture with 50% mesh transparency.



(a)



(b)

Figure S2. Example of the boundaries used for stockpiles volume comparison. Stockpile number 15: (a) the view in Trimble Stratus and (b) the view in ContextCapture with 50% mesh transparency.



(a)



(b)

Figure S3. Example of the boundaries used for stockpiles volume comparison. Stockpile number 16: (a) the view in Trimble Stratus and (b) the view in ContextCapture with 50% mesh transparency.