CHECKING PERFORMANCE

Most of the commercial syringe pumps calculate the flow rate by considering the syringe diameter and other parameters that depend on how they built the pump itself. In our case, the linear actuator has a M8 worm screw with a pitch of 1.25 mm per revolution. In addition the stepper motor rotates in steps of 0.7º then you need to give 360/0.7 steps per revolution (514 steps). With these data, each step implies a linear motion of **2.43 microns** (1.25/514 in mm) **this is the absolute resolution of movement**. These calculations are permanent for our pump because we will always use the same stepper and the same threaded rod. From here, the calculation depends on the syringes you're using and we must redo it every time we change them. We must calculate the volume of a cylinder of 2.43 microns in height and diameter that corresponds to the syringe used. If a 10 mL syringe is used, the plunger diameter is 14.34 mm (we used BD Hypak SCF Glass Prefillable syringes but diameter may differ on manufacturers) then the volume is

$$v\ (mL) = H.\pi.\left(\frac{d}{2}\right)^2 = 2.43 \times 10^{-3}.\pi.\left(\frac{14.34}{2}\right)^2 = 0.392 \times 10^{-3}$$

The calculated value represents the **0.004% of the nominal syringe volume, which is the syringe resolution**. If two identical syringes are used then each step delivers 0.8 µL. Flow of delivering is the volume/time ratio, where time is exactly the interval calculated by the Arduino sketch:

$$t\ (ms) = (1025 - volt).250 \times 10^{-3}$$

where *volt* is a value ranged from 0 to 1023, so *t* is minimum (and flow maximum) when *volt* equals to 1023 and maximum when *volt* is null. According to these data, and using two syringes of 10 mL, the maximum flow reaches 1.57 mL/s and the minimum is 3.1 µL/s.

We can make several experiments measuring the volume of water delivered in a complete cycle (from one limit switch to another) and the time it takes to do it. To get more measurement accuracy, instead of measuring the volume we can weigh the water and calculate the corresponding volume by using the density at experimental temperature. Doing the experiment several times, we can check the precision of the pump. Doing the experiment with different values of *volt* we can check the linearity of flow setting. By comparing the experimental values with those calculated ones we can check the accuracy of pump. Here are the collected data:

Setting	**Measures**			**Data**		**Calculations**	
volt	Temp (ºC)	Mass (g)	Time (s)	Density (g/mL)	Flow (µL/s)	Vol (mL)	Flow (µL/s)
1018	19.5	19.97	36.8105	0.9983081	448.5257	20.0038	543.4277
1018	19.5	22.11	40.2442	0.9983081	448.5257	22.1475	550.3270
1018	19.5	22.16	40.3650	0.9983081	448.5257	22.1976	549.9209
1018	19.5	22.35	40.2280	0.9983081	448.5257	22.3879	556.5248
1018	19.5	23.03	40.1964	0.9983081	448.5257	23.0690	573.9079
1018	20.0	22.68	40.1684	0.9982063	448.5257	22.7208	565.6375
1018	20.0	22.80	40.1202	0.9982063	448.5257	22.8410	569.3135
1018	20.0	22.78	40.2109	0.9982063	448.5257	22.8209	567.5310
1018	20.0	21.55	40.0982	0.9982063	448.5257	21.5887	538.3963
762	20.0	21.130	1418.3650	0.9982063	11.9379	21.1680	14.9242
762	20.0	21.089	1418.7440	0.9982063	11.9379	21.1269	14.8913
762	20.5	21.275	1418.1990	0.9981019	11.9379	21.3155	15.0299
762	20.5	21.140	1399.6190	0.9981019	11.9379	21.1802	15.1328
762	21.0	21.133	1410.1900	0.9979948	11.9379	21.1755	15.0160
762	21.0	20.283	1427.1710	0.9979948	11.9379	20.3238	14.2406
762	21.0	20.966	1402.7800	0.9979948	11.9379	21.0081	14.9761

Setting	Measures			Data		Calculations	
volt	Temp (ºC)	Mass (g)	Time (s)	Density (g/mL)	Flow (µL/s)	Vol (mL)	Flow (µL/s)
762	21.0	20.945	1397.3580	0.9979948	11.9379	20.9871	15.0191
762	21.0	21.100	1414.2780	0.9979948	11.9379	21.1424	14.9492
762	21.0	13.003	892.4510	0.9979948	11.9379	13.0291	14.5993
506	19.5	21.214	2792.4180	0.9983081	6.0495	21.2500	7.6099
506	19.5	21.000	2712.2170	0.9983081	6.0495	21.0356	7.7559
506	20.0	20.940	2704.4700	0.9982063	6.0495	20.9776	7.7567
506	20.0	21.092	2784.2700	0.9982063	6.0495	21.1299	7.5890
506	20.0	19.741	2632.6860	0.9982063	6.0495	19.7765	7.5119
506	21.0	21.102	2826.5760	0.9979948	6.0495	21.1444	7.4806
506	21.0	20.295	2763.5010	0.9979948	6.0495	20.3358	7.3587
506	21.0	21.136	2807.0230	0.9979948	6.0495	21.1785	7.5448
506	21.0	10.320	1350.6560	0.9979948	6.0495	10.3407	7.6561
250	19.0	9.738	2340.2160	0.9984073	4.0512	9.7535	4.1678
250	19.5	13.921	3290.8300	0.9983081	4.0512	13.9446	4.2374
250	19.5	10.100	2103.5620	0.9983081	4.0512	10.1171	4.8095
250	20.0	10.948	2178.6040	0.9982063	4.0512	10.9677	5.0343
250	20.0	10.560	2169.0270	0.9982063	4.0512	10.5790	4.8773
250	20.5	10.104	2025.4400	0.9981019	4.0512	10.1232	4.9980
250	20.5	10.481	2117.1020	0.9981019	4.0512	10.5009	4.9601
250	20.5	15.410	3052.6640	0.9981019	4.0512	15.4393	5.0576
2	20.5	16.252	4161.0360	0.9981019	3.0691	16.2829	3.9132
2	20.0	11.857	3150.1360	0.9982063	3.0691	11.8783	3.7707
2	20.0	14.428	3756.0540	0.9982063	3.0691	14.4539	3.8482
2	20.5	10.070	2631.8330	0.9981019	3.0691	10.0892	3.8335
2	21.0	11.501	3079.1240	0.9979948	3.0691	11.5241	3.7427
2	21.0	10.204	2668.4270	0.9979948	3.0691	10.2245	3.8317

The experiments are performed with remote control by the USB connection, so the *volt* value is set accurately. To take times without error, we have included a few of code in the Arduino sketch, by this way the *Serial Monitor* of Arduino Development Environment informs us about the time (in milliseconds) when the experiment is started and stopped:

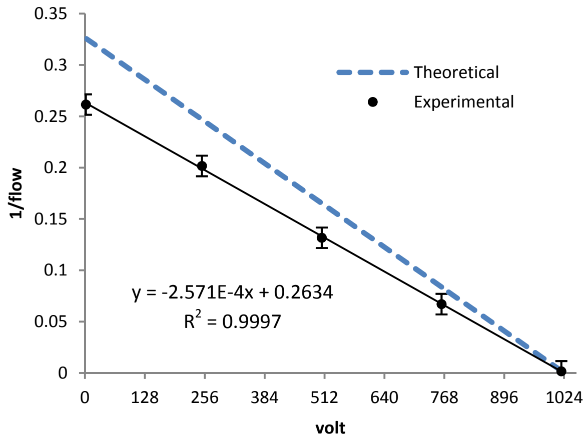
```
....
switch (serialData) {
  case 's':                                    // stop
    runMotor = LOW;
    runLOAD = LOW;
    Serial.print("t");                         // To calibrate
    Serial.println(millis());
    Serial.print("Ok, ");                      // Handshaking Ok
    Serial.println(serialData);
    break;
  case 'g':                                    // go run
    runMotor = HIGH;
    runLOAD = LOW;
    Serial.print("Ok, ");                      // Handshaking Ok
    Serial.println(serialData);
    Serial.print("t");                         // To calibrate
    Serial.println(millis());
    break;
  ....
```

The aspect of the *Serial Monitor* window after doing some experiments looks like that:

```
v756
Ok, r
Ok, f0,250,250
Ok, g
t45639
t2149201
Ok, s
Ok, g
t2424953
t4603557
Ok, s
Ok, g
t4934644
t7103671
Ok, s
Ok, g
t9982913
t12008353
Ok, s
```

To weight the water a three-digit precision balance was used. A glass with water is placed on the weighing pan and a plastic tube connected to the pump gets or loose water into the glass. Before starting the experiment the syringes are manually filled (with the manual control panel) and the balance should be tared with the glass and the remaining water, so we just have to read the weight at the end.

To check linearity we should consider that flow to time relationship is inverse, so a graph of 1/*flow* versus *volt* must be linear. From the experimental data in Table we have:



The blue dashed line represents the theoretical flow, calculated from the equations above. Black dots are the average of experimental flows calculated from the time elapsed and the correspondent weight of water at every value of *volt*. With these values we have calculate the line of least squares fit (black solid line) and compare it with the theoretical.

An experimental flow value higher than the theoretically expected is generally observed. Moreover, the deviation increases when small flows are setting. This difference in slope may be due to inaccuracies in any of the geometric parameters used to calculate the theoretical slope (pitch of screw, diameter of syringes or rotation of step), for example an increase of syringes diameter in one millimeter matches the slopes, keep in mind that we have used syringes for general purposes and of course they are not calibrated. Anyway, what is important is not that there is this discrepancy but it is small. Moreover, the relevant data is the linear behavior of data that reflects the accuracy of the obtained flow regarding the setting. The value of R^2 near to the unit reflects a linear behavior and, if $R^2 = 1$ is the total accuracy, a deviation of 0.0003 in the coefficient represents an **accuracy of 0.03%**

The true **range of flow**, calculated from the least squares fit and for two syringes of 10 mL, goes **from 7.72 mL/s to 0.26 µL/s**.

When experiments had done, we observe that the data dispersion increases if we don’t put attention in avoiding the starting effect. The syringes commonly used for pumping have rigid plungers that do not deform and whose contact surface with the barrel is minimum, but the affordable syringes that we have used have a plunger tip of rubber that adheres to glass, so more pressure must be applied to start moving. When finally the plunger moves, the rubber pushes the liquid very quickly with a flow greater than desired. This effect can be minimized by lubricating the rubber with silicone oil and making the experiments carefully. An alternative would be to make a plunger as that of commercial syringes (rigid and with an o-ring seal on tip) or replace the rubber tip by a home-made rigid plastic piece with the seal included.

The statistical results derived from the collected data are summarized in the table below. The relative standard deviation (RSD) is related to the **reproducibility** of the obtained flow. A value of RDS **smaller than 2% over the whole range of flows** is a good result. Commonly the commercial syringe pumps declare accuracy around 1%. Fortunately there are still rooms for improvement, by changing the syringes? We’ll see!

volt	**1018**	**762**	**506**	**250**	**2**
Geom. Flow (μL/s)	448.5257	11.9379	6.0495	4.0512	3.0691
LS Fit Flow (μL/s)	626.4466	14.8323	7.5050	5.0234	3.8047
Average (μL/s)	559.5410	14.8779	7.5848	4.9561	3.8233
Stand Dev. (μL/s)	10.9455	0.2642	0.1291	0.0958	0.0602
RSD (%)	1.96	1.78	1.70	1.93	1.58
Abs. Error (μL/s)	-66.9056	0.0456	0.0798	-0.0673	0.0187
Rel. Error (%)	-10.7	0.3	1.1	-1.3	0.5