Sensors and Actuators A 103 (2003) 225–230

SENSORS AND ACTUATORS A PHYSICAL

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Highly integrated autonomous microdosage system☆

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Abstract

For the first time a fountain pen is presented incorporating an electronically controlled fluid dosage system. The system is 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 closed-loop control system, consisting of a thin-film liquid level sensor, a micro-valve and a bubble- and particle-tolerant fluidic system, as well as the involved power supply and control electronics. 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.
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Keywords: Electronic fountain pen; Microdosage system; Bubble-tolerant capillaries; Micro-valve; Closed loop control capacitive level sensor

1. Introduction

The operating principle of fountain pens has been known for more than 100 years and has since been utilized without any remarkable changes. Primarily it is based on a capillary transfer of ink from a cartridge to the paper via a nib. Reduced pressure inside the cartridge prevents system leakage while an integrated system of capillary buffers is responsible for ensuring a constant ink flow. The main disadvantage of this concept is the dependency on ambient temperature and pressure conditions, an implication which in some cases is in fact responsible for system failure. A typical example of such a failure is presented by the reduced cabin pressure experienced inside 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 the presented fountain pen was developed in collaboration with two renowned companies in the pen industry. The result of the development is depicted in Fig. 1 showing the new concept of a fully operational micro-dosing 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 including fluidic components such as a valve, a cartridge venting system and a series of bubble-tolerant capillaries, sensor components such as a fluid level sensor, electronic components such as the valve control system, and essentially the pen platform itself providing the housing and mechanical support for the above components. The integration of all components inside this setup is an important aspect of the concept as it provides the reducibility of the number of fluidic and electrical interconnects to a minimum and in consequence reduces the problems encountered in such joints.

In this paper we discuss the novel concept of the micro-valve and, for the first time, the integration aspects including the electronic components as well as the overall performance of the pen.

2. System concept

The presented dosage system guarantees perfect writing conditions by providing a well-defined small amount of ink

☆ This paper was presented at the 15th IEEE MEMS conference, held in Las Vegas, USA, January 20–24, 2002, and is an expansion of the abstract as printed in the Technical Digest of this meeting.

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PII: S0924-4247(02)00349-7

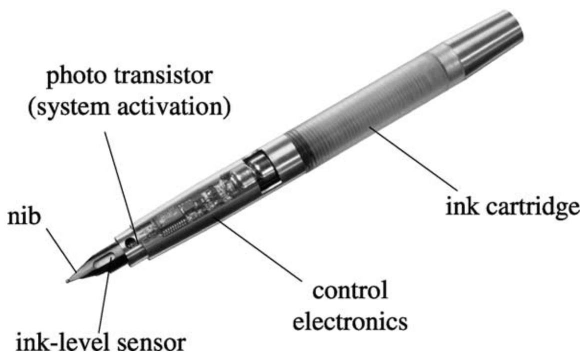

Fig. 1. Photo of the electronic fountain pen (145 mm × 12 mm).

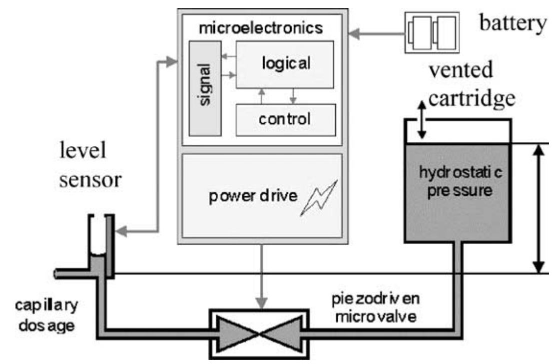

Fig. 3. System concept of the new fountain pen.

in the microliter range for the writing process directly at the nib. This ink is stored in a buffer reservoir positioned beneath the nib. Using a liquid level sensor this buffer reservoir is continuously monitored. The main ink reservoir, typically holding ink in the milliliter range, is provided using a vented cartridge which is connected to the buffer reservoir via a channel and a normally closed valve, controlling the flow between the two reservoirs.

The system idea is to provide a constant ink flow at the nib by introducing a controlled ink level inside the buffer reservoir. The characteristic ink flow is based on the hydrostatic forces involved. System leakage in undamaged conventional pens is typically caused by an overflow of the buffer reservoir. This overflow is prevented in the new system by timely closure of the valve upon detection of a maximum allowed fluid level inside the buffer. Additionally, since the exact ink flow at the nib is defined by the ink volume inside the buffer reservoir, the controlled ink volume in consequence allows a very precise, since controlled, ink flow.

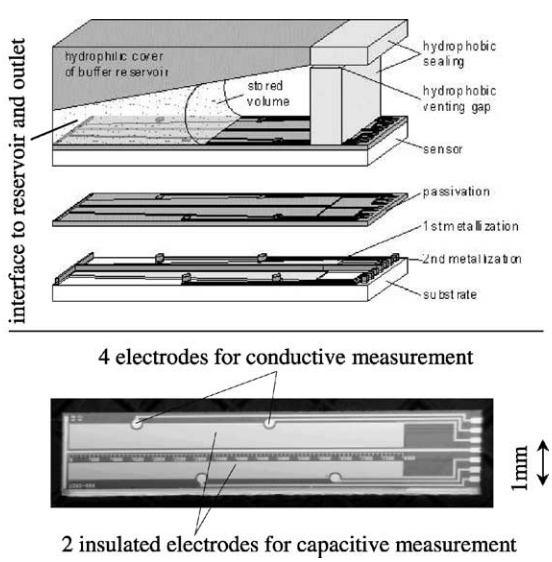

Fig. 2. Schematic and micrograph of the integrated liquid level sensor [1]. The sensor is positioned below the nib (see Figs. 1 and 3), a wedge shaped fluidic channel guarantees that, based on capillary forces, the available ink is found on the tip of the nib.

This is control mechanism is achieved independent of ambient conditions by using a closed-loop control system consisting of a liquid level sensor (Fig. 2), an electronic control unit (Fig. 3), a micro-valve (Fig. 4), a series of bubble-tolerant capillaries [5].

In the course of the system development the complete dosage system was dramatically decreased in size and energy consumption which was only achievable by the development of a completely new packaging concept based on injection-molding [10]. The electronic control system (Fig. 5) had to be adapted in size, here an ASIC approach was utilized.

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 [4]. This transistor is capable of detecting light at 0.1 lx (moonlight intensity is sufficient to activate the system).

When activated the sensor measures the ink volume inside a fluid buffer reservoir using a combined capacitive and conductive micro-machined sensor [1,2]. The sensor provides the two mentioned sensor principles on a single chip, i.e. two insulated electrodes as well as a set of four electrode in contact with the fluid, nevertheless only the capacitive method is currently active and sufficient in the presented system.

Once the sensor detects a low ink level a micro-valve 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 and 100 μl/min (see Fig. 6). When the sensor detects a predefined ‘‘high’’ fluid level the valve is closed. The ink transfer from the cavity to the paper is achieved by conventional means taking advantage of capillary forces as the nib 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 at up to 30 μl/min, depending on the operators individual writing speed and pressure. The design and exact performance of the liquid level sensor and the micro-valve have been published elsewhere [1–3] and are therefore not described in detail.

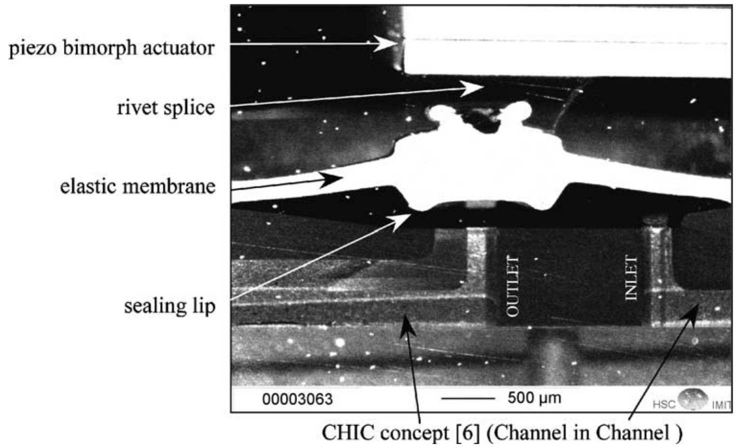

Fig. 4. Valve with integrated *CHIC-concept* (channel in channel) for self priming [5].

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. As mentioned above, 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 resistances. The latter effect is additionally improved by application of the *CHIC-concept* (channel in channel) [5] in 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 to compensate the encountered forces, e.g. surface tension effects and hydrostatic forces acting on the enclosures.

3. Valve concept

A significant number of micro-valves has been worked on in the past years covering different operating and actuation principles [6]. Most of these valves employ silicon micromachining 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 ($E_{\text{Si-11}} = 166.000\ \text{N/mm}^2$). 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

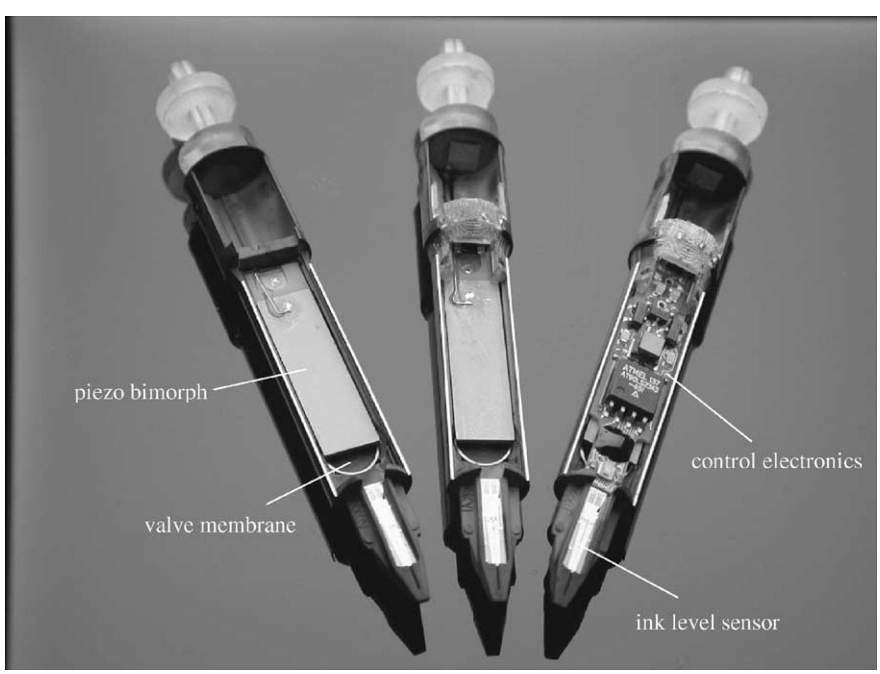

Fig. 5. Active parts of the dosage system.

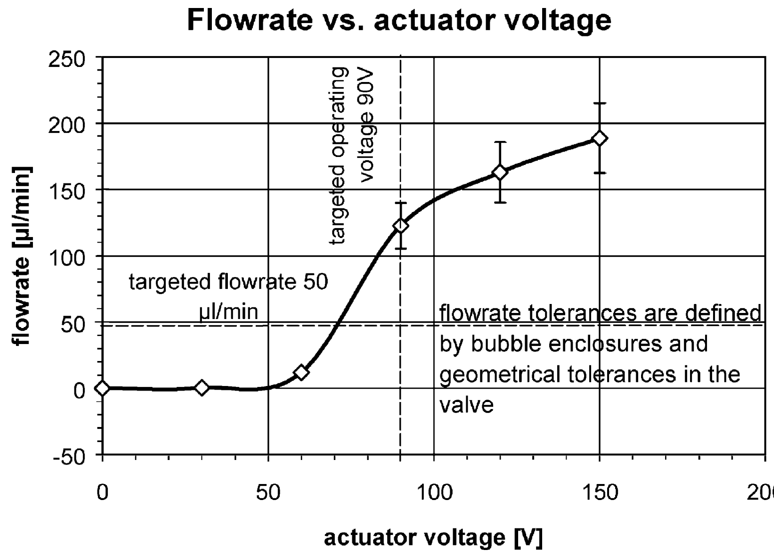

Fig. 6. Flow characteristic of the complete system.

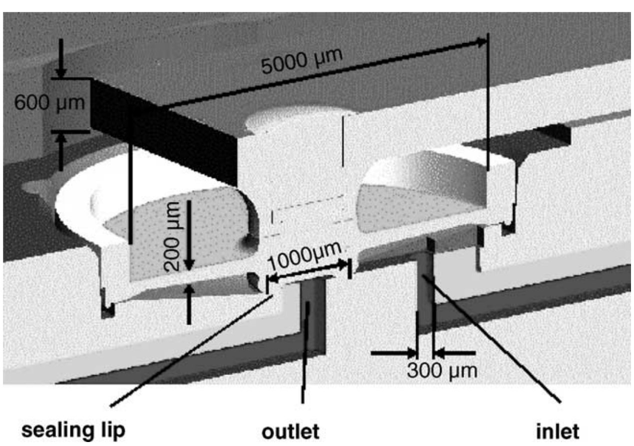

Fig. 7. Sealing lip fabricated in injection-molding technology.

cover smaller particles, i.e. fully enclose them, thereby maintaining the sealing effect of the closed valve.

For this purpose Santoprene® ($E_{Sa} = 2$–$3\ N/mm^2$) [7] was chosen as valve lip material versus a thermoplast material (ABS) as valve seat. Santoprene®, also a thermoplastic elastomer (TPE), is capable of sustaining the given conditions of pH-levels from 1 to 9, additionally the material is FDA approved and would therefore allow the application of the valve, and the entire dosage system, 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 [3]. The only known disadvantage using this material is an insignificant fluid diffusion across the valve which is not encountered in silicon. Although,

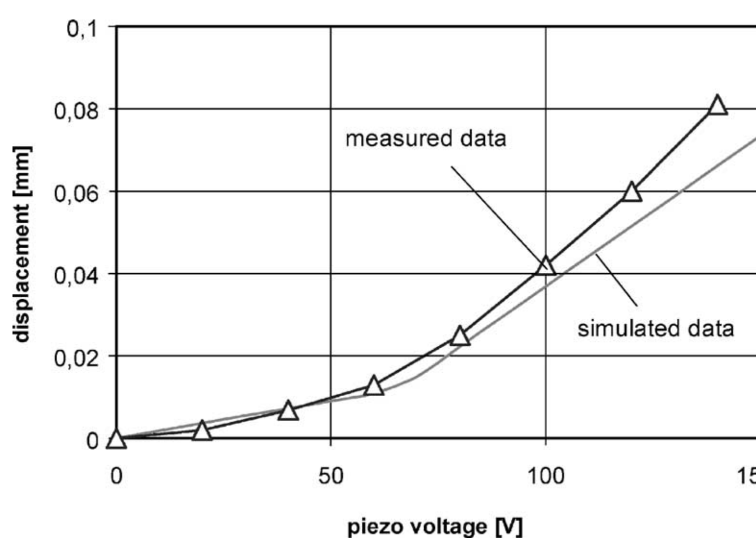

Fig. 8. Characteristics of the valve, measured and simulated using FEM approach.

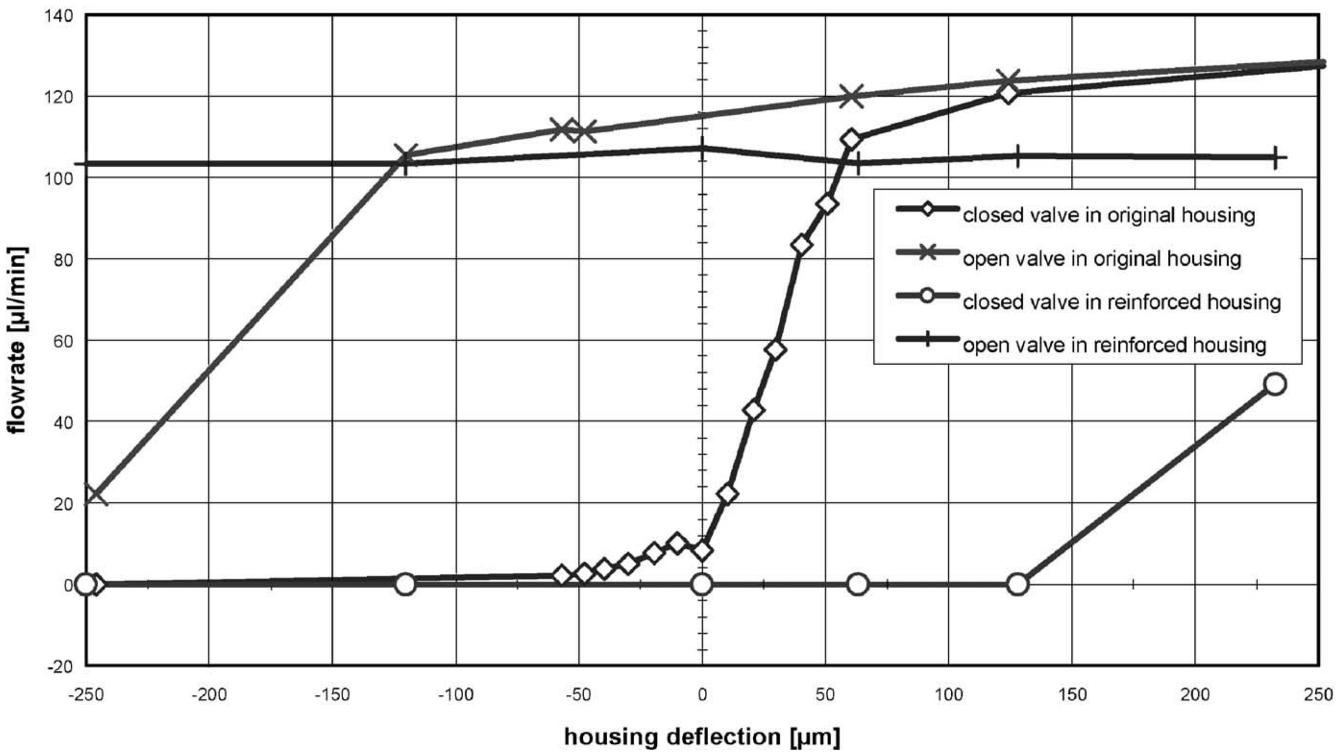

Fig. 9. Effect of mechanical reinforcement: test of micro-valves in different housings.

polymers have been experimented with in thin-film technology [8], a hybrid approach was chosen in the presented case where the valve lip was manually assembled following the machining of the seat material (Fig. 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 components. Here in particular the reproducibility of the actuation voltage and the resulting displacement were found to be problematic as shown in Fig. 8. This problem is dealt with by appropriate packaging means, yet still to be addressed by the piezo suppliers.

4. 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 optically by registering the velocity of a gas bubble inside an auxiliary glass-capillary which was fluidically connected with the dosage system. The results are shown in Fig. 6 and indicate two important effects. The first is the influence of the altering deflection of identically specified actuators, a problem mainly reflecting aging effects of the applied actuators. The deflection defines the width of the opening inside the valve and thereby the ink flow as derivative of the pressure difference.

The second effect is the change in flow-rate with identical actuator deflection, measured using a laser interferometer. The reason for this behavior is to be found in additional, unexpected fluidic resistances as presented by partial system clogging, likely to be caused by bubbles or dirt particles as they move through the capillary system. Nevertheless a complete clogging, i.e. zero flow, was encountered in none of the tests. Here particle tolerance achieved using the *CHIC-concept* [5] has proved its efficiency.

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 overall operation of the system. A sufficient flow was achieved throughout the experiments ascertaining the pens operation. In detail this was guaranteed by the flow between cartridge and nib-buffer exceeding that of the actual writing process between the buffer and the paper. Should the system need to be adapted to an application requiring greater precision an additional flow-rate detection could be introduced to the system [11] to further improve the control mechanism.

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 was investigated [9] as, e.g. provided by the operators handling of the pen. Here particularly the housing deflection, i.e. the actual bending of the pen as compared to its normal position, was of importance. The bending of the pen causes a displacement of the valve relative to the valve seat in turn influencing valve leakage. A significant influence on the flow-rate was found as illustrated in Fig. 9. Here the deflection of the housing is shown to strongly influence the deflection of the valve, i.e. the flow-rate. This was to be expected as the actuator deflection of around 50 μm is small as compared to the possible deflection of the housing of around 100 μm. As a result of this the stiffness of the housing across the actuator was enhanced by applying of a steel collar around the appropriate section of the pen. The resulting improvement of the system sensitivity towards mechanical loads is presented in Fig. 9 and shows the targeted 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 consequence the need for a more deflection-tolerant actor. Here an actuator deflection of several hundred micrometers would be advantageous. Unfortunately adequate actuators are currently not commercially available.

5. Conclusions

A fully operable closed-loop micro-dosing system is presented employing a wide range of technologies for the setup of its individual components.

A micro-machined liquid level sensor is based on conductive and capacitive detection of ink (Fig. 2). A piezoelectrically driven micro-valve is fabricated by precision injection-molding including a highly elastic membrane resistant against a wide range of mechanical loads. Maximum leak rates of 2 nl/min at 1 kPa are attained. The complete system is particle-tolerant for particle diameters below 10 μm and resistant against a wide variety of inks (pH 1–9).

The most important conclusion to be drawn from the presented project is the requirement for flexibility in the system concept. 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 result not from the individual components but from the complex interaction between them. Assuming an adequate effort single elements may be designed to individually 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. 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, a base support and fluid buffer compartments in a vibration tolerant setup. It was the interactive design of all components which made the presented system a success.

The complete system was designed as a mass market consumer product, an accordingly solid and economically favorable design was chosen.

Acknowledgements

The authors wish to thank the project partners for enabling them to work on the project. The project MIKRODOS is funded by the German Federal Ministry of Research and Technology BMBF under Grant 16SV736.

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