Lab Report

PX1015 - Experiment 5 - Counting and Timing

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Abstract

The following experiments explore how digital counting can be used to collect very precise data from experiments. The experiments especially focus on how to use the digital counters to measure time intervals very precisely. This enabled measuring human reaction time, the frequency up to which a human can discriminate between flashes of a LED and the acceleration of a falling ball. With this goal in mind, the experiment also lead to an exploration of the fundamentals that go into digital counting, like wiring up a circuit, using a function generator, using an oscilloscope and understanding how digital counters work.

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1 Introduction

Our modern world is heavily relying on electrical circuitry. More specifically integrated ones (ICs). A common way how such circuits operate is by utilizing a clock cycle. I. e. they do something every pulse. Today the most advanced circuits (computers) run with frequencies (clock cycles per second) of up to a few billion Hz (Ghz). A very basic circuit that can make use of a such cycles is a counter. It simply counts +1 for every pulse it receives. If the pulses are at a constant frequency this method can also be used to measure time.

2 Theory

2.1 Electrical

When wiring up any electrical circuitry some base theory is needed. First there is Ohms law, it tells us how resistance, Current and Voltage are related as such:

$$I = \frac{V}{R}$$

The law is helpful, whenever we need to figure out how to wire up a component that has limits on either the current or voltage it can handle, or how a resistor (i.e. any consumer) will affect the circuit. It tells us that the current is inversely proportional to the resistance. Thus if we want to decrease the current we need to increase the resistance. Then there is also the Laws on how to combine resistors:

Series:

$$R_T = R_1 + R_2$$

Parallel:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$$

They tell us that if we combine resistors in parallel the overall resistance will decrease. On the other hand if they are combined in series their resistance will add up.

2.2 Binary counting

Digital circuits have two basic states: off and on (0 and 1). They can't handle other values. In order to count base 10 (0-9) is therefore unusable and and the usage based on base 2/binary (0-1) is necessary. One digit of a binary number is called a bit.
Some examples for binary numbers with their decimal counterparts:

Binary	Decimal
0000_0100	4
0000_1000	8
0001_1000	24

Translating from binary to decimal is easy. It can be done with the following formula:

$$d = n_0 * 2^0 + n_1 * 2^1 + \ldots + n_m * 2^m$$

Where n, the corresponding binary digit.

2.3 Kinematics

Furthermore some Kinematic equations will be used to calculate the acceleration (constant) of a falling object. Using two section, within which the objects velocity is measured, the acceleration can be calculated as such:

Average velocity

$$v_{avg} = \frac{l}{t}$$

We can then take the difference between v_1 and v_2 to get Δv as well as the difference between t_1 and t_2 to get Δt.

Therefore

$$a = \frac{\Delta v}{\Delta t}$$

Plugging everything in:

$$a = \frac{2(\frac{l_2}{t_2} - \frac{l_1}{t_1})}{t_1 + t_2}$$

3 Experimental Procedure

3.1 Wiring up an LED

To test and verify the electrical setup the first step was to wire up a LED. For quick reconfiguration of the circuits a breadboard was used. To operate a LED and do so safely two things have to be taken into account

1. Direction: LEDs are diodes (LightEmittingDiode) so they only let electricity pass in one direction
2. Current: LEDs can only be used up to a certain current, beyond that they gets damaged.

Finding out the direction was done by testing which way it lit up. This can be done as the LED is not damaged if wired up the wrong way around. To limit the current flowing through the LED a resistor wired up in parallel was used. As can be seen from $I = \frac{V}{R}$ the current can be decreased by increasing the resistance. The documentation on the LED called for a 330Ω resistor. As such a resistor was not available, instead two 160Ω where used in series instead. After connecting a 5 volt power supply the LED lit up successfully.

3.2 Function generator and Oscilloscope

The next step was trying out the function generator. As it had a 5 volt output as well it could be used as a direct substitute for the power supply. As the circuits used later needed square waves to work properly, that setting was also chosen to test the LED. To verify that everything worked properly a low, human perceivable frequency of 1Hz was chosen. After turning on the function generator the LED started to blink.

Next the oscilloscope was brought out to take a closer look at the output of the function generator. It was wired up as illustrated in the manual:

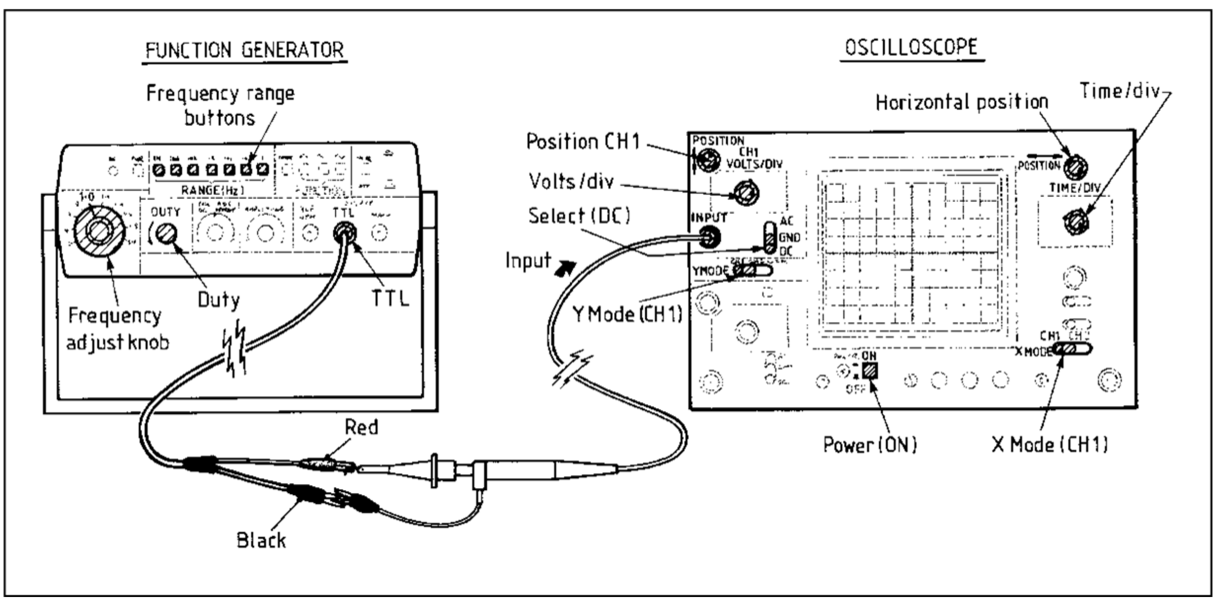

Figure 1: Function Generator wired up to Oscilloscope

First the Time/div knob was set to a very high value, this resulted in just a spot showing on the oscilloscope. By centering (Position CH1) that point (0V) the oscilloscope could be calibrated. After that the Volts/div slider was set such that it lay within the 5V range of the function generator. This resulted in two spots showing. In a third step the Time/div slider was set such that the time interval was close to what the function generator was producing as an output. The result was a square wave showing on the oscilloscope:

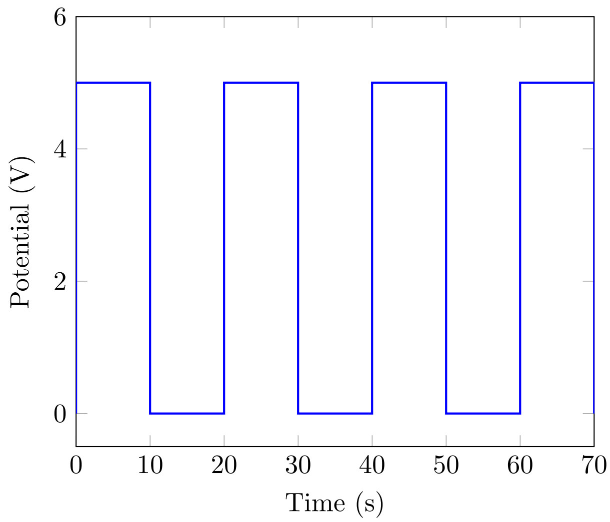

Figure 2: Idealized plotted square wave

Increasing the frequency of the function also changed how long each of the pulses on the oscilloscope where showing. This setup now let us take a reading on what frequency the human eye can perceive. To do so the frequency was set to 100Hz (No perceivable flickering), and slowly lowered until flickering could be perceived.

3.3 Counting

To count different counting circuits where wired up instead of the LED. They needed a constant Voltage of 5V so the power supply was used again. All of the different counter circuits offered two pins to connect a clock. The function generator was connected to those pins as such a timing device. The first circuit had just two buttons start and reset without any additional pins as well as a bar of LEDs to show the current count. With it the overall setup was confirmed to be working.

Afterwards the a counting device with a 7-segment display was connected. It offered an additional switch to either use the direct output of the counting IC or put it through a binary to BCD translation IC. BCD stands for Binary-Coded-Decimal. BCD uses 4 bits per decimal digit to represent it. 4 bits are used as $2^4 = 16 > 9$.

Proceeding we wired up a circuit that counted the number of pulses within a given time period (switchable between 0.1s, 1s or 10s). By connecting the function generator again we could test how many pulses where generated by it in a given second.

Last a counting device with four 7-segment displays was connected, it could count up to 9999 (10^4). In addition it also had a start, stop and a reset button with electrical pins, that if grounded also activated the corresponding action. The stop button was then wired to a hand-held thumb-actuated button. The function generator was then set to a 1000Hz such that a value of 1 on the counter would represent 1ms. One person then covered up the start switch with their hand, reset the counter and prepared to press it. The other person held the stop button, their job was it to press it as soon as they could see the counter starting to count. This way the reaction time of the person holding the stop-button could be tested. We both recorded our reaction-times four times varying the time the person had to wait before the start button was pressed.

3.4 Measuring Gravity

With the counting circuits setup and verified we could proceed to use them to measure the gravitational acceleration on different objects. To do so a drop tower with three gates was used. Additionally two of the previously introduced four 7-segment counters where used. The gates of the tower where then wired up such that gate one was connected to the start pin of the counter one, gate 2 to the stop pin of counter one as well as the start counter of counter two and gate three to the stop pin of counter two. Thus creating a setup that could count the number of pules passing while a object traveled between the respective gates. By setting the function generator to produce an output of 1000Hz this could then be translated into time. With this setup different objects where dropped down the tower. Balls of two sizes and 4 different materials where used as well as a small pen as an object with minimal air resistance. To get additional precision the actual produced frequency displayed on the function generator was also recorded to apply it as a later correction. To improve accuracy further a run with done with the function generator set to 10,000Hz.

4 Experimental Results

4.1 Human perceivable frequencies

Person	Frequency (Hz)
Sidney	36
Bray	30

4.2 Digital Counting

BIN/BCD circuit While testing the BIN/BCD switchable counting circuit it was observed that the 7-segment display did not go through the numbers correctly all of the time. If the switch was set to BCD the counting worked correctly with the display going form 0 to 9 and then resetting. Setting the switch to BIN this did not work properly. The display was instead counting up to 6 and then did show different numbers in a random seaming way.

Function Generator output verification When connecting the function generator to the 1s resetting counter, we set different frequencies on the function generator and observed what the counter counter showed. The observation where as follows:

1. When changing the frequency on the oscilloscope it took a while for the number of counts to stabilize.
2. When pressing any of the buttons or moving the cables of the counting circuit the same happened
3. Once settled the counter showed the same value as the reading on the oscilloscope up to 1 count of difference

4.3 Reaction Time

Person	1	2	3	4	5	Average	Standard Deviation
Sidney	242.3	225.5	156.5	163	228.7	203.2	40.2
Bray	189.5	330.5	252.9	150.2	171.1	218.84	73.3

4.4 Gravity

Material	t_0	t_1	Correction	$t_{0_{corrected}}$	$t_{1_{corrected}}$	g
Rubber	0.175	0.1	0.996015936	0.174302789	0.099601594	9.425604156
Wood	0.179	0.1	0.996015936	0.178286853	0.099601594	9.567281072
Plastic	0.182	0.104	0.996015936	0.1812749	0.103585657	8.714500884
Wood small	0.18	0.1	0.996015936	0.179282869	0.099601594	9.600152381
Glass small	0.181	0.099	0.996015936	0.180278884	0.098605578	9.884637057
Metal	0.181	0.099	0.996015936	0.180278884	0.098605578	9.884637057
Glass	0.18	0.099	0.996015936	0.179282869	0.098605578	9.853528837
Dart	0.1441	0.097	1.005025126	0.144824121	0.097487437	8.302050935
Metal (10kHz)	0.1765	0.0981	1.005025126	0.177386935	0.098592965	9.794882365

5 Discussion and Analysis

5.1 Human perceivable frequencies

Here we don't have a lot of data so a real analysis is not possible. Still some interesting things can be said. The first observation made was that there is no hard boarder between no flickering and flickering. There is analysis area inbetween where there is no flickering perceived, but the LED is also not percived as being continuously on. The perceived effect, might, in appearance, be comparable to candle light. There is flickering, but not with a frequency of the set 20Hz-40Hz more in the range of 5-10Hz. There might be to possible explanations:

1. There is an error in the electronics and the LED sometimes stays of for longer thant what is configured
2. Past a certain frequency the flashes are to fast for a person to perceive them. Instead they only catch e.g every other flash. This could be similar to a shutter in a camera that depending on the set frequency either catches the Light being on or off. Of course human eyes have no shutter, but this could be something happening in the brain.

Hypotheses one seems to be a bit more unlikely. This is because these supposed slip-ups are not observable at other frequencies. Also the other examinations with the oscilloscope did not reveal anything of the like.

5.2 Digital Counting

While testing the 7-segment display counter wired behavior was observed while the switch was set to BIN. A possible explanation is that the 7-segment display driver IC expects a BCD input and thus if that translation does not happen, still assumes the input is BCD. This can be confirmed by looking at what the 7-segment display would output in such a case:

Binary	BCD	Actual Decimal	Displayed Decimal
0000_0001	0001	1	1
0000_0010	0010	2	2
0000_0011	0011	3	3
0000_0100	0100	4	4
0000_0101	0101	5	5
0000_0110	0110	6	6
0000_0111	0111	7	7
0000_1000	1000	8	8
0000_1001	1001	9	9
0000_1010	0001 0000	10	2
0000_1011	0010 0000	11	3
0000_1100	0011 0000	12	4

It can be seen that as soon as the counter reaches double digits it would be different from the actual number. While it can't be confirmed that this is the exact behavior exhibited by the counter (as the sequence produced by it was not recorded), it is likely that this or something similar happened.

5.3 Reaction Time

Again with the limit of only having two human test subjects the results of the experiment are quite limited. Also it has to be noted that the recorded numbers might differ slightly, because of the jitter of the function generator that could be observed if any of the buttons where being pressed. This can likely be neglected here as the jitter seamed to be happening equally in both directions and should therefore average out over the runs. Additionally the standard deviation is in any case a lot higher than what the jitter alone could explain. This is because the jitter was observed to be in the single millisecond domain, while the standard deviation is in the 100 millisecond domain.

Keeping this in mind there are again some interesting observations to be made. First the reaction time of 20 year old test subjects seams to lie in the 200-220 millisecond range. This is close to the value stated in online resources. Also noteworthy is the high standard deviation. It shows that human reaction time is not consistent. This might have different reasons, one of them could be if the subject focuses on the LED or is distracted. Another factor could be the waiting time until the LED lights up. It could happen that the subject involuntarily loses interest after a while. It would definitely be insightful to repeat the experiment with more test subjects, with more trials spread over the a longer time span.

5.4 Gravity

The last experiment seams to be the one that should produce the most precise results as no humans as test subjects are involved. Besides that there are likely some caveats that might still contribute to not getting precise measurements. One factor could again be the effects of the aforementioned jitter in the function generator. This is a problem because

$$\Delta a \propto \frac{1}{\Delta t^2}$$

As a result any slight variatons in the measured time have a big impact on the measured acceleration. To mimize this problem we added a correction term to our calculations. It states how the exact frequency that the function generator displayed during the specific trial. This correction can only account for a general offset, not for the jitter induced by the falling object triggering the gates.
Other factors hindering the precision of the experiment are the imprecise measurement of the tube length (only accurate to 10^-1m) as well as the tube itself potentially trapping air and thus causing a air cushion to be formed.

Also potentially affecting the results is the time resolution of the counter. With the function generator set to 1kHz only time-steps of 1ms can be recorded. To get more precision, we set the function generator to 10kHz for the last trial, giving us a 10x improved time resolution. It again is debatable if that improved things, as the aforementioned jitter might at this point be a lot bigger than the smallest measurable.
If this experiment is repeated, the most important thing is to reduce the jitter, this might be possible to do by modifying the circuits (e.g. adding a capacitor), so that any electrical effects induced by the switching get reduced. Additionally doing multiple trials with the same object might improve the situation as well.

The results itself are on a first look not surprising. Heavier materials, as well as bigger objects fall faster. This is easily explained by a looking at the formulas governing the fall:

Air resistance:

$$F_a \propto A$$

Force due to gravity:

$$F_g = gm$$

as the mass of a sphere is given by

$$m = \rho\frac{4}{3}\pi r^3$$

thus,

$$F_g = g\rho\frac{4}{3}\pi r^3$$

while the area is described by

$$A = 4\pi r^2$$

thus,

$$F_a \propto r^2$$

while

$$F_g \propto r^3$$

therefore $F_a >> F_g$ for big r and

$$F_g \propto \rho$$

(With F_a as air resistance, F_g as force due to gravity and $F_{total} = F_g - F_a$)

While this part of the result is confirmed by theory, another detail is a lot harder to explain. In some of the trials the measured acceleration was higher than what is commonly quoted as g in Aberdeen ($9.1ms^-2$). This might point to a systematical error of the experiment that shifts all of the measured results up, above the actual present acceleration. Curiously, the last trial where the function generator was set to 10kHz was a lot closer to the expected value of g (note that a big metal ball was used, thus reducing the effect of air resistance as shown). Without making more measurement it is not conclusive if this was just a statistical fluke or actually the result of the improved time resolution.

6 Conclusion

Overall it could be observed that using electronic circuits and counting devices, allows for a wider range of experiments to be conducted. This is especially true for processes that happen fast and can thus not be fully grasped by mere unaided observation. It is also clear that electronic counting/measuring allows for a lot higher time-resolution while conducting experiments. This is highlighted by the fact that the highest achievable time-resolution within the experiment was 0.1ms (10kHz), while the highest time-resolution that was achieved by a human lay only at around 33ms (30Hz). As noted it might even be possible to improve this with better electronics and by conducting more runs.

7 References

[1] MacPherson, Ross Franklin, First Year Physics Lab Manual (2009), University of Aberdeen.
[2] Wikipedia, `https://en.wikipedia.org/wiki/Mental_chronometry`, Mental Chronometry, 03.12.2021