Electronic Fountain Pen -
A Highly Integrated Stand-Alone Microdosage System

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ABSTRACT
For the first time an electronic fountain pen is presented equal in size with conventional pens. It can be regarded as the first fully functional, highly integrated, miniaturized and self-sustaining microdosage system of its kind operating under real world conditions. The main components are a liquid level sensor, a microvalve and a bubble- and particle tolerant fluidic system. The pen has been optimized with respect to minimum energy consumption. It contains a programmable ASIC and is powered by two standard watch batteries ensuring operation over a period of 2 years under standard conditions.

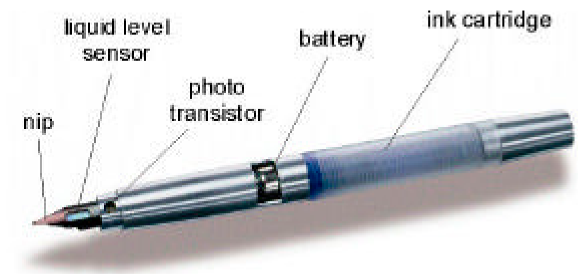

Fig. 1: Photo of the electronic pen (145mm x 12 mm).

INTRODUCTION
The operating principle of fountain pens has been know for more than 100 years and has since been used without any remarkable change. Primarily it is based on a capillary transfer of ink from a cartridge to the paper via a nip. Reduced pressure inside the cartridge prevents leakage while an integrated system of capillary buffers is responsible for ensuring a constant ink flow. Fountain pens offer the highest quality of type face and are used e.g. to sign important documents. The main disadvantages of this concept are the dependence of temperature and ambient pressure shifts as are experienced e.g. in aircraft cabins at high altitude. This pressure shift causes the gas inside the cartridge to expand and in consequence results in leakage of the pen. In order to overcome this problem and to achieve an outstanding writing performance at a constant high quality a new fountain pen was developed in collaboration with two renowned companies in the pen industry. The result of the development is depicted in figure 1 showing a completely new concept presenting a fully operational microdosing system developed using the full range of available technologies from thin-film technology to injection-molding.

The presented system consists of a number of elements namely a valve, a series of capillaries, a level sensor and a venting system for a cartridge, all of which are integrated on one platform. This allows the reduction of the number of fluidic and electrical interconnects to a minimum and in consequence reduces the problems involved in such joints.

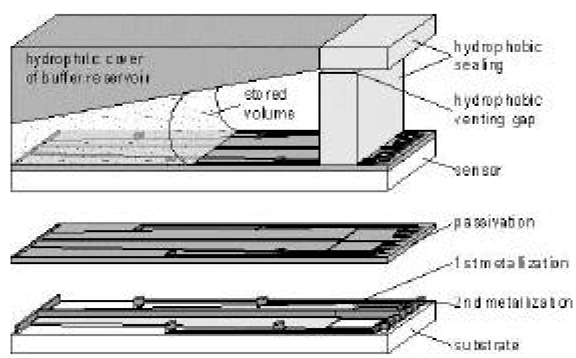

Fig. 2: Integrated liquid level sensor [2].

SYSTEM CONCEPT
The presented dosing system guarantees perfect writing conditions by providing a well-defined small amount of ink in the microliter range directly beneath the nip. The remaining ink, typically in the milliliter range, is held back and stored inside a cartridge. This is achieved independent of ambient conditions by using a closed-loop control system consisting of a liquid level sensor

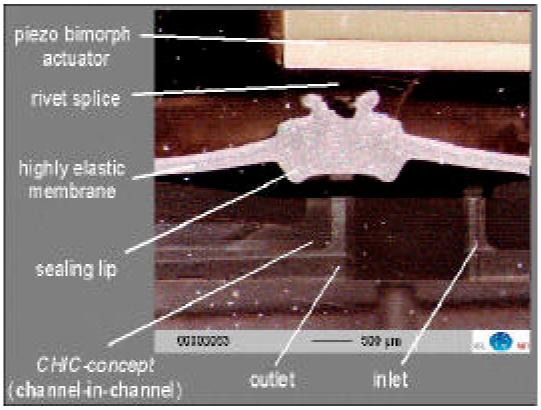

Fig. 3: Valve with integrated *CHIC-concept* (**ch**annel **i**n **c**hannel) for self priming [6].

(figure 2), a microvalve (figure 3), a series of capillaries and an electronic control unit (figure 4).

The complete dosing system has been dramatically shrunk down in size and energy consumption which was only achievable with the development of a completely new packaging concept based on injection molding. An earlier design of the liquid level sensor and the microvalve have been published previously [2, 3, 4].
In this paper we discuss the novel concept of the microvalve and, for the first time, the integration aspects including the electronic components (figure 5) as well as the overall performance of the pen.

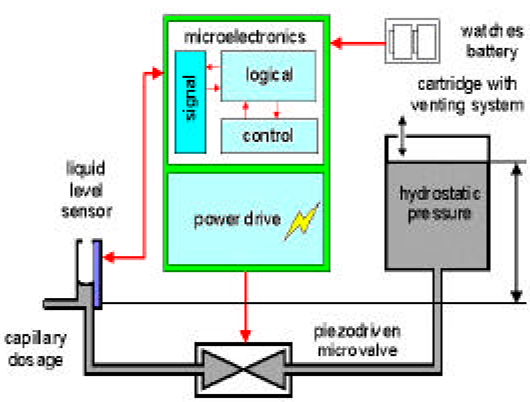

Fig. 4: System concept of the new fountain pen.

For minimum energy consumption the system is switched into sleep mode when not in use. The electronics is activated by removing the pen cap using an integrated phototransistor detecting IR light [5]. This transistor is capable of detecting light at 0,1 lux (less than moonlight).
When activated the sensor measures the ink volume inside a fluid buffer reservoir beneath the nip using a combined capacitive and conductive micro-machined sensor [2, 3]. Once the sensor detects a low ink level a microvalve is opened and, driven by capillary forces and hydrostatic pressure differences, ink is allowed to flow into the buffer at a flow rate of between 50-100µl/min (see figure 6). As soon as the sensor detects a predefined fluid level it closes the valve. The ink transfer from the cavity to the paper is achieved by conventional means taking advantage of capillary forces as the nip and paper are brought into direct contact. This process requires the fluid buffer to properly be vented for reasons of internal pressure equilibration. The approximate flow rate between buffer and paper is found up to 30µl/min, depending on the operators individual writing speed and pressure.

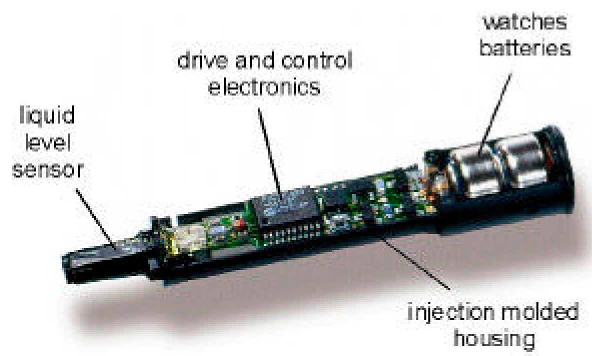

Fig. 5: Active part of the system (75 x 10 mm).

An important aspect of the presented system is an integration of all elements on one injection-molded platform. This includes the fluidic as well as the electric components. This concept results in a reduction of the commonly encountered problems with fluidic interfaces between the individual components, thereby ensuring a reduced susceptibility to sealing problems and better defined fluidic resistance. The latter is additionally improved by application of the *CHIC-concept* (**Ch**annel **in** **C**hannel) [6] for the capillary structures. This approach presents a solution to clogging caused by gas bubbles and larger particles inside of micro-fluidic structures by adapting the channel cross-section.

VALVE CONCEPT

A significant number of micro-valves has been worked on in the past years covering different operating- and actuation principles [7]. Most of these valves employ silicon micro-machining for the valve seat as well as for the sealing lips. This silicon to silicon contact of the closed valve provides a rigid joint that is highly sensitive to any kind of particle. This is due to the high modulus of elasticity of the involved material (E_{Si-11}= 166.000 N/mm^2). Particles caught between the valve lips and seat are not tolerable and will inevitably cause an increased leakage by blocking the valve.

This problem can be avoided using a material with a lower modulus of elasticity. A more flexible material is able to cover smaller particles, i.e. fully enclose them, thereby maintaining the sealing effect of the closed valve.

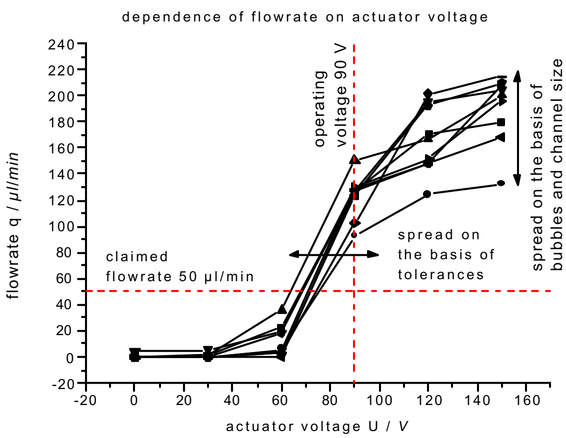

Fig. 6: Flow characteristic of the whole system.

For this purpose Santoprene® (E_{Sa}= 2-3 N/mm^2) [8] was chosen as valve lip material versus a thermoplast material (ABS). Santoprene®, also a thermoplastic elastomer (TPE), is capable of sustaining the given conditions of pH-levels from 1 to 9, also the material is FDA approved and would therefore allow the application

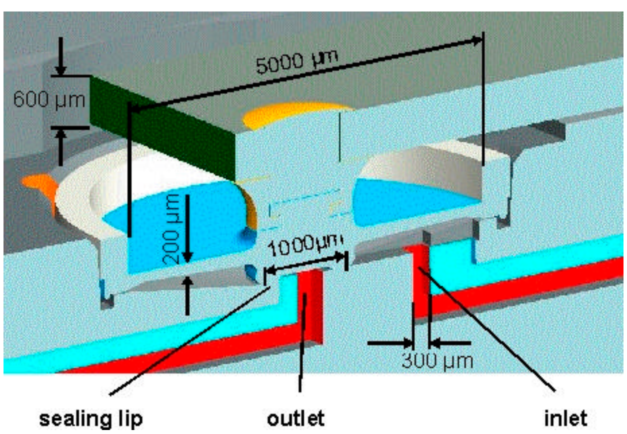

Fig. 7: Sealing lip fabricated in injection molding technology

of the valve for medical applications as also worked on at the authors' facilities. The "soft to hard" contact of the valve lip and seat greatly increases the particle tolerance of the system and ensures a low leakage rate [4]. The only known disadvantage using this material is an insignificant fluid diffusion across the valve that is not encountered in silicon. Although polymers have been experimented with in thin-film technology [9], a hybrid approach was chosen in the presented case where the valve lip was manually assembled following the machining of the seat material (figure 7). The hybrid approach was an important aspect in the design of the presented device not focusing on a specific technology but choosing the optimum available approach such as in this case precision machining.

For the valve actuation a piezo bimorph was chosen. Although this element is perfectly suitable for the given problem and suits the purpose quite well, a number of problems arise from the quality of the available

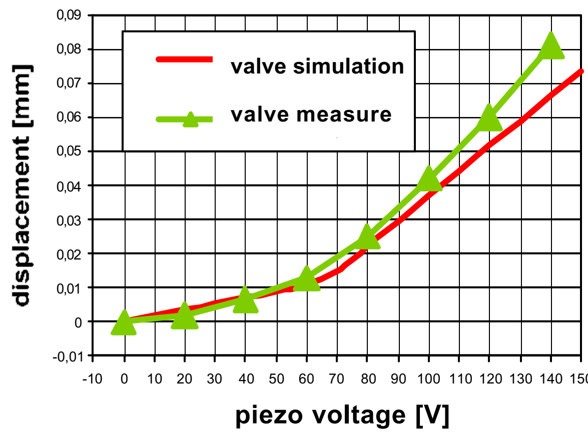

Fig. 8: Characteristic of the valve, measured and simulated by FEM

components. Here in particular the reproducibility of the actuation voltage and the resulting displacement were found to be problematic as shown in figure 8. This problem is dealt with by appropriate packaging means, yet still to be addressed by the piezo suppliers.

MEASUREMENTS

The complete dosing system was tested with respect to the reproducibility of its performance. For this purpose several identical systems were actuated at defined voltages and the resulting flow-rates between the cartridge and the buffer were measured optical in a capillary (velocity of gas bubble). The results are shown in figure 6 and indicate two important aspects. The first is the altering deflection of the intentionally identical actuators, a problem mentioned above. The deflection defines the width of the opening inside the valve.

The second was the change in flow-rate with identical actuator deflection, measured using a laser interferometer. The reason for this behavior is to be found in partial system clogging, likely to be caused by bubbles or dirt particles as they move through the system. Nevertheless a complete clogging, i.e. zero flow, was encountered in none of the tests. Here particle tolerance achieved using the *CHIC-concept* [6] proved its feasibility.

As a conclusion to the presented test the encountered tolerance of the flow as a function of actuation voltage was not found to influence the operation of the system since a sufficient flow was achieved to ascertain the pens function. In detail the flow between cartridge and nip-buffer exceeded that from the buffer to the paper. Should the system need to be adapted to an application requiring greater precision an additional flow-rate detection would be required.

A second important measurement conducted in the system design process involved the rigidity of the complete setup. Here the influence of the curvature of the housing, resulting from an external bending momentum applied across the full stretch of the pen, as e.g. provided by the operators handling of the pen, was investigated. Here particularly the housing deflection, i.e. the actual bending of the pen as compared to its normal position, was of importance. Bending of the pen causes a relative motion of the valve against the valve seat influencing its leakage. A significant influence on the flow rate was found as illustrated in figure 9. The deflection of the housing was found to strongly influence the deflection of the valve. This was to be expected as the actuator deflection of around 50µm is small as compared to the possible deflection of the housing of around 100µm. As a result of this the stiffness of the housing across the actuator was enhanced by the use of a steel collar around the appropriate section of the pen. The results are shown in figure 9 and indicate an important improvement as well as the necessity of this measure.
An important conclusion derivable from this finding is the need for adequate mechanical measures or in

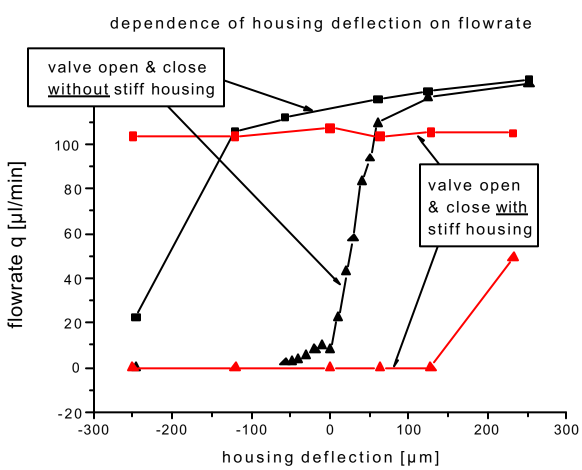

Fig. 9: Test of microvalve in different housings

consequence the need for a more deflection-tolerant actor. Here an actuator deflection of several hundred micro-meters would be advantageous.

CONCLUSIONS

A fully operable closed loop micro-dosing system is presented employing a wide range of technologies for its individual components.
The micro-machined liquid level sensor is based on conductive and capacitive detection of the ink (figure 2).
A revised piezoelectrically driven microvalve is fabricated by injection molding. It contains a highly elastic membrane resistant against a wide range of mechanical loads. Maximum leak rates of 2nl/min at 1 kPa are attained. The complete system is particle tolerant for particle diameters below 10 µm and resistant against all types of inks (pH 1–9).
The most important conclusion to be drawn from the presented project is the need for flexibility in the approaches. Also the importance of the packaging issues and the system integration has to be underlined. Specifically in micro-fluidic systems this aspect must not be underestimated as a great number of problems derive not from the individual components but from the complex interaction between them. Assuming an adequate talent single elements may be designed to work as desired. The combination of two or more of these components does not necessarily result in a functional product.
In the course of this project we have shown that not only the single elements in the system need careful consideration but that the complex interactions between them must be accounted for. For this reason the presented system design was carried out under consideration of all involved components and functions. This resulted in an integrated design of mutually compatible elements namely a fluid supply cartridge, a valve, a number of channels, a fluid level sensor, and fluid buffer compartments in a vibration tolerant setup.
The complete system was designed for a mass market consumer product, an accordingly solid construction was made.

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