Ubi-T: Smart Surveying Instrument Using Ubiquitous Computing Concept

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Key words: Smartphone, Sensor, Ubi-T, Kalman Filter, Total Station, Location-Based Services

SUMMARY

Over time, surveying instruments have evolved to the current stage of Total Stations that can measure various geometric aspects of different surveying operations with desired accuracies. Nowadays, they can measure distances, horizontal and vertical angles, store data into the computer memory, and display results automatically and perform robotically. In parallel with these traditional usages, location and positioning applications also appear in smartphones using the sensor- and infrastructure-based positioning techniques. The comparison between smartphones and Total Stations shows that, a Total Station even with high weight or usage complexity must be used depending on the application. However, due to the low cost, weight and small size of the smartphones, affordable effort to train operators and the role of modern technologies in the development of today's phone, the term of Ubiquitous Total Station (Ubi-T) is presented. In this paper, the novel realization of Ubi-T is introduced and evaluated in different aspects to discuss, if there is a possibility to use a smartphones-based equipment instead of a Total Station. The system accuracy performance is compared with a Total Station during a field work experiment. While the accuracy of the laser ranging sensor reports from the data-sheet, the mean error of 0.700° and 5.401° in vertical and horizontal angle measurement is realized respectively. The fusion of all used smartphone sensors is realized with Kalman filtering (KF). The KF was implemented based on three main placements. First with attaching the smartphone on the test Total Station, second by mounting it on a tripod and finally by taking the smartphone in a freehand mode. At the end, discussion shows that the smartphone sensors can provide a variety of location-based services and applications.

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1. INTRODUCTION

Today's Total Stations operations include construction of different kinds of roads such as railways, tunnels, and bridges, industrial surveying, urban and suburban infrastructure development, and more. Pioneer companies always have tried to develop easy and user-friendly software interfaces, in addition to providing devices with the most operational capabilities. Overall, Total Stations seem to meet the needs of surveyors to a large extent. Although these devices have a high level of accuracy, this level is not required in many simple and primary surveying operations, daily applications as some GIS applications or public usages such as a rough draw of an apartment plan. Moreover, today's Total Stations cannot play any role in modern data acquisition methods as crowed sourcing, Volunteered Geographic Information (VGI) or other technologies such as Augmented reality (AR) or Virtual reality (VR).

To deal with the above-mentioned issues a Ubiquitous Total Station (Ubi-T) system based on a portable device that includes a smartphone with proper user-friendly applications is developed. The Ubi-T concept is introduced before (Shoushtari and Sadeghi-Niaraki 2014). Ubiquitous computing concept started in 1988, where Mark Weiser and his group at Xerox PARC introduced it as a vision of invisible computing integrated in people's everyday lives (Markoff 1999). If a technology can be available anywhere and anytime, to everyone, then eventually it will be in the state of ubiquity.

Among researches about using a smartphone as a surveying tool, those which are about capturing points of interests from remote landscapes are mostly related to the context of the above-mentioned issues. In (Egenhofer 1999), the author has predicted that developments in information technologies will provide new opportunities to improve problem solving in the geo-spatial domain. Spatial analysis enters the daily lives of people with employing built-in sensors. Moreover, a geographic pointer is introduced, which allowed users to identify remote geographic objects by pointing to them. Geo-Wands were portable, location, and orientation aware devices with a GPS receiver to identify location, and an orientation sensor like a gyroscope or compass to determine the direction of the pointing device. The map of the environment was also needed to match direction and find points of interest. The map would provide information about the object distances to the user. However, a ranging sensor is suggested in (Shoushtari and Sadeghi-Niaraki 2014) and the availability of this sensor on the smartphone was predicted. The Cat S61 smartphone (Cat Phones 2021) including a laser assisted distance measure is already available in the market. Other alternatives such as smartphones with multi-camera and Light Detection And Ranging (LIDAR) sensors can be also used.

Orientation tracking would the next challenging part. In the context of orientation aware devices, it is the problem of continuously estimating the orientation of the mobile devices. Typical orientation tracking algorithms with smartphone sensor data are based on Kalman

Filters (KF) (Huyghe, Doutreloigne, and Vanfleteren 2009; Yun and Bachmann 2006; Suh 2010). A simple KF model was used in (Willemsen 2016), which has been re-produced in this work. The standard method of tracing the orientation with KF is to update the orientation using the angular velocity from gyroscope and compensate for the long term gyroscope drift with the magnetic field and gravity field from magnetometer and accelerometer respectively (Xiao 2014). With the development of mobile devices like smartphones, which were equipped with built-in GPS or 5G chips, orientation, and tilt sensors, different location-based services were developed in the context of location and orientation aware devices, e.g. indoor positioning (Shoushtari, Willemsen, and Sternberg 2021; Schuldt et al. 2021).

In this paper, the smartphone is going to be used as a surveying instrument. An attempt is made to have a compression between the smartphone and the operations of a high-tech Total Station. Range finding, leveling and angle measurement are among these operations. The goal is to design, develop, and evaluate performance of a portable device which can solve the issues of orientation aware approaches using a smartphone associated with a custom-built laser range finding equipment. We first used the laser range finding sensor, then we have evaluated the leveling and angle measurement in comparison with a Total Station. The orientation tracking has been done using a KF by using the smartphone sensors values. In a discussion, an attempt is made to answer this question: *Would it be possible to use a smartphone-based equipment instead of a high-tech Total Station?*

In this way, we demonstrate the development of a novel realization of Ubi-T and evaluate it in different aspects to discuss, if there is a possibility to use smartphones instead of a Total Station. We are not looking for some yes/no answer, but the realized accuracy should guide us through the appropriate application. This realization of the Ubi-T, works as a portable module which can be attached to a smartphone. Unlike, popular Total Stations, software aspect of the suggested device is enhanced in relation to hardware using a popular mobile operating system. This increase the ease-of-use for operator, because user interact directly with the application layer of the system.

The remainder of this paper is structured as follows. In Section two, evolution of surveying instruments is reviewed. Section three illustrates the proposed concepts for Ubiquitous Total Station. Section four describes the implementation of the generation of Ubi-T. Section five contains an evaluation of this new system. Finally, section six concludes the paper with a discussion on the main research question.

2. HISTORY OF SURVEYING INSTRUMENTS

Land surveying and mapping have a long history at least as early as 2900 B.C., in the construction of Gizeh, the Great Pyramid. Over time, many surveying instruments have evolved to measure directions, angles, and distances from compass and chain through theodolites and tapes, into optical theodolites, electronic distance measuring devices, and finally into the current stage of robot Total Stations.

One of the first surveying instruments was the diopter which was employed for astronomical observations as well as property surveys about 120 B.C. Thereafter, Romans developed several surveying instruments like Groma which was used for sighting about 1st century A.D., The compass which was used earlier for navigation about 13th century, later employed for determining directions in land surveying. There was little progress in developing surveying instruments after the fall of Romans until 16th century, when Thomas Diggs described theodolite as a new surveying instrument that was used for topographic surveying (Physics-School 2021). The device included sighting mechanism and a disk which was graduated into 360̊ to measure horizontal angles. Afterwards, with the development of Vernier and telescope in the 17th century the utility and accuracy of surveying instruments improved.

Transit, an American version of theodolite, was first invented by William Young in 1831(Bedini and Smart 1964). They were the most important surveying instrument for over 100 years in the United States. They could be used to measure horizontal and vertical angles, determine horizontal and vertical distances using stadiametric range finding, perform ordinary leveling, and measure magnetic directions by compass. With technological advances, European theodolites became smaller and more accurate with microscopic angle measuring systems.

Electronic Distance Measuring systems (EDM) which was one invented by a Swedish physicist Erik Bergstrand, replaced the use of chains for measuring distances in 1948. The device measured the time of travel for visible light to a reflector and converted the result to distance using the velocity of light. As time goes by, smaller, more accurate, and more reduced power requirement EDM instruments employed using infrared or laser light (NMAH 2021).

Finally, in about 1980, an EDM component integrated with an electronic theodolite to create a single instrument called the Total Station. Measuring distances and angles and determining coordinates of interest points became possible through a computer interface. Today, Total Stations are equipped with reflector-less distance measuring devices. They can now measure distances, horizontal and vertical angles, store data into the computer memory, and display results automatically. They are integrated with Global Navigation Satellite Systems (GNSS) to determine coordinates of points in desired global reference systems and equipped with a built-in camera and laser scanner sensors to benefit 3D digitalization technologies. Figure 1 shows the timeline of some popular surveying instruments.

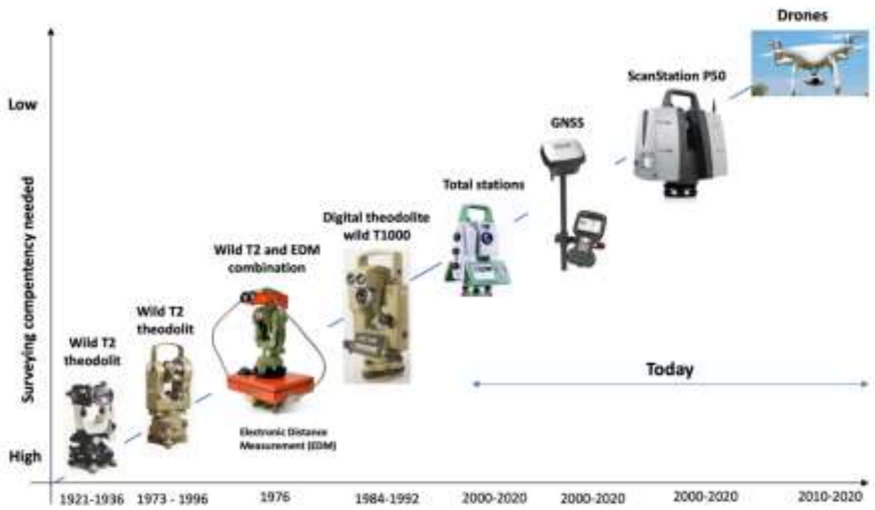

Figure 1: Examples of the development of surveying instruments (3D Digitization Workshop 2020)

3. CONCEPT FOR UBIQUTOUS TOTAL STATION

All technologies are answers to the variety of questions at different levels. Every technology tries to solve some needs of any client in anytime, anywhere or any other situation. Mobiles are examples that began to solve communication problems at first for everyone in somewhere that support telecom services, but now a day, smartphone are approximately suitable for any person, in anywhere, anytime and even any communication need. In this way of thinking, Ubi-T is introduced as a new technology for Geomatics specialists particularly surveying engineers.
Ubi-T as a mobile and small instrument with a user-friendly system provides measurement usage in anywhere, any physical ability and economic power. Also, Ubi-T acts in line with ubiquity to solve surveying problem at any time and with any surveying knowledge of a client. In order to be useful for any client, Ubi-T application is designed user friendly with different and smart manual on a popular platform like android and IOS, just against the traditional Total Stations those are employed complicated interfaces. The smartphone base applications allow the developer to add many visualization features. The application can provide some information in text, voice, video for the client. For example, when a surveyor entered to a site, the important point or necessary information can present to the Ubi-T client. Also, Ubi-T as a context aware surveying system can automatically apply the correction by getting the different sensor values like pressure sensor, temperature sensor and etc. The small size of the Ubi-T act as the main component that help client to use it anywhere. Ubi-T would have Low weight and economic price to be on hand for every physical ability and economic power.
Ubi-T can be known by separate pieces and a smartphone as the core. In other words, a Modular Ubi-T can offer the costumers to select the sensors or equipment that one may need for specific application. Different sensor like ultrasonic sensor, laser scanner sensor and different equipment like Micro lenses, eyepieces, scaled horizontal and vertical circles or different types of tripod are possible in order to design a modular Ubi-T.

4. IMPLEMENTATION

The main goal of this section is to describe the design and implementation of a smartphone-based instrument (i.e. the suggested Ubi-T in this study). It has two main elements, an electronic circuit as laser ranging equipment and orientation tracking by using smartphone sensors.

4.1. Laser Ranging Equipment

Although there are smartphones equipped with the laser ranging equipment, initial observations show error of $\pm$ 3% in range of 8 meters. It means that the accuracy is available only in the decimeter range. An external laser ranging sensor not only can improve this performance, but also it can be attached to any smartphone. Such a module does not cost more than a middle-class smartphone, and different sensors like laser ranging, LIDAR or ultrasonic can be used based on the application. We generate an electronic circuit, to measure the distance by using the laser emitter and the receiver. The laser ranging sensor is connected to the electronic circuit. Makita LD050P laser distance meter used with the accuracy of ± 1 millimeter for maximum precision based on the sensor data-sheet. The measurement range would be between 0.05 up to 50 meters. Because of the high-speed data measurement, a chip was employed to reduce the speed of data transfer to a microcontroller. Following this, the microcontroller receives the data and process the measurements. Then, it sends the information to the smartphone by using a GSM module as a Short Message Service (SMS). Figure 2 shows the laser ranging equipment.

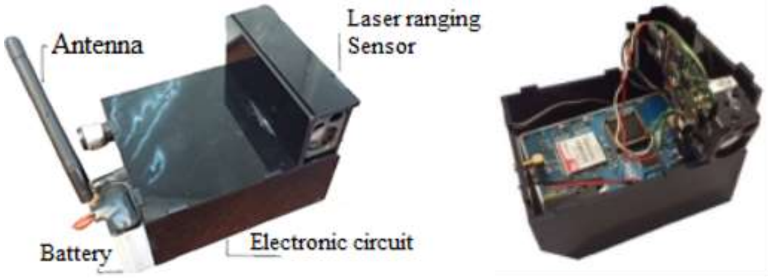

Figure 2: The laser ranging equipment. Left: The main elements. Right: The electronic circuit.

In this way, any smartphone can be used for the measurement tasks. The equipment will be small and easy to setup. Moreover, we have realized the possibility of using camera tripods for public users. The generated mobile support is shown in Figure 3.

Figure 3: The laser ranging equipment on a normal tripod, attached to the smartphone

4.2.Orientation Tracking

In order to do the orientation tracking, a KF was developed in MATLAB environment. It consists four core steps named as prediction, innovation, gain matrix and update (see Figure 4). In the prediction, the next orientation of the smartphone ($\bar{x}_t$) is determined with a movement model (T) updating the system using the last estimation ($\hat{x}_{t-1}$). For the sake of simplicity, a static motion model from (Willemsen 2016) was used here. It was developed by manipulating variables that are calculated from the angular accelerations (ω), which are multiplied with the time difference (B). Since the accuracy of the prediction ($\sum \bar{x}_t$) is also needed as a weighting element, this is also calculated according to the variance propagation law.

The innovation (d_t) describes how far the prediction deviates from the observations (l_t). For this, a suitable observation model (A) is needed. It is done by calculating the rotation and manipulating variables in advance in order to minimize the complexity of the equation, as it is converted to a linear one. In prediction, an associated covariance matrix ($\sum d_t$) is calculated which plays a role in the next step. This step is the weighting between prediction and innovation. The relative weighting (K_t) is derived from the respective covariance matrices and the design matrix from the observation equation. Finally, the update ($\hat{x}_k$) is calculated from the prediction and the weighted innovation, and again the covariance matrix ($\sum \hat{x}_k$) is calculated, out of the difference between a unit matrix and the product of the Gain matrix and the design matrix multiplied by the covariance matrix from the prediction. This matrix is needed for the covariance matrix of the next prediction. The process will be repeated for each new measurement.

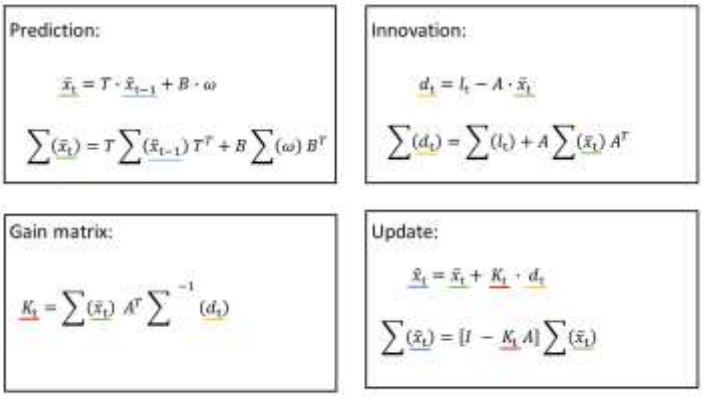

Figure 4: Core steps of the Kalman-Filter

4.3. Smartphone Application

To connect the different elements, an android prototyping using the Android Studio Integrated-Development-Environment has been done. Figure 5 shows the implemented application that includes distance measurements, horizontal and vertical angle and a simple calibration. As the smartphone and the laser ranging sensor are not always fixed to the same position, one may use a reference length and measure it with the Ubi-T, to calibrate the distance estimation. Finally, local 3D coordinates of target point will calculate. When a user has a known length in its measurement range, this will force as a fixed length to make estimation more acceptable. Several capabilities can be considered for the system, measurement and calculation of width, area and Perimeter was implemented as the sample of public use application.

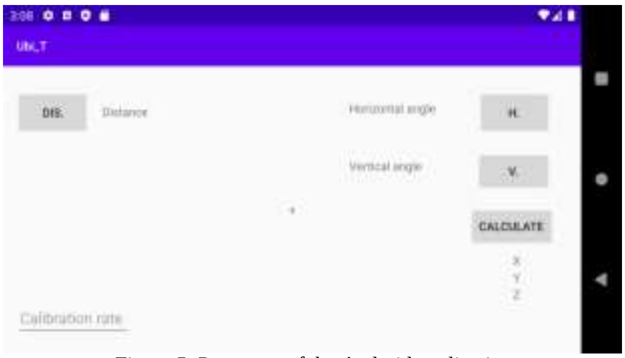

Figure 5: Prototype of the Android application

5. EVALUATION

We have evaluated the Ubi-T elements separately, similar to the implementation. Therefore, the laser ranging equipment and orientation tracking has been compared with a Total Station performance. A measuring field was set up, which consisted of several measuring marks that were set up in a circle at different distances and heights (Figure 6). In each round of measurement, targets were initially measured by a Leica TS16 Total Station, i.e. the Total Station is considered to be the reference. The measurement is compared with the references from the Total Station and a deviation is determined.

Figure 6: The Measuring field environment. Left: Orientation tracking evaluation. Right: Laser ranging evaluation.

While the accuracy of the laser ranging sensor reports from the data-sheet, it came out that the reported accuracy is achievable. Especially one can use the calibration rate in order to measure up to 50-meter of distance with at least decimeter accuracy. However, orientation tracking was more challenging. In order to estimate the both vertical and horizontal angles, Samsung Galaxy S8 has been used, in which the gyroscope, the accelerometer and the camera served as sensors. While the gyroscope and accelerometer provided measurements, the camera was used with the additional crosshair for targeting.

Before doing any measurements, the unknown standard deviations of the used sensors were first determined. For this purpose, the standard deviation was calculated by using a few second of sensors measurement at rest (see Table 1). These were inserted into the covariance matrix of the observations in the filtering procedure.

Table 1: Standard deviation of utilized sensors (in degree)

Sensor	**Accelerometer**		**Gyroscope**			**Magnetometer**
Axis	Pitch	Roll	Pitch	Roll	Yaw	Yaw
Samsung Galaxy S8	0.051	0.055	0.018	0.029	0.010	1.20

The measurement procedure consisted of three different placements. First, the smartphone was attached to the lens of the Total Station so that its orientation matched that of the Total Station. The robotic targeting of the Total Station was used for targeting. As the second placement of the measurement, the smartphone was mounted on a tripod using a nodal point adapter (holder) that can be rotated in both the vertical and horizontal axes (Figure 7). The measured target marks were targeted with the camera modified with crosshairs. There was possibility to only rotate vertically or horizontally. Finally, we have estimated the angles by rotating the smartphone by hand. The aim was to see, how much of precision in such a public case without using the tripod can be achieved. This placement is defined as freehand, in which we tried to only rotate the smartphone and keep the center in the approximate same position coordinate.

Figure 7: Different Smartphone placements. Left: using the tripod and the holder. Right: Smartphone attached to the TS16

By randomly measuring the different targets using the smartphones attached to the Total Station, the deviations up to -13.140° in the horizontal direction and up to -1.044° in the vertical direction have been recorded (See Table 2 and 3).

Table 2: Horizontal direction: TS16 vs. S8 (attached on the TS16)

TS16 [°]	**0.000**	**73.895**	**182.911**	**322.520**	**225.782**	**155.941**	**64.480**
S8 [°]	0.000	72.901	180.512	322.905	230.036	164.622	77.620
Deviation	0.000	0.994	2.399	-0.385	-4.254	-8.681	-13.140

Table 3: Vertical directions: TS16 vs. S8 (attached on the TS16)

TS16 [°]	**0.488**	**-18.240**	**-1.511**	**12.061**	**18.933**	**-17.979**	**-0.531**
S8 [°]	1.274	-17.196	-0.700	12.728	19.670	-17.055	0.129
Deviation	-0.786	-1.044	-0.811	-0.667	-0.736	-0.924	-0.660

The same experiment has been done for the holder placement. In this case, the smartphone was placed in the holder on the same tripod as the Total Station. Table 4 and 5 shows the measurements and deviations for both horizontal and vertical directions.

Table 4: Horizontal directions: TS16 vs. S8 (holder)

TS16 [°]	**0.000**	**137.741**	**235.073**	**137.741**	**46.454**	**-172.401**	**-264.261**	**0.000**
S8-holder [°]	0.000	135.365	229.051	134.063	44.721	-158.686	-247.117	11.469
Deviation	0.000	2.376	6.021	3.677	1.734	-13.715	-17.143	-11.469

Table 5: Vertical directions: TS16 vs. S8 (holder)

TS16 [°]	**2.612**	**-6.309**	**4.467**	**-6.309**	**-17.872**	**-2.459**	**4.356**	**2.612**
S8-holder [°]	2.227	-6.427	4.701	-6.408	-16.968	-1.683	3.975	2.286
Deviation	0.385	0.118	-0.235	0.099	-0.904	-0.776	0.381	0.326

From the random freehand measurements (Table 6 and 7), higher deviations can be determined on average.

Table 6: Horizontal directions: TS16 vs. S8 (freehand)

TS16 [°]	0.000	-141.144	-49.858	-141.144	0.000	47.474	407.474	310.142
S8-freehand [°]	0.000	-131.743	-47.422	-129.314	-2.815	45.180	400.345	307.020
Deviation	0.000	-9.401	-2.436	-11.830	2.815	2.294	7.129	3.121

Table 7: Vertical directions: TS16 vs. S8 (freehand)

TS16 [°]	-2.489	-17.872	-6.309	-17.872	-2.459	4.467	4.467	-6.309
S8-freehand [°]	-3.204	-16.877	-5.721	-17.085	-3.718	3.478	3.596	-5.777
Deviation	0.745	-0.995	-0.588	-0.787	1.260	0.989	0.870	-0.532

As the last rounds of measurement, a 360° of horizontal angle and few stops in between have been measured. In this case, we have increased the time of a measurement. The increasing deviations are achieved as expected (Table 8). The evaluation shows the colored noises available in the measurements, adding to the propagation of the white noises. This propagation is also well-known as the sensor drift. Therefore, it came up that the speed of the rotation has also a considerable influence on the accuracy of the measurement.

Table 8: 360° of horizontal angle: TS16 vs. S8 (holder and freehand)

TS16 [°]	0.000	47.474	172.401	218.856	268.141	310.142	360.000
S8-holder [°]	0.000	46.654	172.416	217.974	262.443	303.819	351.958
S8-freehand [°]	0.000	46.158	169.043	216.450	263.180	303.391	352.751
Deviation-holder	0.000	0.820	-0.015	0.882	5.698	6.323	8.042
Deviation-freehand	0.000	1.316	3.358	2.405	4.960	6.751	7.249

6. DISCUSSION AND CONCLUSION

The developed concept of the Ubi-T can be used to make Total Stations more user-friendly, smart and up to date. It can reduce the costs for operator trainings. With such a platform, one can use the sensors, which is needed for any need. Moreover, Ubi-T can make the surveying application more public. Any user with any knowledge in surveying and Geomatics may need to measure the lengths, angles and etc. Ubi-T is the implemented concept which ensures the functionality of Ubiquitous surveying applications. As a proof of concept, the implementation shows the usages of the Ubi-T for everyone such as developers, experts and public user. By asking different group of people (data scientist, developers, Geomatics expert and possible public), a survey has been conducted that they prefer to use Ubi-T instead of a Total Station to collect spatial data. We could see a high rate of overall satisfaction, both in main concept as well as the desired system.
The external laser ranging sensor showed a good performance. Distance measurement with decimal accuracy in the range up to 50 meter can be used in many applications. However, the challenges are in angle measurements. Due to the error drift effect, small period of measurements can cause better angle measurement performance. Figure 8 illustrates the achieved results for all of the measurement's rounds (Table 2-8). Based on the above-mentioned experiments, the mean errors of 0.700° and 5.401° in vertical and horizontal angle measurement have been achieved. We did not consider the deviations which are bigger than the reference values, happened in three very small measurements and ±3% and ±15% of deviations has been

also reported for the vertical and horizontal angles respectively. The results would be valid for similar measurement scenarios.

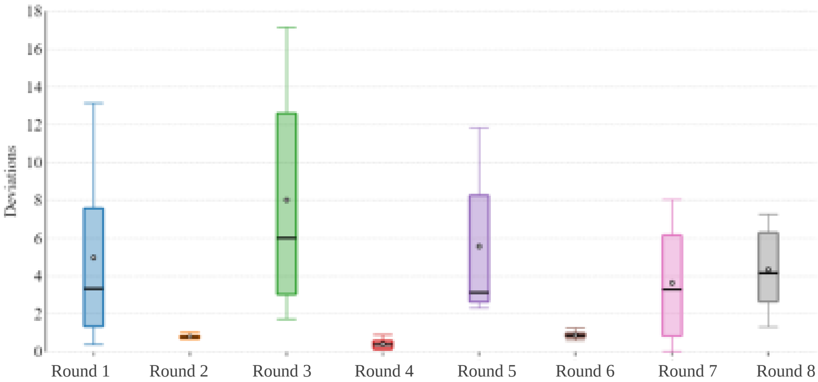

Figure 8: All of the measurement's rounds in both horizontal or vertical directions.

Back to the main question of the research, it can be concluded that smartphone-based instruments can be used instead of a Total Station, but not in any application. It should be decided based on the desired precision. However, there are surveying tasks and public applications which can be done using the Ubi-T, for instance. GIS data collection using pointing techniques are among those applications. The conversion of the distance and angle deviations to positions shows circa 20 cm of mean positioning error in only 2 meter of object distance.

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