Max B. Schäfer*, David Reichert, Kent Stewart, Alois M. Herkommer, Carsten Reichert and Peter P. Pott

Smartphone-based low-cost microscope with monolithic focusing mechanism

Abstract: Microscopy enables fast and effective diagnostics. However, its functionality is not accessible to everyone. Smartphone-based low-cost microscopes could be a powerful tool for diagnostics and educational purposes. Current smartphone-based microscopy approaches struggle with high cost, poor image quality and/or insufficient smartphone compatibility. In this paper, a very feasible and effective low-cost microscope is presented which addresses these issues. To minimize cost, a monolithic foldable structure is designed for production by injection molding. The design has a high order of functional integration, minimizing the number of components, while still enabling a micrometer focusing accuracy.

Keywords: microscope, low-cost, injection molding, monolithic, parallel kinematics, solid-state hinge, smartphone camera lens

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1 Introduction

Light microscopy is an essential tool for science and education. It enables fast and effective diagnostics of for example haematological and infectious diseases. However, especially in emerging nations, the accessibility of such equipment is still not ensured [1].

The ability of modern smartphones to capture high resolution images, process the recorded information in real-time, and transfer data via the internet are ideal conditions to design a smartphone-based microscope [2]. There is a number of existing approaches applying a smartphone to microscopic tasks. Some of these approaches include using a standard microscope objective [1,3], a simple ball lens [4] and/or an external light source [1,5]. As a result, these approaches are either expensive or provide good image quality over a strongly limited field of view.

In this work, a design of a very low-cost, smartphone-based microscope is described. The imaging system only relies on an additional smartphone camera lens, making it a very cost effective and simple solution to convert a smartphone into a microscope [5–7].

The main demand of smartphone-based microscopy is a resource-friendly design. Injection molding is proposed for cost-effective manufacturing. A monolithic manual focusing mechanism will allow for simple assembly with very few components. The device should be easy to use and compatible with a wide variety of current smartphone-models. In addition, in case of poor light situations, the internal flash of the smartphone must be usable. Lastly, easy shipping of the microscope is required.

In this paper, the design of the low-cost and smartphone-based microscope is outlined. In addition, a cost analysis is performed, and the first microscopic images are presented.

2 Materials and Methods

2.1 Cost Analysis

The costs of each of the smartphone-based microscope components were evaluated. The calculated manufacturing costs for the 3D printed components include material costs, power costs and investment costs for the 3D printer. Specifically, the cost of the plastic filament was calculated as a percentage of the total cost of the complete filament unit. Additionally, linear depreciation of the 3D printer over a period of 4000 operating hours was considered. The expense in electricity was calculated by multiplying the printer's maximum electric power consumption of 221 W with the printing time and the current electricity price. The cost of purchased standard parts were taken from requested quotes of reasonable bundle sizes. For injection molding production, costs of purchased standard parts and costs for contract manufacturing were taken into account. According to our

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supplier, the approximate production cost is known for a given number of units.

2.2 Finite Element Analysis

Structural analysis of the designed microscope was done by using ANSYS Mechanical (ANSYS, Inc., Canonsburg, Pennsylvania, US). The Preconditioned Conjugate Gradient Solver was selected for handling of 146,210 solid elements with 243,403 nodes. The chosen SOLID187 element is a higher order three-dimensional, 10-node tetrahedral element [8]. Manually controlled and specific meshing helped to obtain detailed results with relatively low computational effort.

2.3 Smartphone Dimensions

The overall dimensions of 34 smartphone models were collected by the specifications from following manufacturers: Apple Inc. (Cupertino, US), BQ S.L. (Madrid, ES), HTC Corp. (Taoyuan, TW), Huawei Technologies Co. Ltd. (Shenzen, CN), Lenovo Ltd. (Hongkong), LG Electronics Inc. (Seoul, KR), Samsung Electronics Co. Ltd. (Suwon, KR), Sony Corp. (Tokio, JP). Maximum, minimum and arithmetic mean of the smartphones length, width and height were recorded.

The position of the camera lens relative to the top left corner of the smartphone, as well as the position of the internal flash relative to the camera lens were measured for the mentioned models. Due to known overall dimension, this was done by reference to pictures of the smartphones. The desired distances were calculated out of the number of pixels using a proprietary MATLAB (The MathWorks Inc., Nattick, Massachusetts, US) script.

2.4 Prototyping

Various prototypes were made using the Ultimaker 3 (Ultimaker B.V., Geldermalsen, The Netherlands) 3D printer. Each of the prototypes were evaluated in regard to compatibility to the smartphone, functionality of the focusing mechanism, and ease of use. The prototype which best satisfied all of these requirements was selected.

3 Results

Based on an additional reversed camera lens, a low-cost microscope, with integrated focusing mechanism, and a smartphone mounting system was designed. In order to keep manufacturing costs low, the foldable design was oriented for production by injection molding. Tooling costs were minimized by avoidance of undercuts. Overall, a fully operational prototype was manufactured by 3D printing, which had a minimal number of off-the-shelf components.

3.1 Objective lens

According to a conventional setup of a digital microscope, this device consists of an objective lens (formed by an inverted external smartphone lens) and a tube lens plus sensor (formed by the smartphone camera system). Thus, an infinity ray path is achieved in between the objective and tube lens. As a result, it is possible to vary the distance between these two components without manipulating the size and the position of the intermediate image [9]. This gain of flexibility allows the usage and alignment of a smartphone camera system. Due to the good correction of geometric aberrations and a reasonable price, the optical module of the Apple iPhone 5s was selected as the objective lens.

3.2 Monolithic Design

As the integration of functions is required to minimize the number of components, a monolithic design is suitable for the manual focusing mechanism. Using solid state hinges and two leaf spring elements, parallel guidance of the specimen slide is enabled. A displacement reduction by a lever allows accurate adjustment with an accuracy of < 30 µm.

Due to the kinematic components not requiring assembly of moving parts, clearance and stick-slip effects caused by external friction are not an issue. Only a focusing screw must be attached. The planar microscope is folded along film hinges to a spatial structure which is connected by dovetail joints.

The mechanical properties of Ultraform W2320 003 PRO (BASF SE, Ludwigshafen, Germany) is well suited for the occurring stresses. A maximum lever deflection of 4 mm results in a slide table translation of about 1.8 mm. The parallel guidance ensures a tilting of less than 0.01° and negligible lateral offset of the slide table. At the lever support, a maximum von Mises stress of approximately 45 MPa occurs (Figure 1) which results in a safety factor of 1.44 against permanent plastic deformation.

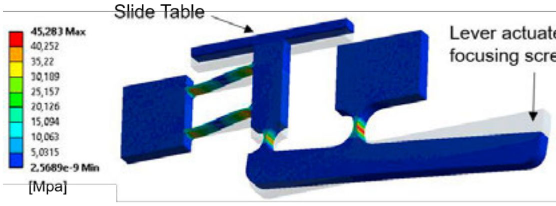

Figure 1 Von Mises stress in the solid state hinges at a maximum lever deflection of 4 mm.

A prototype of the microscope was produced by additive manufacturing using acrylonitrile butadiene styrene (ABS) filament material. Figures 2 and 3 show the planar and the folded version of the microscope.

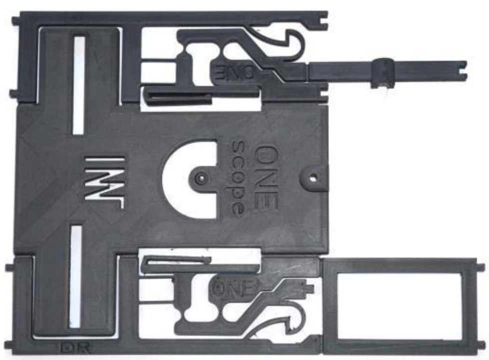

Figure 2 Planar, foldable structure of the microscope

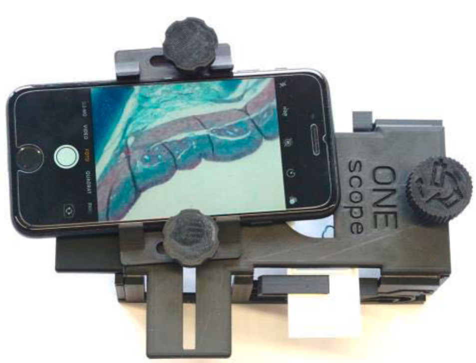

Figure 3 Assembled microscope with smartphone.

3.3 Smartphone Compatibility

In addition to the overall dimensions of the smartphone models, the camera lens position and relative position of the internal flash were of interest in terms of compatibility. The maximum size of the considered smartphone models is a length of 162 mm, a width of 88 mm and a height of 11 mm. From the analysis of lens positions, it was found that they were commonly positioned in the top left corner or middle of the smartphones reverse side.

A wide variety of current smartphone models can be mounted in different positions depending on the relative position of their camera lens. An integrated clamping device offers a maximum of flexibility by elongated holes in combination with standard cup square bolts. For all measured smartphone models, the internal flash is usable.

3.4 Cost Listing

A distinction is made between costs for prototyping by additive manufacturing and production by injection molding. However, some purchased parts are necessary (Table 1). In case of 3D printing, the depreciation of the printer and electricity costs must be taken into account additionally. Thus, the total production costs add up to 29.08 € (Inc. tax). The major part in this sum is caused by the investment costs for the printer.

Costs for mass manufacturing are difficult to estimate due to the fact, that costs for production by injection molding depend heavily on the number of units. Assuming a quantity of 10,000 units, injection molding leads to approximate overall costs of 8.24 € (Inc. tax).

Table 1: Purchased parts with approximate costs.

Qty.	Description	Specification	Approx. Cost /€ Inc. tax
1	Camera module iPhone 5s	-	2.99
1	Focusing screw	DIN 912 M4x25	0.04
1	Screw-nut for focusing screw	DIN 934 M4	0.02
2	Cup square bolt	DIN 603 M5x20	0.06
2	Screw-nut for cup square bolt	DIN 934 M5	0.02
	Total		**3.13**

Assembly costs are low due to few components and a complete tool-free setup. The major cost factors are the camera module and the production of the microscopes base frame. Finally, the planar and lightweight design is a crucial benefit in terms of transport and storage. The overall weight of the microscope is only 106 g. A standard DIN A4 envelope is suitable for the unfolded microscope including all components if shipping is an issue.

4 Discussion

Orth et al. suggest a simple 3D printed microscope add-on clip that does not need an additional illumination system and can be assembled easily. This approach uses diffuse light scattering of the internal flash of the smartphone to illuminate the sample. The light channel was defined especially for the iPhone 6s, thus disqualifying most other smartphone models. However, this design fully depends on the touch-based auto focusing mechanism of the smartphone as no manual focusing mechanism was present [7]. This auto focusing mechanism is based on the measurement of edge contrast which is not guaranteed in all illumination circumstances. Further, there is no possibility of adjusting the distance between the sample and the objective, which is especially challenging in case of varying sample thicknesses.

The design which is presented in this paper, allows the use of most of the common smartphone models including the illumination with the internal flash in case of poor light situations. For the adaption to different sample thickness and to focus upon the desired region, manual adjustment can be done by a focusing screw. As a result, the presented microscope is not dependent of the quality of the auto focusing mechanism of the smartphone.

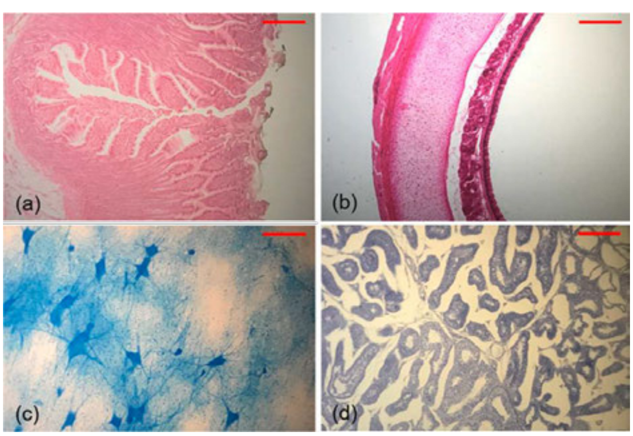

Figure 4 Mammalian samples: (a) small intestine, (b) oesophagus, (c) nerve cells, (d) testes. The red scale corresponds to 300 µm. All microscopic images showed in this paper are recorded using an Apple iPhone 7.

Figure 4 shows a variety of microscopic image sections. They were all recorded with indirect illumination by daylight. Objects are mapped on the sensor in their original size. Due to the high number of pixels of modern smartphones, microscopic resolution still is achieved. Reichert et al. showed that this approach enables a resolution of potentially 362 line pairs per millimeter. That means that it is possible to detect structures with a size of 1.4 µm [10].

Overall, the simple, effective, and low-cost proposed microscope greatly improves the potential of microscopy being widely accessible to emerging nations. Future work should look into defining processes for basic diagnostic tasks and evaluating specific applications for the device.

Author Statement

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