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Anomalies in measuring speed and other dynamic properties with touchscreens and tablets

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Abstract: Touchscreens and tablets are often used in different studies and applications to capture high-resolution drawing, handwriting, or signatures. Several studies tend to analyse different properties, such as peaks or changes of the time derivatives of the coordinates; like velocity, angular velocity, acceleration or jerk of the movements. These are substantial features to analyse drawing, analyse or recognize handwriting, to examine the fluency of handwriting or verify signatures. The reliability of such a study strongly depends on the fidelity of the acquired data. We have tested several touchscreens and tablets which are widely used in different research studies, focusing on the resolution and accuracy of the coordinates and the uniformity of sampling. We have found that the vendors' performance specifications (to the extent the vendor gives meaningful specifications) may seriously deviate from reality. Even if some of the raw data may look satisfactory at first sight, our examination uncovered several potentially significant bad behaviors, and instances in which the specifications from the vendors are, at best, misleading and incompletely informative. Some authors mention that the reliability of tablet data is unclear [Ha13, Fr05], but researchers may underestimate to what extent it could influence their results. This paper uncovers some aspects of the unreliability of the data and emphasizes the importance of understanding and addressing (or at least, knowing) the revealed problems prior to any analysis.

Keywords: handwriting; speed; reliability; reporting rate; tablets; timestamps; touchscreens.

1 Introduction

Accurate time data would be important in a number of studies and applications in handwriting, e.g. several researchers apply first, second and third derivatives of the coordinates (velocity, acceleration and jerk) in handwriting analysis [Ca15, Mi99, De13, TM84, PP88, Pl93, RFT12, Ca12, RW06]. Thus, it is important to know that the time and the coordinate information from the sensors of the handwriting tablets is sufficiently accurate. In an ongoing examination of handwriting tablets, we have found the time data to be less reliable than the vendor's specifications imply – assuming that the vendor even gives specifications for timing accuracy. We tested eight tablets marketed as high-quality writing tablets: most of them are widely used among researchers. About one minute long monotonous circular motion data were acquired using a stroboscopically-controlled turntable. The acceleration was $\mathbf{0 \pm 0.001 \frac{revolution}{s^2}}$, the accuracy was guaranteed by the measuring setup described in a video and a related paper[3].

The turntable is stroboscopically accurate, with very constant rotational velocity. With such precise, uniform circular motion, equitemporal samples will all be equally spaced in

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actual position. To the extent that the reported position data from the tablet is differentially accurate, the timestamp or report-rate accuracy can be checked by verifying the distances between reported samples. If the distances are inaccurate by more than the quantization of coordinates, then either

1. the coordinates reported by the device are not accurate, or
2. the timestamps reported by the device are not accurate.

If the timing was uniform, then the acceleration should vary between $\pm\mathbf{0.05}$ pixel/ms^2. Figure 1 shows that the noise of the acceleration of one examined device is roughly 10-20 times higher than it should be.

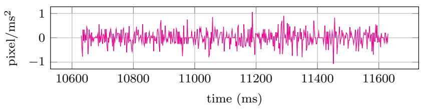


Figure 1: Acceleration of a signature pad

From our investigations, we are concerned that any research study based on raw acceleration data could be questionable. This acceleration was just an example, other time dependent properties and features should be treated with care. Therefore understanding timing behaviors of the particular device and having adequate remediation are essential.

Sampling rate, reporting rate and timestamps

When a pen movement is digitized using a device, the sampling rate measured in Hertz (Hz) expresses the number of data points acquired per second. It is important to have a sufficiently high sampling rate to have a good resolution of handwriting and especially about signing which is a fast movement, so it requires high sampling rate to get sufficient data for examination. The Nyquist-Shannon sampling theorem [Ny28] suggests having at least twice as large sampling rate as the type of the data would require based on its highest frequency components to detect information without aliasing.

The question of what sampling rate is "high enough" is vitally important. However, there are well-known trade-offs of sampling rate to noise filtering, sampling rate to frequency response, and filtering to frequency response. We have also observed that tablet firmware itself often includes low-pass and other kinds of "noise" filtering, as well as other behaviors that are not disclosed by the vendors. And in many applications, additional filtering is done in the application, based on experience with a *particular* tablet. Thus, specifying a "required" sampling rate is, at best, very incompletely useful. What would be better instead is a measure of the actual frequency response and positional accuracy, not the report rate or coordinate scale.

We also note that the need depends on the application. For example, we have observed that handwriting signatures tend to be faster, more idiosyncratic, and "jerkier" than usual connected handwriting. Thus they may require higher "true" sampling rates, and better frequency response at higher velocities.

Teulings et al. said there is no information above 10Hz, Howbrook said 20Hz [TM84, Ho]. 10Hz would imply, a sampling rate of 20 samples/second could be enough but for biometrics, almost all researchers want higher sampling rates. The sampling rate of the Anoto pen is 75 samples/second, while most of the handwriting tablets used for capturing handwriting or signatures have 200 samples/second or higher.

Some specifications use the term report rate in points per second (PPS) or use a different name for the same unit (e.g. reports per second, RPS). Here we distinguish the sampling rate from report rate in the following way: in an ideal ”world” sampling rate and reporting rate are equal, because the device reports what it samples, no less and no more. However vendor wants to give a better impression and tends to show that the device has better resolution in time, so interpolation is applied between real samples, which makes the report rate larger with additional interpolated samples between the real sampled datapoints.

If the difference between the sampling times of each consecutive data point is equal, one can say that the data is evenly-sampled and the time data is equitemporal. Although generally it is assumed that most devices are equitemporal, some devices report a “timestamp” value with each point, ostensibly to ensure timing accuracy even with variations in sampling. For example one or two samples are missed, because of internal problems capturing data, or because of “noise” filtering, or because the sampling rate is intentionally lower at the margins of the tablet or in certain proximities, to deal with weaker electronic signals. During handwriting or signing it is also informative if the device report timestamps, because it is one way to measure the in-air time, when the writer holds the pen above the device surface, e.g. between two parts of the signature or between words or disconnected letters during handwriting.

Here we summarize our observations related to timestamp, sampling rate and speed-related issues.

2 Description of the analysis

Our earlier mentioned measurement protocol was used to acquire uniform circular motion data. We used a precision audio/phonograph turntable: rotational speed was set stroboscopically to precisely $33\,{}^1\!/_3$ rpm or 45 rpm. The tonearm holds the stylus at a constant radius from the center, the tablet rotates underneath.

Using the coordinate time-series of a uniform circular motion, the reporting rate can be measured by counting how many data points fall between two consecutive local maximum points of the sinusoidal timeseries of the x (or y) coordinate (i. e. within one full circle). The number of data points in a full circle, divided by the time that it takes to rotate a full circle gives the sampling rate. A full rotation takes 1.8 seconds for $33\,{}^1\!/_3$ rpm and ${}^4\!/_3 \approx 1.33$ seconds for 45 rpm speeds.

If more circles are acquired, more local maximum points can be detected, thus it is possible to measure the number of data points within several circles and use the mean of these values. With the acquisition of more circles stability of the reporting rate can be measured using the standard error of the number of points within one circle.

It is possible to analyze the absolute velocity (speed), which should be constant. Using the original timestamps we could see a repeated pattern of uneven timestamps, thus we also calculated speed assuming even timestamps: based on the uniformity of distance between reported points, and the uniformity of speed of the turntable, we strongly believed this to be more reliable. The difference between consecutive generated timestamps was calculated using the reciprocal of the measured reporting rate.

3 Results

3.1 Timestamp differences

Based on our observations, only a few devices report equitemporal data in all circumstances, but if we examine the data further, we can observe that many devices report substantially *unreliable* timestamps. Opposite to what one would expect, in a number of the actual devices that do provide timestamps, we have found that the timestamps often have been substantially less valid than simply inferring the timing from the reporting rate.

We note that if the timing period is not an exact multiple of the clock resolution, there will be a “Moiré effect”. For example, if the reporting time is exactly 7.5 milliseconds, and the clock resolution is 1 millisecond, the time delta will alternate values of 7 and 8. If the reporting time (or the clock) is *inexact*, there will not be equal numbers of 7’s and 8’s in the values, or they will not alternate precisely.

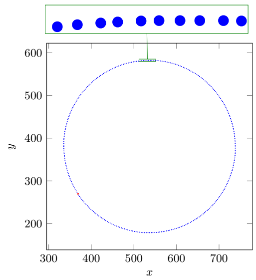
Figures 3a-3h show plots about the differences of timestamps for 50 consecutive data points. Device D is the only device with even timestamps out of the eight devices. Devices B, E, F and G show a $\mathbf{\Delta t}$ pattern which could be caused by the Moiré effect. The differences of the consecutive timestamps vary between 5 and 6 for device B, and between 7 and 8 for devices E, F and G. The timestamps pattern of Device C could not be caused by Moiré effect alone, and appears to include incorrect rounding in the firmware. However Device C shows a slightly better pattern than Device A. Device A shows an unexplained distribution, the timestamps change between 3, 4, 6 and 7. At the beginning of the measurement the timestamps’ differences are 3 and 7, after a while more and more often timestamp differences become 4 and 6. The reporting rate of this device is 200 samples/second, thus $\mathbf{\Delta t}$ should always equal 5, but it was never 5. Device H also shows similar strange behavior: the timestamp differences change between 6 and 9.

3.2 Reporting rate

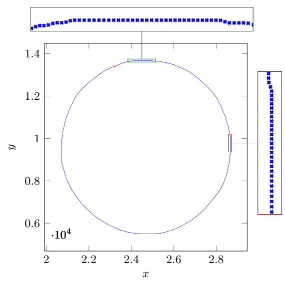
Table 1 shows the measured reporting rates and the official reporting rate for a few of the devices, where the vendor specified it. The calculation is based on the method given in Section 2, the mean and standard error ($\mu \pm \mathrm{SE}$) is given. In the last column of the table the number of data points included in the measurement is shown. The devices have reporting rates between 130 and 500 with negligible standard error, thus the reporting rate is stable through several measured whole circles. Unfortunately the official sampling rate is not provided in most of the cases.

3.3 Speed

The speed plots using both the original timestamps and reporting-rate timestamps are shown on Figures 4a-4f. Each plot shows the speed for 400 consecutive datapoints. The plots clearly show, that because of the alternating timestamp differences, the calculated speed also alternates. If the timestamps are “dropped”, so evenly generated timestamps are used, the speed remains about consistent for devices A, E, G and H, but have larger deviation for devices B and F, and especially for device C. The reporting-rate speed shows a repeating pattern for devices E and F, which could be caused by inproper leveling of the device on the turntable. Device D reports even timestamps, thus we could only examine the original timestamps which also resulted in a speed with large deviation. Briefly, based on the precision of the turntable, the timestamps are not required, and in addition are generally not reliable. For some devices by dropping the original timestamps, one can see still large deviation, thus further analysis is required in order to find out the reason of not having uniform speed.



(a) Device C - uneven spacing



(b) Device D - “angle snapping”

Figure 2: *x*-*y* plots about one whole circle

Invalid speed can be caused not only by invalid timestamps, but also by position errors. One whole circle is visualised for device C on Figure 2a and device D on Figure 2b. The zoomed part on Figure 2a shows uneven spacing between consecutive datapoints which might explain the large deviation of the speed values on Figure 4c. The zoomed parts of Figure 2b show the “angle snapping” effect which is known to be related to the computer mouse usage. Angle snapping is applied if the vendor’s firmware *intentionally* alters correct data, by changing sections of near-horizontal or near-vertical motion into straight lines, because that is “better” for touchscreen user interfaces. But of course, this is worse for signature analysis and biometrics. This was not disclosed in the vendor’s specifications. Table 1 summarizes the mean ±

ID	Model	Type	Reporting rate (Hz) Official	Measured	Speed in RPM ($\mu \pm$ SD) Original	Reporting-rate	No. of points
A	reMarkable		N/A	199.56 ± 0.15	52.82 ± 20.4	45.21 ± 0.74	10852
B	Wacom Mobile Studio Pro 13	multi-touch	N/A	194.67 ± 0.09	34.20 ± 3.01	33.94 ± 0.74	11058
C	Apple iPad Pro 9.7”	multi-touch	240	238.59 ± 0.12	44.52 ± 7.79	43.50 ± 4.19	4648
D	Signotec Delta	signature pad	500	498.99 ± 0.20	32.90 ± 2.45	–	19675
E	Wacom Intuos Pro S	writing tablet	N/A	129.98 ± 0.09	47.85 ± 3.21	46.55 ± 0.29	1936
F	Lenovo X230T	multi-touch	N/A	132.09 ± 0.03	46.61 ± 3.73	46.07 ± 2.02	9230
G	Samsung SM-P600	multi-touch	N/A	132.53 ± 0.07	45.56 ± 3.10	45.14 ± 0.42	4040
H	Samsung GT-5110	multi-touch	N/A	134.26 ± 0.05	45.53 ± 3.86	45.55 ± 1.08	10388

Table 1: Reporting rates and speed statistics of the devices

SD ($\mu \pm$ SD) values of the speed for each device also for the original and for the generated timestamps.

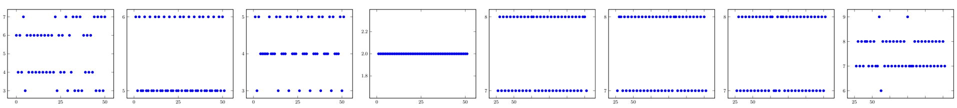
4 Discussion

Using the substantially unreliable timestamps definitely leads to accumulated error when performing handwriting analysis or signature verification using the second and third derivatives of the coordinates, e.g. acceleration and jerk of the movements. At higher derivatives with respect to time, the effects of even small timing inaccuracies may become very large. Errors which are not "smooth" or well-behaved – e.g. the error changes sign, or just magnitude point-to-point – can be *especially* problematic, because they can be hard to remediate. For remediation, it may be best advised simply not to use the firmware's timestamp values, but to count sample reports instead. But uniformity of sample report rate should also be checked carefully. There are some issues responsible for the low accuracy of time dependent features:

Quantisation in location: physical size of the sensor pixel (versus the display pixel), while small, is not negligible, and pixel size quantization should not be ignored naively. The lower the speed and/or higher the frequency, the more the pixel size quantization could influence the speed data. Some sensors have pixels that are not square: this yields different influence on accuracy in different directions.

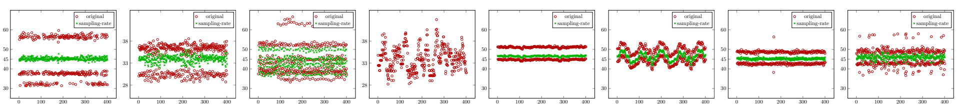
Alternatively measured coordinates: owing to the physical construction of tablets, in some sensors x and y coordinates cannot be collected at the same time [CSHT81, WP87]. Motion in varying directions is then distorted when stylus velocity is not constant.

Uneven sampling and re-sampling: there is no guarantee that a device measures location at even times. Points are missed, miscalculated, lost, doubled. As noted, timestamps are not reliable. Some devices have a higher "internal sampling rate", and a



(a) 200 (b) 195 (c) 239 (d) 499 (e) 130 (f) 132 (g) 134 (h) 134

Figure 3: Timestamp differences on 50 consecutive datapoints (caption: samples/second)



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 4: Speed plots of 400 consecutive datapoints (speed is in rpm)

different report rate, wherein complex algorithms create the reported points: this is called ”re-sampling” the original signal. The firmware may also interpolate (by some undisclosed algorithm) to replace missing points. If the signal strength is weak, or if the stylus is near the edges, the sensor may simply ”miss” reporting some samples or have a varying sampling (or reporting) rate.

Uneven time data or quantisation of time: there can be Moiré-like effects in timestamps: e.g. 300 Hz reporting time would mean **3**$^1/_3$ **ms** intervals. If the timestamp is in integral milliseconds, the reported time intervals are $\Delta\mathbf{t}_i$ is likely to be something like $\mathbf{3},\mathbf{3},\mathbf{4},\mathbf{3},\mathbf{3},\mathbf{4},\mathbf{3},\mathbf{3},\mathbf{4}\ldots$ repeating pattern. 275 Hz or slightly varying frequency could result in more odd complex patterns. In addition, in some sensors, the firmware makes rounding errors in calculations.

Firmware or software - inappropriate ”remediations”

angle snapping: the firmware intentionally changes sections of near-horizontal or near-vertical motion into straight lines, because that is “better” for touchscreen user interfaces.

low-pass filtering: sensor firmware may have performed low-pass filtering or averaging on the sample, before they are reported, to suppress noise in the data. This means that the effective Nyquist limit for frequency and velocity analysis is lower than that of the specified sample rate.

There may be some other unknown issues; only the vendor can know for sure how they have changed the ”true” data.

5 Conclusions

Many applications analyzing handwriting motion – be it for signature verification, biometric studies, or forensic examination – rely on measures such as velocity profiles, momentary accelleration, or rapid jerk, in which very accurate timing information is important. In a review of actual writing tablets, we have found a number of ”bad behaviors”of the tablet devices, where the accuracy and/or reliability of timing information is suspect. This is not described in the vendors’ specifications (assuming the specifications are given in a useful fashion for handwriting capture). These kinds of behaviours were noted 12 years ago [SD07], but still persist in tablets designed today. For a valid and reliable analysis of handwriting, for whatever application, it is important to know the characteristics and bad or limiting behaviors of the sensors, so that they can be remediated, or at least taken into account: this information cannot be naively taken from the vendor’s specifications. We are not trying to say that any particular tablet is bad, just that they all need to be checked for bad behaviors.

Additional information can be found at www.ruetersward.com and the related ResearchGate project website: [4].

[4] https://www.researchgate.net/project/Tablet-performance-examination

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