Assessing the Potential of a Low-Cost 3-D Sensor in Shallow-Water Bathymetry

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***Abstract*— Highly detailed 3-D geoinformation about bathymetry is crucial to understand a wide range of processes and conditions in the geosciences. Recently, low-cost sensors such as Microsoft's structured-light 3-D camera Kinect for Xbox 360 have been deployed to complement established sources of 3-D bathymetric data like light detection and ranging or sound navigation and ranging. In this letter, we assess the Kinect's applicability to capture the bathymetry of shallow waters. Therefore, the maximum capturing range through water, accuracy, and precision of Kinect measurements are examined. Additionally, we test a recording setup which allows for the mitigation of waves and which features advantages in terms of refraction correction on a scene containing submerged gravels. As a result, water depths of 30 cm (outdoors) and 40 cm (indoors) can be penetrated. The accomplished accuracy [mean standard deviation (SD) 7 mm] and precision values (mean SD 3.1 mm) are similar to the ones achieved by terrestrial laser scanning bathymetry. Derived gravel sizes highly correspond to the manual reference measurements. Overall, the findings show the Kinect's applicability in researching shallow natural water bodies.**

***Index Terms*— Granulometry, kinect, quality assessment, shallow water bathymetry, wave mitigation.**

I. Introduction

DETAILED topographic information is a prominent requirement for a variety of research fields that intend to model, map, exploit, and increase the comprehension of natural phenomena on the earth's surface [1]. Starting around the year 2000, Airborne Laser Bathymetry scanners that can penetrate a water column have gained importance as powerful instruments in bathymetry [2]. Additional approaches such as Terrestrial Laser Bathymetry (TLB) or unmanned aerial vehicle-borne topo-bathymetric laser scanning, offering higher spatial resolutions and accuracies, slowly emerge [3], [4]. However, light detection and ranging (LiDAR) methods exhibit certain constraints. In shallow-waters featuring depths of about 25 cm or less, the distinction of measurements capturing the water surface or the bathymetry is not feasible [5]. The lack of information about the water surface in these so-called vertical "dead zones" prevents the application of refraction correction [6] and, subsequently, accurate bathymetric measurements. Similarly, the well-established bathymetric method sound navigation and ranging features a minimum operating depth of approximately 1 m [7], excluding data acquisition in shallow water. A further aspect when capturing bathymetric data with optical methods such as LiDAR are waves, causing a heterogeneous water surface, inconsistent laser incidence angles, and thus demanding local refraction correction algorithms [8]. Being not affected by surface waves, the method of underwater close-range digital photogrammetry has been applied successfully in bathymetry tasks [9]. Although comprising specific advantages such as low costs and flexible handling of equipment, photogrammetry still requires extended field campaigns, and laborious data processing in the laboratory, which prevents near real-time on-site data availability [10].

To tackle the mentioned restrictions and to provide a complementary tool, we examine the performance of a low-cost 3-D recording device in shallow-water bathymetry. The structured-light 3-D camera Kinect for Xbox 360 (from here on referred to as Kinect) is applied due to its capability to penetrate water [11]. Originally developed as an indoor gaming device, it has already been tested within the scope of geoscientific studies for capturing karst objects [12], for determining surface roughness [13], and in granulometry [14]. However, few studies examine the Kinect's capabilities of underwater measurements. Laboratory experiments and outdoor tests at a shallow creek (about 7-cm water depth) are presented by Mankoff and Russo [11]. Digurmati *et al.* [15] describe a study dedicated to short-range data capturing and volume estimations of submarine features in a coral nursery. Chourasiya *et al.* [16] conduct laboratory experiments to evaluate the influence of water depth, turbidity, object color and lighting on the Kinect measurement accuracy, and to monitor sand bar erosion and the filling of a modeled mining gap. Based on the experiments, the authors provide recommendations on how to use a Kinect for bathymetric studies.

The more recent Kinect for Xbox One was also used to measure through water columns up to 30 cm [17]. However, preliminary experiments conducted for our study led to erroneous measurements in the form of emphasized geometric deformations such as interconnected objects, smoothing of structures, and misrepresentations of water surface reflections as objects. Thus, we focus on recording with the first Kinect version.

The studies mentioned above provide valuable insights into the application of low-cost structured light 3-D cameras for bathymetric measurements. The main aim of this letter is to complement the existing work with a systematic examination of maximum water depth penetration indoors and outdoors,

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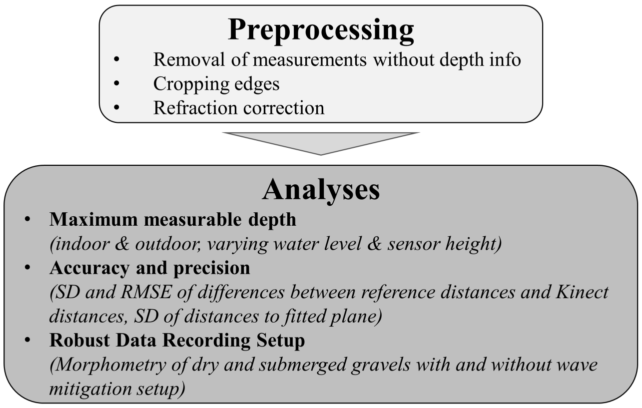

Fig. 1. Experimental design to assess the Kinect's performance for shallow-water bathymetric measurements.

as well as bathymetric range measurement precision and accuracy. In addition, we propose a wave mitigation setup similar to the concept of Fryer [18], which can be used to achieve a homogenous water surface level at a known distance, and which is of advantage for refraction correction.

Our results emphasize the high potential of the Kinect sensor to capture bathymetric data especially in shallow water up to about 30-cm water height. The device and our measurement setup can strongly support geoscientific studies which cover areas featuring dry and wetted surfaces as well as shallow water, such as wetlands, caves, and near shore areas [6], [12], [19].

II. Sensors and Methods

The Kinect measures distances between sensor and object by means of structured light and triangulation, being able to record 640 × 480 pixel depth images at a rate of up to 30 Hz. A light beam at a wavelength of 830 nm [20] that can penetrate water projects a speckle pattern on the captured scene within a field of view (FOV) of 43° vertically and 57° horizontally. Objects in the scene distort the pattern depending on their 3-D surface structure and their distance to the Kinect device. Via the differences of the undistorted reference pattern and the received pattern, depth images are derived with each pixel containing a value representing the range between sensor and object. Subsequently, each pixel is defined by three coordinates (*xyz*), resulting in a point cloud of *xyz* values covering the whole depth image [21]. The nominal measurement range of the device lies between 0.5 m and about 5 m [21], [22]. Depending on the range between sensor and object, the distance between depth image cell centers, i.e., the spatial resolution, ranges from 1 mm at 0.5-m to 75 mm at 5-m measurement range [11]. Data acquisition and the conversion of depth image pixel values into metric point clouds is done with OpenNI Grabber [23]. To exclude FOV portions with low accuracy, only data in the central area of the FOV which covers the captured object are analyzed [24]. Accordingly, no further calibration of the device was conducted.

The methodic work done for this letter is shown in Fig. 1. To examine the Kinect's applicability for shallow-water bathymetric data acquisition, we assess the device's maximum underwater measurement range, accuracy, and precision. A series of experiments comprising a submerged plane and simulated gravel beds is conducted. Measurements of gravels are taken without and with a wave mitigation setup.

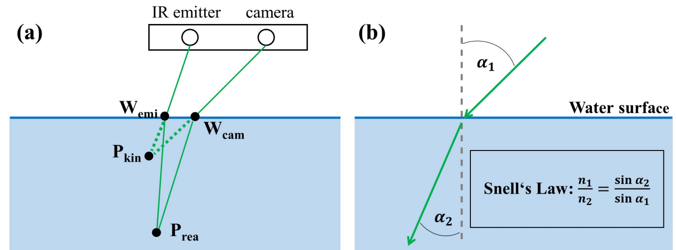

Fig. 2. Principles of the ray-based refraction correction algorithm. (a) Ray intersection for point coordinate derivation. P_{kin} is the originally captured point (intersection of dashed green lines) and P_{rea} is the point after refraction correction (solid lines). W_{emi} and W_{cam} are the ray intersections with the water surface. (b) Snell's Law. The refractive indices of air and water are n_1 and n_2.

During preprocessing, returns containing no depth information are removed. On all measurements through water, a ray-based refraction correction algorithm is applied (Fig. 2). The pseudo code below outlines the algorithm:

Algorithm 1 Pseudo Code of the Applied Ray-Based Refraction Correction Algorithm

```
For each depth image pixel:
   Model infrared (IR) signal paths = ray
   from IR emitter to camera.
   Determine incidence angle α1 between
   ray and normal to water surface.
   Determine refraction angle α2 via
   Snell's law:
```

$$\alpha_2 = \arcsin\left(\frac{n_1}{n_2} * \sin\alpha_1\right)$$

```
   Derive refraction corrected coordinate
   by intersecting underwater rays from
   IR emitter and IR camera with angle α2.
```

To keep the refraction correction straightforward and to achieve homogeneously distributed measurements at any distance from the Kinect, the device is mounted parallel to the water surface.

A. Assessment of Shallow-Water Applicability

1) Maximum Measurable Depth Determination: The maximum measurement range underwater is determined both under indoor laboratory (submerged plane board) and outdoor conditions (concrete well with planar bottom). First, Kinect measurements are taken through a water depth of 5 cm while having the Kinect placed at 1 m to the water surface. After a measurement, the Kinect is approached to the water surface in 5-cm steps until recording fails (i.e., when the respective minimum range is undershot). The procedure of stepwise approaching the Kinect to the water surface is repeated every time after increasing the water depth by 5 cm, until no complete data sets can be acquired at any Kinect-water distance.

2) Accuracy and Precision Evaluation: Accuracy (conformity of recorded data to true value) is derived from a comparison between a given distance and the Kinect's measurement of this distance [11], [25].

To derive accuracy parameters: 1) the distances between the dry reference and underwater measurements and 2) the differences between the hand-measured reference distance and Kinect measures are analyzed. A flat wooden board fixed to the bottom of a plastic trough is captured under dry conditions and being submerged by 10 and 20 cm. The Kinect is mounted at 50-cm distance to the respective water surface.

Both calculations are done: 1) point-wise directly in the point cloud and 2) based on a 2 mm $\times$ 2 mm cell size raster. The raster surface model is created by fitting a plane into a local neighborhood of four range measurements and assigning the elevation of the plane center to the respective cell. Finally, standard deviation (SD) and root-mean-square error (RMSE) of the differences between measured and reference distances are calculated.

Precision (repeatability of measurements) is described by Mankoff and Russo [11] as the spread of measurements around a mean value. In our study, precision is determined as the SD of the residual distances between the Kinect data and a plane fit (least-squares fitting) into the Kinect data.

B. Development of a Robust Data Recording Setup

To exclude the influence of surface waves on the Kinect measurements, we test a wave mitigation setup. The Kinect is mounted above a glass box positioned flush against the water surface. The water depth is 34.5 cm and the Kinect is positioned at a distance of 56 cm to the glass-water boundary.

We conduct a laboratory experiment for bathymetric gravel size measurements as an application example. The experimental setup consists of gravels (diameters reaching from 22 to 28.5 mm with an average of 24.7 mm) placed on a board. Data are recorded of dry and submerged (10 and 20 cm of water) scenes with and without the wave mitigation setup. For the wave-mitigation setup, the refraction correction algorithm is extended so that it considers both the water-glass and the glass-air media boundaries. In the Kinect point clouds, gravel dimensions are measured and compared to manual Vernier caliper reference measurements. To additionally demonstrate the effect of waves on bathymetric data acquisition, waves of approximately 5-cm magnitude are induced by hand. Subsequently, Kinect measurements of a submerged flat wooden board and the gravels were taken at different wave settlement stages without the wave mitigation setup.

III. Results and Discussion

A. Assessment of Shallow-Water Applicability

1) Maximum Measurable Depth Determination: The maximum water depths for which seamless data are achieved are 40-cm indoors and 30-cm outdoors. Measurements through higher water levels contain gaps even after combining multiple Kinect data sets into one point cloud. Under specific laboratory conditions (e.g., no insolation, reflections, turbidity, and turbulences) higher water depths up to 100 cm can be achieved [11]. Regarding field work, however, the Kinect's main area of usage can be seen in very shallow water with depths up to 30 cm, which can decrease when water turbidity increases.

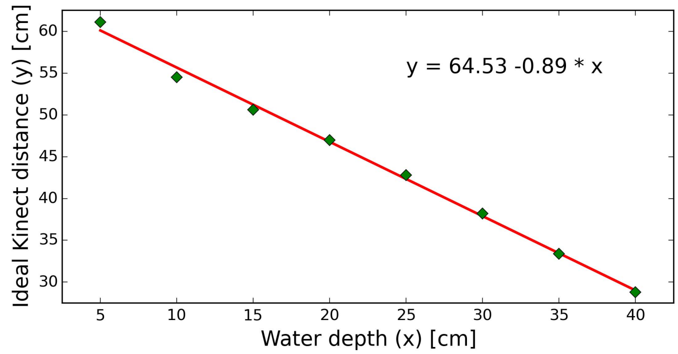

Fig. 3. Ideal Kinect-water surface distances to achieve seamless point clouds in relation to water depth. Green dots: Experimentally determined ideal distances at given water depth, red line: simple linear regression function derived from distance–water depth value pairs.

TABLE I
Comparison of Kinect Measured Distances and Hand-Measured Reference Data (Accuracy)

Setup		Raster [mm]			Point cloud [mm]		
Depth [cm]	Sample No.	SD	RMSE	Cells	SD	RMSE	Points
(reference)		6.5	8.4	25,800	6.5	8.4	28,263
10	1	6.6	10.0	25,670	6.7	10.1	29,802
10	2	6.6	10.0	25,680	6.8	8.1	29,798
10	3	5.8	8.0	25,673	6.0	8.1	29,884
20	1	8.6	11.4	25,650	8.7	11.4	31,512
20	2	8.6	11.3	25,679	6.7	11.3	31,522
20	3	5.8	8.3	25,638	5.9	8.3	31,507
Mean		7.0	9.8	25,665	6.8	9.6	30,671

Fig. 3 shows: 1) the maximum indoor measurable depths and 2) the distances between Kinect and water surface for which a seamless point cloud can be recorded. Concerning the ideal measuring distance between Kinect and water surface it was found that data sets proved to be most dense and complete when the Kinect was positioned according to its respective minimum measuring range (Fig. 3). As an example, at a water depth of 30 cm, the recommended distance between Kinect and water surface is 38 cm.

A further observation is that data acquisition can fail even when the real range between Kinect and water bottom is larger than the minimum "air" measurement range. This effect occurs because due to refraction, the device records the water depth lower than it actually is. For example, placing the Kinect 30 cm above the bottom of a 20-cm water column, it would not be possible to generate depth data as the device "sees" the target at a range of less than 50 cm which is lower than the minimum measurement range. Furthermore, placing the Kinect sensor directly at the water surface results in a complete loss of measurements for any water depth. This derives from: 1) the maximum penetration depth of 30 cm (outdoors) or 40 cm (indoors) and 2) the device's minimum measurement range.

2) Accuracy and Precision Evaluation: Tables I and II summarize the raster and point cloud-based accuracy

TABLE II
COMPARISON OF KINECT RECORDED DISTANCES UNDER DRY AND SUBMERGED CONDITIONS

Setup		Raster based [mm]			Cloud based [mm]		
Depth [cm]	Sample No.	SD	RMSE	Cells	SD	RMSE	Points
10	1	1.9	2.9	25,583	1.4	2.8	29,802
10	2	1.9	2.8	25,596	1.4	2.8	29,798
10	3	2.7	2.7	25,571	1.4	2.7	29,884
20	1	3.4	4.0	25,565	2.1	3.7	31,512
20	2	3.3	3.8	25,575	2.1	3.7	31,522
20	3	2.4	2.5	25,559	1.3	2.5	31,507
Mean		2.6	3.1	25,575	1.6	3.0	30,671

TABLE III
STANDARD DEVIATION OF DISTANCES BETWEEN KINECT MEASUREMENTS AND A LEAST-SQUARES FIT REFERENCE PLANE (PRECISION)

Setup		SD from plane [mm]
Depth [cm]	Sample No.	
0	1	2.2
10	1	2.9
10	2	2.9
10	3	3.3
20	1	3.2
20	2	3.3
20	3	3.1
Mean		3.1

parameters derived from the Kinect measurements taken from 1-m distance between Kinect and wooden board. For each setup, three Kinect data sets are shown exemplarily.

The SD of differences between Kinect and manual measurements is found as low as 5.8 mm and as high as 8.7 mm (Table I). RMSEs lie in the range between 8 and 11.4 mm. In case of the differences between Kinect recorded data of the dry scene and submerged scenes (Table II), SD and RMSE values are generally lower, ranging from 1.3 to 3.4 mm for the point cloud-based analysis and from 2.5 to 4 mm for the raster analysis.

The accuracy values derived from the comparison of measurements from the dry and submerged wooden board (Table II) correspond well to the results presented in others studies, which all consider dry scenes. Boehm [24] for example presents about 2.7 mm (SD) which resembles the values obtained here. Regarding studies applying the method of TLB, Smith and Vericat [6], for example, report values of <10 mm for water depths lower than ~65 cm. Against this background, the Kinect's performance is promising as it can outperform LiDAR in terms of accuracy. Additionally, no emphasized difference between the submerged and the dry case is observed, thus there seems to be no negative effect when measuring through water.

The higher SD and RMSE values presented in Table I may derive from the method itself: the range between Kinect and board being hand-measured with a pocket rule and the parallel setup of the Kinect can contain small alignment errors, influencing the accuracy assessment. The sensor's accuracy might thus be higher as stated in Table I.

The results for the precision assessment are reproduced in Table III. From 10-cm water depth to 20 cm, SD values increase except for the third data set captured at 10- and 20-cm depth. The lowest SD for 10 cm is 2.9 mm and 3.1 mm for 20 cm.

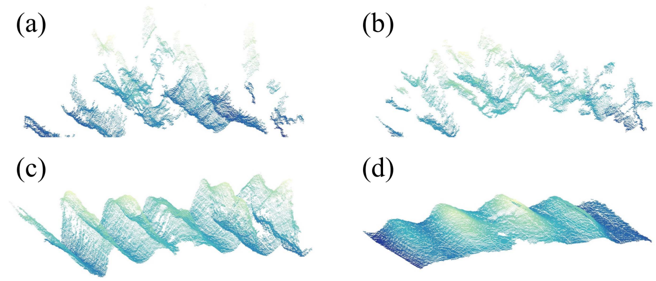

Fig. 4. Point clouds of a submerged planar surface for four consecutive surface wave settlement stages (a)–(d). Width is about 45 cm and length about 75 cm.

A comparison of precision values derived from the dry Kinect measurements (SD) that is reported to be 2 mm at 1-m range [21] with the one measured here (2.2 mm) shows that very similar results can be obtained. Mankoff and Russo [11] presenting values of about 3 mm at 1-m range reinforce this perception. For bathymetric TLS, precision values are reported to be at about 2.2 mm for 0.2-m water depth under laboratory conditions [3]. In the work at hand, SDs between 3.1 and 3.3 mm at 0.2-m water depth are generated under laboratory conditions. Like accuracy, the precision determined in our study shows that the Kinect's performance is similar to the one TLB offers.

B. Development of a Robust Data Recording Setup

Recordings of the submerged board at subsequent wave settlement stages are depicted in Fig. 4(b)–(d). In the point clouds, the surface of the board shows geometric deformations according to the waves, even amplifying their magnitude of about 5- up to 30-cm distance between crest and trough in the Kinect measurements [Fig. 4(a)].

The stones of the simulated gravel bed are only discernible in the latter two settlement stages. Considering the relatively low water depth of 34.5 cm and the sizes of the pebbles with maximum heights of about 2 cm, such wave-affected data sets are not applicable when accurate measurements of small bathymetric structures are desired. Furthermore, a refraction correction assuming a steady water level will fail.

In contrast, when applying the wave mitigation setup and the adjusted refraction correction, submerged pebbles down to heights of about 11 mm can be distinguished in the Kinect point clouds. Exemplary gravel dimensions derived from data captured: 1) with the wave mitigation setup (wavy water surface); 2) without the wave mitigation setup (still water surface); and 3) with the Vernier caliper reference method are summarized in Table IV. Kinect and Vernier caliper measured dimensions differ in average by 2 mm (6.8%, *a*-axis), 1.4 mm (7% *b*-axis), and 1.8 mm (11.4%, *c*-axis). The differences between Kinect and reference data are not significant (t-test, 95% confidence interval).

Thus, the wave mitigation setup enables measuring in wavy water, which strongly extends the operational usage of the Kinect in real-world environments: without being able to cope

TABLE IV

VERNIER CALIPER AND KINECT MEASURED GRAVEL DIMENSIONS. WITHOUT (a) AND WITH (b) GLASS OF WAVE MITIGATION SETUP

Piece	a-axis (long) Kinect (Caliper) [mm]	a-axis (long) Diff. [mm] ([%])	b-axis (short) Kinect (Caliper) [mm]	b-axis (short) Diff. [mm] ([%])	c-axis (height) Kinect (Caliper) [mm]	c-axis (height) Diff. [mm] ([%])
1A	31 (35)	4 (11)	22 (22)	0 (0)	15 (15)	0 (0)
1B	34 (35)	1 (3)	23 (22)	1 (5)	12 (15)	3 (20)
2A	34 (33)	1 (9)	18 (19)	1 (5)	13 (15)	2 (13)
2B	29 (33)	4 (12)	20 (19)	1 (5)	15 (15)	0 (0)
3A	24 (26)	2 (8)	19 (17)	2 (12)	14 (14)	0 (0)
3B	23 (26)	3 (12)	15 (17)	2 (12)	12 (14)	2 (15)
4A	31 (31)	0 (0)	23 (21)	2 (10)	18 (19)	1 (5)
4B	29 (31)	2 (6)	19 (21)	2 (10)	16 (19)	3 (16)
Mean A	30.0 (31.3)	1.8 (7.0)	20.5 (19.8)	1.3 (6.8)	15.0 (15.8)	0.8 (4.5)
Mean B	28.8 (31.3)	2.5 (8.3)	19.3 (19.8)	1.5 (8.0)	13.8 (15.8)	2.0 (12.8)

with turbulences on the water surface, geoscientific studies, and field work are not imaginable, especially when aiming at small bathymetric structures such as the gravel bed examined in this letter. This opens a variety of applications for Kinect bathymetry data. Roughness estimations can be conducted as well as grain size determinations reaching into the grain size of medium gravels (6.3–20 mm according to [26]).

IV. CONCLUSION

The goal of the letter at hand is to evaluate the potential of Microsoft's Kinect for shallow-water bathymetry measurements. In this regard, our findings are encouraging: maximum depth penetration capabilities about 30 cm for outdoors and 40 cm for indoors are identified. Range accuracy and precision values for bathymetric surveys prove the Kinect's applicability for geoscience tasks as results are similar to corresponding parameter specifications of the terrestrial bathymetric LiDAR systems. Single pebbles of the simulated gravel bed are recognizable as soon as their height exceeds about 11 mm. This indicates that precise roughness estimations or granulometric measurements can benefit from Kinect data. It is furthermore shown that the distortions evoked by surface waves can be mitigated by putting a glass layer between air and water without distinct quality losses. In addition, the distance between Kinect and water surface can be fixed, which all facilitates refraction correction.

Other interesting research paths can be examined based on the results presented in this letter. Processes in shallow-water bathymetry can be monitored over time [16], [27] and outdoor applications can be addressed. Overall, our study emphasizes the great potential for applying the Kinect for shallow-water bathymetric measurements.

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