Drop Measurement System for Biomedical Application

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I. Introduction

IN CLINICAL practice, infusion systems are very common [1]–[4]. They are utilized to administer intravenous liquids and solutions to a patient. There are many different ways to administrate these medical liquids: via pumping systems [3] or using apparatuses that exploit the principle of drip by gravity. In these cases, there is a need for pumps specially built and regulated through electromechanical systems, with high performances in terms of precision of volume flowing out without any leakage. For this reason, these types of pumps have a very high cost of purchase, which when combined with the maintenance costs, makes their usage in hospitals very limited, preferring, where possible, the cheapest gravity drip systems.

The infusion technique most widely used is the intravenous therapy. The intravenous [6], [7] apparatus is very simple and low cost, and it is formed by an intravenous bag on a pole connected to intravenous lines and an infusion needle, as shown in Fig. 1. The outflow of the medicinal solution occurs through a drop chamber and a terminal: the former is the responsible for the descent of the liquid, by force of gravity, in the form of drops and the latter regulates the flow velocity. The dosage requires the administration of a precise amount of active principle, but it is customary to prescribe this quantity in terms of drop rate, called the drop factor.

The absence of electronic controls in the intravenous bags and the possibility of only a coarse adjustment of the drop factor do not guarantee the administration of a precise amount of medication. It is also necessary to note that the dosages expressed in terms of drop factor do not consider several factors, such as morphological diversity of the drops; different speeds of the drop, variable in function of the amount of liquid in the bottle; different temperatures and viscosities of the liquid; and different specific weights, according to the quantity of active principle dissolved in the physiological substance. Thus, it results of great interest to the study of a system capable of making a low-cost intravenous drop system more accurate, maintaining the same ease of use and cost. Different strategies were implemented to address this problem: a capacitive system [8] or an optical mechanical system [9], but no system had the sufficient accuracy and robustness to work. Specifically, in this paper, an optical system was designed and developed for measuring the volume of liquid drops. The instrument was realized through a simple laser diode and a photoreceiver, and it is designed to be added on the typical intravenous infusion systems already present in the market, to constantly monitor the solution volumes with good accuracy and reliability.

Fig. 1. Intravenous bags on a pole connected to the intravenous lines.

II. System Description

The design of the measuring system is based on the phenomena of reflection, refraction, and scattering of light that occurs as a result of the interaction of light with the

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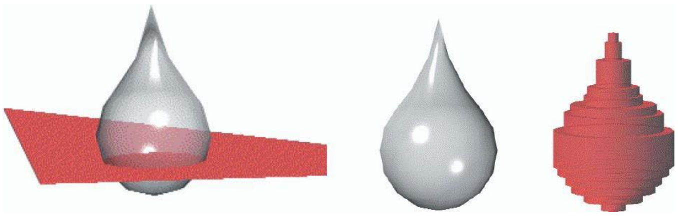

Fig. 2. Drop approximation as a discrete sum of different radius cylinders.

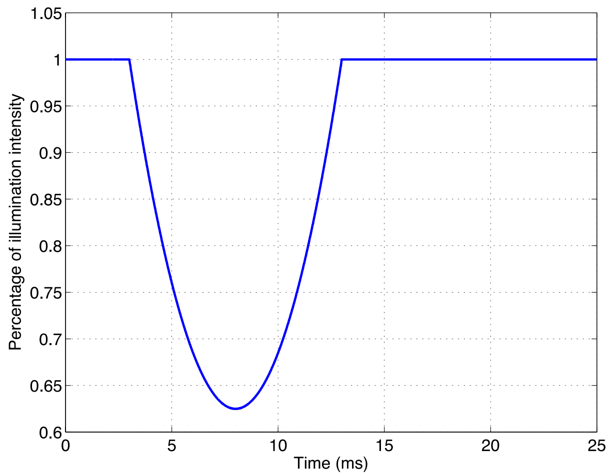

Fig. 3. Simulation of the signal normalized to the maximum detected point.

liquid solution [10], [11]. For our experiments, we used a saline solution as the target medium. The phenomena of reflection, refraction, and scattering occur each time a light beam passes from one medium to another; part of the light is reflected and scattered and the other part may be transmitted depending on the refraction index of the two materials. In the present case, considering the transparency of the saline solution, the phenomenon that appears to be predominant is the refraction compared with reflection and scattering. Therefore, it was decided to detect the variation of light intensity as a result of the passage of the drop through the light beam and to relate such variations to the radii of the drops, supposing their cylindrical symmetry [12].

Intercepting, with the aid of a suitable optical system, a very small portion of the drop, theoretically infinitesimal, it is possible to approximate the drop itself to a sum, theoretically continuous, of cylinders, as shown in Fig. 2. Focusing on the single cylinder is then possible to detect the variation of optical intensity and estimate the radius. With the voltages sampled on the photodetector, subsequent to the passage of the liquid drop through the light beam, we calculate the normalized vector as the measured voltage divided by the maximum voltage value acquired, and we call it the obscuration percentage. During its passage, the drop originates a voltage signal similar to that theoretically calculated, as shown in Fig. 3.

The drop radius is experimentally calculated after calibrating the system, a divergent laser beam with a collimating optics facing a photodiode with a lens, as shown in Fig. 6. By placing different radius objects between laser and photodiode, it was possible to measure experimentally the percentage of overshadowing due to different radius

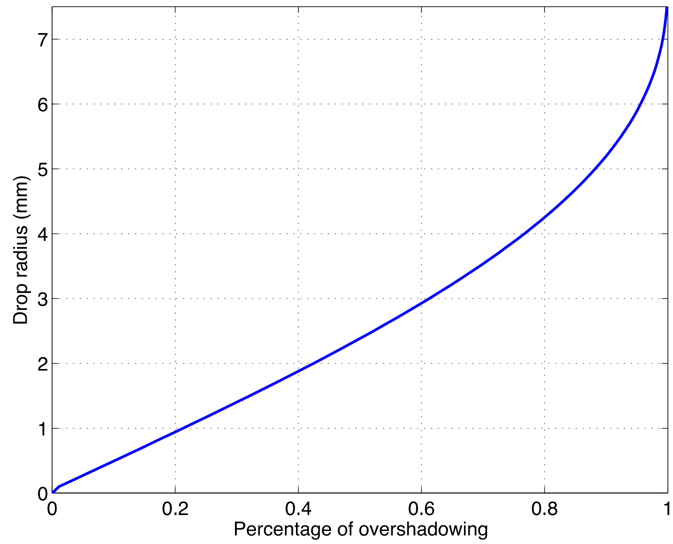

Fig. 4. Drop radius as a function of the overshadowing percentage.

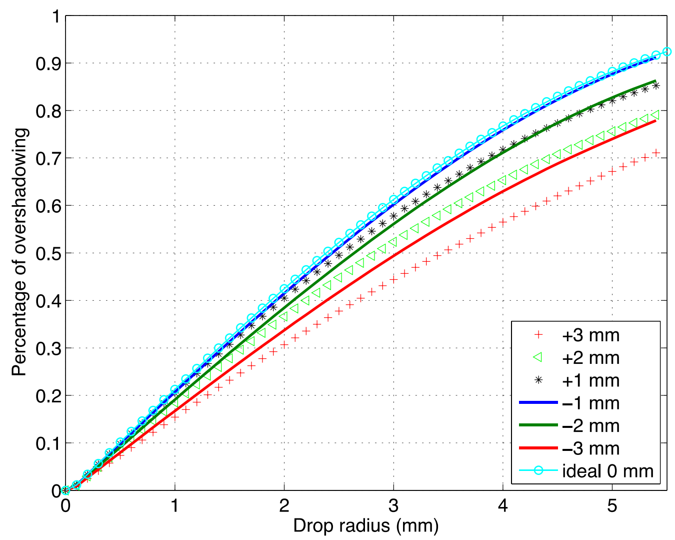

Fig. 5. Characterization of the overshadowing percentage shifting the drop from the center of the laser beam.

targets (Fig. 4), induced by different amounts of light scattered by the drop. Moreover, it was calculated the percentage of overshadowing change due to the drop shifting from the center of the laser beam, ranging between -3 and $+3$ mm (Fig. 5). It is clear that within ± 1.5 mm of shifting, considering drop radius up to 3 mm, it is possible to have a curve within the 5%, which is the goal of this paper. Considering the mechanical construction, it is quite easy to achieve this result when placing the sensor at the wall of the drip chamber.

Once the radius is known, it is easy to calculate the correspondent area of a drop slice hypothesizing a cylindrical symmetry of the drop itself. In addition, the drop speed can be evaluated by the time of flight between two photodiodes placed in the drop flow direction, as in Fig. 6. The evaluation is not trivial, because the drop is not a solid: the initial time of flight indicates the speed of the lower part of the drop, at that specific time, and the drop has not yet reached its speed

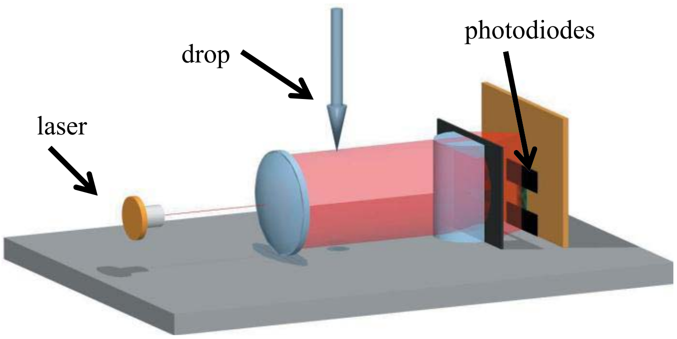

Fig. 6. Design of a volume measurement system.

regime in air. For calculating the speed evolution during the fall, we considered two limit situation: the drop as a solid (all the sections moves at the same speed) and as completely released shape (each section has its own speed independent of the other sections). These conditions lead to two different calculations of the speed for each drop section. We empirically found the best approximation as a weighted averages between the two cases. The coefficients of the averages have been found experimentally during the calibration described in Section IV. The measurement of the speed of single drop section plays a fundamental role in the present discussion: in this way, it is possible to calculate the height of the single cylinder and so to estimate the drop volume.

III. Hardware Setup

To realize the described project, we must choose carefully every single component of the setup. To reduce power consumption and the noise due to environmental light, sunlight, or artificial light sources, we decided to drive a laser (APCD 630, Roithner Lasertechnik, 650 nm) instead of a light-emitting diode in pulsed regime rather than in continuous one.

To facilitate the decoupling, during the light detection, of the useful from the unwanted light, it is necessary to make some considerations. The sunlight in the short term is almost constant: this behavior is thus similar to an offset in an electrical point of view, and therefore, does not require special conditions on the driving frequency of the light source. The optical sources, such as lamps, generate a light intensity that is proportional to the square of the current that circulates in them. Therefore, typically, they generate a spectral component that doubles the power line frequency.

To avoid this disturbance, it was decided to drive the source with a working frequency of approximately 15 KHz and a duty cycle approximately equal to 10%, to scan correctly the drop radius. In fact, it takes a few milliseconds to the drop to travel a few millimeters, the vertical drop dimension in front of the light beam.

Afterward, it was studied with an optical system with the fewest number of optical elements, to lower the influence of their mechanical placement and the sensor cost.

This system, shown in Fig. 6, produces a large light beam. For reducing the light beam to a couple of lines on the photodiodes, it is used a mechanical barrier with two slits. The quality of measured signal is still preserved as the light beam touching the two photodiodes is very thin.

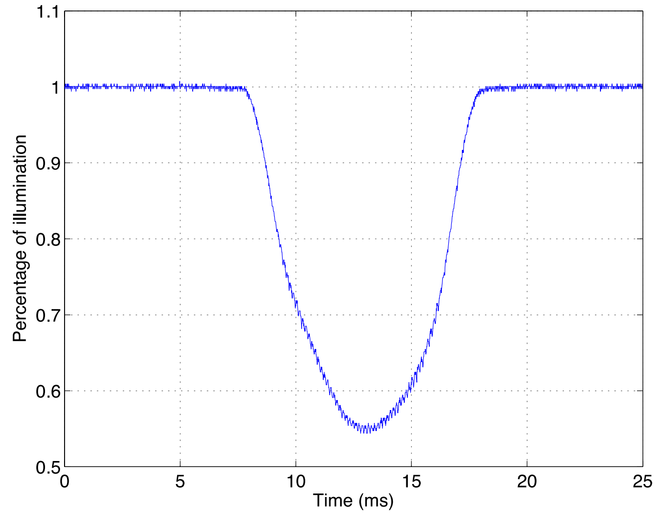

Fig. 7. Signal acquired using one cylindrical lens measurement system.

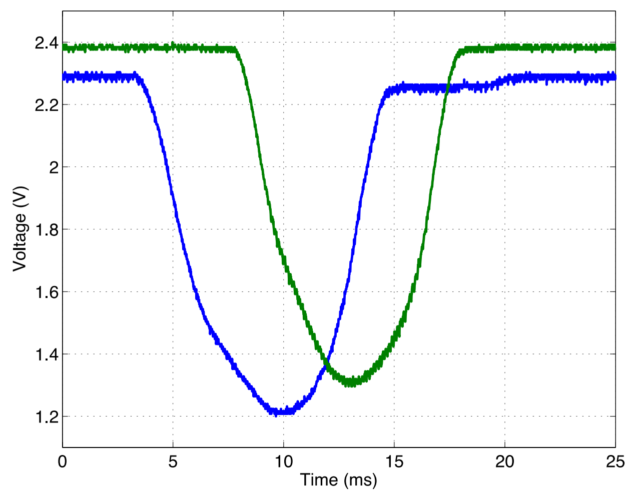

Fig. 8. Signal measured by the two photodiodes during the falling of one drop.

The system is realized using only two lenses, a convex lens and a cylindrical one. The first, with a diameter of 25 mm, is placed close to the drip point at a distance equal to the focal distance from the light source; you get a light beam that follows the trend shown by the arrows, indicated as a drop, in Fig. 6. The cylindrical lens, with a diameter of 5 mm, has the task of laterally tightening the beam as in previous cases focusing it on the photodiodes. To select two precise laser lines, the cylindrical lens is mounted on a special support with two slits in correspondence with the two photodiodes.

Fig. 7 shows an acquisition of the signal from the first photodiode, after an envelope detector, during the fall of a drop with diameter of about 5 mm (the values are normalized to 1). The presented solution, realized by only two lenses, is capable of generating a light beam suitable to the purposes of the project and solves the problem related to the bump shown in [13]: the light refracted by the drop is not collected by the two slits, and therefore, the drop generates a pure shadowing effect, as observable from Fig. 7.

Fig. 8 shows an example of acquisition measured by the two photodiodes after the envelope detector (the laser is pulsed).

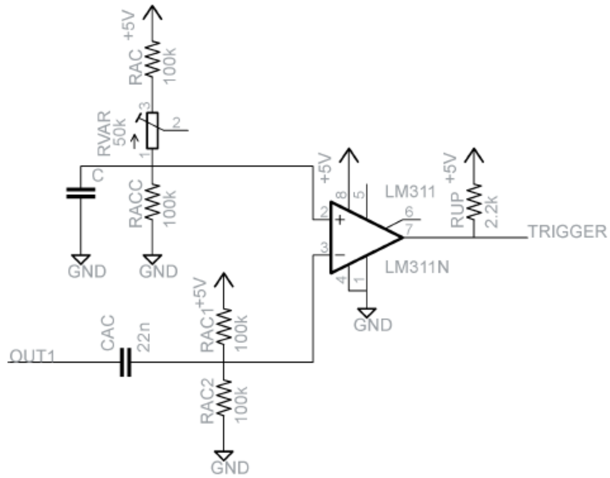

Fig. 9. AC-coupled triggering circuits.

To synchronize the signal acquisition, a trigger signal is realized through the circuits shown in Fig. 9: the peak signal is fed to a comparator through an ac coupling. In this way, the trigger switches when the signal decreases to a certain amount, decided by the trimmer R8, independently of the dc level. This kind of triggering alleviates the mechanical and optical requirement: it works without the need for precise calibration and even if the absolute light values changes due to laser aging or different transparencies of the employed drill chambers.

The system was tested through a data acquisition board (The National Instruments USB-6212, aggregate sampling rate of 400 kSa/s) with triggered acquisition. The final prototype was realized with a DSPIC33 microcontroller (microchip). It drives the pulsed laser, acquires the signal from the two photodiodes triggered by the circuit shown in Fig. 9, elaborates the data, and writes the results on a display.

IV. Experimental Results

We make some volumetric measurements to calibrate the system and estimate the instrument accuracy. The calibration makes use of the data reported in Fig. 4, for calculating the radius of each drop section. To find the coefficients for the weighted average between the fall as a solid and as a completely free shape, we realized a measurement campaign for different fall heights. Using an approximated drop speed evolution equal to 70% as free shape and 30% as a solid, the drop volume measurement becomes almost independent of the fall height and therefore of the initial speed; therefore, we implemented these coefficients in elaboration.

After the calibration of the instrument, we used a 1-ml syringe filled with 1-ml of water, and we proceeded to make the drip from the point prepared, as visible in the photo of the prototype (Fig. 10), and a campaign of one hundred measurements was performed. The results are reported in Fig. 11.

Subsequently, using the same calibration, fifty volumetric measurements were exploited also using a 2.5-ml syringe filled with 2-ml of water (Fig. 12). In this way, it was possible to verify the overall performance of the instrument also by changing the drop dimensions very different between the

Fig. 10. Photo of the prototype.

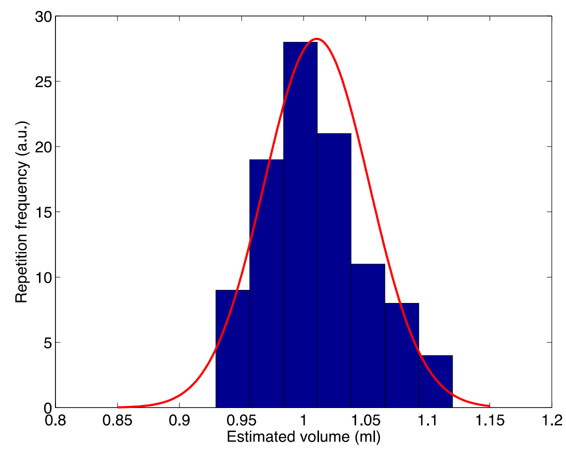

Fig. 11. Acquisition histogram for a campaign of measurement done with a drop of about 0.04 ml for a volume of 1 ml. Thick line: normal distribution.

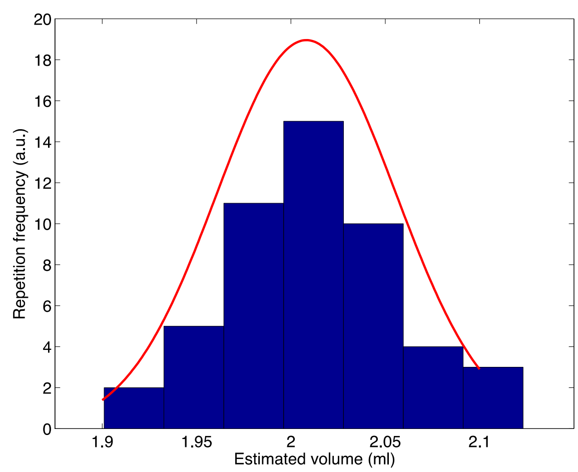

Fig. 12. Acquisition histogram for a campaign of measurement done with a drop of about 0.06 ml for a volume of 2 ml. Thick-line: normal distribution.

two syringes (about 0.04 ml for the first syringe and 0.06 ml for the second one).

Observing the measurement results, reported in Table I, it was observed the repeatability of the measurement is guaranteed. Small changes in the height of the point of drip do not affect the computation of the final volume. The measurements made with the 1-ml syringe are affected by increased uncertainty for these reasons: the low number of drops passing

TABLE I
MEAN VALUE AND STANDARD DEVIATION OF THE PERFORMED MEASUREMENTS

	V=1 ml	*V*=2 ml
V	1.011	2.009
σ	0.042	0.047

through the light beam, dependent on the total volume infused; the not precise vertical alignment of the syringe, function of the size of the small diameter of the syringe spout. It then states that the standard deviation relative to absolute volume infusions of 2 ml is estimated more accurately. To confirm the robustness of the measurement technique adopted, we proceeded to do other measurements from a point of greater height than the previous ones, obtaining errors always below 2%.

Finally, we performed different volumetric measurements on a continuous drop flow and also inside the plastic drip chamber shown in Fig. 10. We found an error below 2% for the global volume between 10 and 100 ml and below 1% for the volume higher than 100 ml. As expected, the drip chamber only attenuates the laser signal, but do not affect the global performances. An error of 2% is indeed completely adequate to the application and is a good achievement, even if compared with the resolution of volumetric pumps.

V. CONCLUSION

The proposed volumetric sensor is based on the measurement of the shadow induced by a drop during its fall. After the campaign of measurements, it can be said that the principle of operation, though simple, proves to be of good precision (lower than 2% in infused volume) and adequate to the specific biomedical application. The realized prototype is low cost, battery operated with very low power consumption (lower than 50 mW) and can be placed directly to some commercial drip chambers. Future developments regard the complete engineering of the prototype very promising for a future commercialized system.

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