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Design of an experimental four-camera setup for enhanced 3D surface reconstruction in microsurgery

Abstract: Future fully digital surgical visualization systems enable a wide range of new options. Caused by optomechanical limitations a main disadvantage of today's surgical microscopes is their incapability of providing arbitrary perspectives to more than two observers. In a fully digital microscopic system, multiple arbitrary views can be generated from a 3D reconstruction. Modern surgical microscopes allow replacing the eyepieces by cameras in order to record stereoscopic videos. A reconstruction from these videos can only contain the amount of detail the recording camera system gathers from the scene. Therefore, covered surfaces can result in a faulty reconstruction for deviating stereoscopic perspectives. By adding cameras recording the object from different angles, additional information of the scene is acquired, allowing to improve the reconstruction. Our approach is to use a fixed four-camera setup as a front-end system to capture enhanced 3D topography of a pseudo-surgical scene. This experimental setup would provide images for the reconstruction algorithms and generation of multiple observing stereo perspectives. The concept of the designed setup is based on the common main objective (CMO) principle of current surgical microscopes. These systems are well established and optically mature. Furthermore, the CMO principle allows a more compact design and a lowered effort in calibration than cameras with separate optics. Behind the CMO four pupils separate the four channels which are recorded by one camera each. The designed system captures an area of approximately 28 mm × 28 mm with four cameras. Thus, allowing to process images of 6 different stereo perspectives. In order to verify the setup, it is modelled in silico. It can be used in further studies to test algorithms for 3D reconstruction from up to four perspectives and provide information about the impact of additionally recorded perspectives on the enhancement of a reconstruction.

Keywords: Four Camera System, Surface Reconstruction, Surgical Microscope, Microsurgery, Fully Digital Microscope, Virtual Reality, Optical Design

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1 Motivation

The surgical microscope is a widely used medical instrument in many surgical fields. Its ability to magnify and illuminate a surgical scene as well as easing the working position, gives a benefit to many surgical procedures and even opens up new methods for treatment [1]. However current systems show limitations when it comes to providing images from different perspectives to multiple users. Current systems aren't able to provide a stereoscopic view to more than two observers. The reason for this restriction is the increasing optomechanical effort necessary for additional optical stereoscopic perspectives. Whereas two perspectives can be sufficient for the daily routine in the operating room, medical education and documentation would benefit extensively from a system being able to visualize a microsurgical scene in 3D from arbitrary perspectives. By fully digitalizing the surgical microscope and reconstructing the scene in 3D, arbitrary views on the scene can be rendered and passed to any observer. Additionally, this would comply with the current trend of augmenting additional 3D data in the view of the surgeon [2].

Current systems allow replacing the eyepieces with stereo cameras and displaying this stereo image on a 3D screen. A 3D reconstruction from these images is hardly possible, because of masking it can be faulty for perspectives different than the one of the recording cameras. By adding cameras recording the scene from additional angles, more data on the surface is acquired. This is enables an enhancement of the reconstruction. To be able to research the optimization of a fully digital microscope, regarding its number of cameras and its video processing hardware, an experimental setup is needed. The images acquired by this setup can then be used to reconstruct the surface of the surgical field. From this reconstruction, stereo views can be generated as output.

The design of an optical front-end with four cameras for a fully digital microsurgical visualization system will be discussed in this paper.

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2 Methods

2.1 Concept

Surgical microscopes are based on the principle of a common main objective (CMO) [3, 4] Instead of using a separate compound microscope for both eyes, as it is done in a Greenough binocular microscope, a large objective lens is creating an intermediate image at infinity for both channels. Behind this lens, the individual channels are separated and the eyepiece creates a magnified image for the eye. This gives the following advantages:

- Focussing and zoom can be adjusted by a pancratic and an afocal zoom system equally for both channels.
- A higher numerical aperture than in a Greenough microscope can be reached.
- Behind the CMO the beams for all channels are parallel. The stereo angle is created by the main lens. Thus, no mechanical components are needed to adjust the optical path when zoom or focus is changed.

These advantages apply also for a fully digital system without direct optical output but with camera optics and sensors instead. A front-end for a fully digital system would benefit from a minimum of optomechanical parts and less effort on calibration and adjustment of the cameras. Therefore, our approach is a design based on the CMO principle.

As current surgical microscopic systems are optically mature and their handling well establish among surgeons, the aim of the design is to keep the basic concept close to the current principle of surgical microscopes. This incorporates the following properties [5]:

- *Working distance.* Surgical microscopes require a large working distance in the range of 200 mm – 500 mm.
- *Size of the CMO.* For the use in an operating room surgical microscope should be as compact as possible. The size of the CMO features a diameter of around 50 mm enclosing both optical channels. As this dimension is essentially limiting the optical properties of the system, our four-camera solution should keep to this limit too.

For a first approach and a proof of concept of the system, we deviated from the concept of a surgical microscope to simplify the design. Therefore, we used a fixed focal length lens (focal length: $f = 400$ mm) as CMO without pancratic and afocal zoom system. The presented design will still allow to add them later into the afocal course of beam.

The channels of our setup direct all the light to a camera instead of an eyepiece. This way beam splitters used to branch off a part if the light for the eyepieces for a camera can be left away to use the light as efficient as possible.

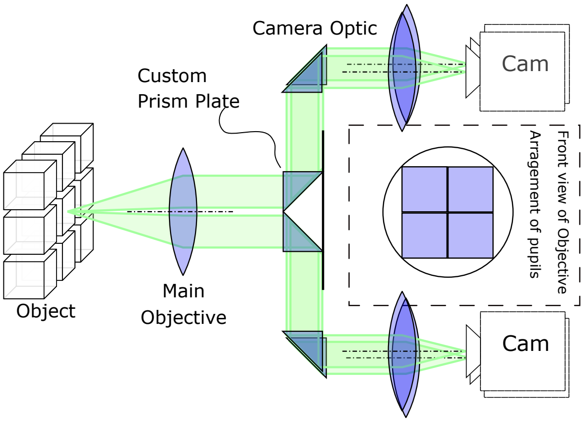

Figure 1: Concept of a front-end for a visualisation system with four cameras based on a surgical microscope.

As we want to research the enhancement of the reconstruction from additional camera perspectives, we need more than two cameras in our setup. Therefore, our setup was designed featuring four cameras. Whereas it is the aim of subsequent experimental research to determine an optimum number of cameras, the number four was chosen to make best use of the limited size of the CMO. Four pupils can be arranged compactly to leave less empty space in the entrance window. For basic examination of more than four perspectives on the scene, the setup was designed to be rotatable. The concept of our approach is illustrated in Figure 1.

For an experimental purpose the setup needs to be flexible to adapt to changes to its requirements to it. Therefore, the distance of the four optical axes behind the division by the pupils is increased. This gives more room for placement and adjustment of camera and optic as well as mounting support. Behind the CMO the light is divided into four channels. For the redirection of the beams two prisms are used for each channel. This way camera optics and sensors fit behind the CMO and can be aligned equally. The aim is to bring the first level prism as close together as possible to catch most of the light inside the area of the entrance window. Therefore, a custom prism mount was designed.

To capture the image CMOS cameras with objectives where positioned behind the second level prisms.

2.2 Analytical evaluation

For the selection of the components a paraxial approximation on a central axis for one single channel of the system (shown in Figure 2) was used. From this approximation, the necessary focal length of the objectives, the resolution and size of the

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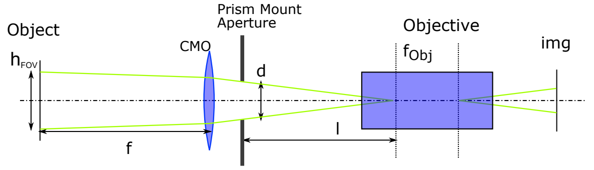

Figure 2: Paraxial approximation used for the design of the system (Not to scale). Displayed are the chief rays at the margin of the field stop, used to calculate the field of view.

sensor and the scale of the system are calculated. The design was calculated for $\lambda = 550$ nm as it is the centre of the visible spectrum.

Prisms of 20 mm width where used. Due to the mount, their clear aperture was a rectangle of 16 mm resulting in a minimum diameter of 50.91 mm necessary for the clear aperture of the CMO. The aperture of the first level prism restricts the field of view (FOV). But as it is positioned in the afocal beam, it also restricts our numerical aperture NA and therefore the spatial resolution to:

$$R_A = \frac{0.61\lambda}{\text{NA}} \text{ with NA} = n \cdot \sin\alpha = 1 \cdot \frac{d}{l} \tag{1}$$

As aperture stop of the entire system, the aperture stop of the camera objective is used. The approximation shows up the following relations:

- The object distance must be equal to the focal length of the main objective f_{CMO} for the system to be afocal. The camera objective must focus into infinity to capture the image.
- The FOV is given by:

$$h_{FOV} = 2\tan\left(\frac{\alpha_O}{2}\right) \tag{2}$$

- Where α_0 is the opening angle of the camera objective if not restricted by the aperture of the prism mount to:

$$\alpha_O = 2\arctan\left(\frac{d}{2l}\right) \tag{3}$$

- When limited by the aperture stop, the visible FOV can be larger than calculated by this approximation, as it only calculates the field opened by the chief rays of the system.
- For paraxial approximation, this setup will image the object with a scale of:

$$\beta = \frac{f_{Obj}}{f_{\text{CMO}}} \tag{4}$$

2.3 Numeric simulation

As the approximation for the design is differing for the actual setup, to validate the designed setup, it is simulated in Zemax OpticStudio (Version 16.5, Service Pack 1). It allows a characterization of the system by numerically tracing various rays through a sequence of surfaces. The setup is modelled to fit the build. As OpticStudio does not feature the calculation of a common FOV for this kind of system, the single channels where implemented as four configurations in OpticStudio. For each channel, chief rays at the borders of the field stop (i.e. the sensor area) where traced to determine the projection into the object plane. This process was automated by a MathWorks MATLAB (2016b) script. By plotting these projections together, a common FOV was determined.

3 Results

3.1 Calculations

Because of the mount of the two prisms a minimal distance of approximately 225 mm lays between the entrance pupil of the prism mount and the position of the objective. From the given formula (3) this limits our opening angle to $\alpha_O = 4.072°$ and a FOV of $h_{FOV} = 28.44$ mm. As we want to use this FOV as efficient as possible, we searched for a combination of objective focal length and chip size that would result in a similar opening angle. This is given for a 100 mm objective and a 2/3 inch chip ($\alpha_O = 4.066°$). Such a chip has a dimension of 8.2 mm × 7.1 mm as the aperture is of quadratic shape, the additional space at the sides will be affected by vignetting.

This setup will feature the following specifications: The resulting scale of the setup will be $\beta = 0.25$. The prism mount aperture creates a numerical aperture of $NA = 0.02$. This results in a resolution limit of $R_A = 16.8$ µm by diffraction. From resolution and FOV follows a maximum necessary resolution of 1680 pixel for the 2/3 inch sensor.

3.2 Simulation

The simulation was implemented with the calculated specifications (100 mm focal length and a 2/3 inch chip). The setup can be seen in Figure 3. The resulting coordinates for the corners of the FOV are noted in Table 1. From the simulation can be seen, that the fields of view overlay with a maximum Euclidean distance of 144.2 µm in the corners of the image. If the difference of the images is set into relation to the calculated resolution, we can give a statement on the measurable errors in the camera. Whereas in the centre of the object plane the absolute difference is < 16 µm and therefore below the resolution, it will be imaged on the same pixel. Towards the corner the same object can be imaged with a shift of up to approximately 9 Pixels between two cameras.

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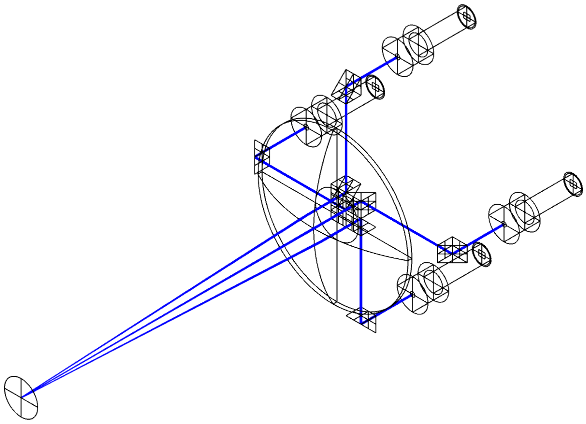

Figure 3: The complete optical setup implemented in OpticalStudio. The four arms are implemented as different configurations in Zemax to allow sequential mode simulation.

Table 1: x,y coordinates [mm] of the corner points of the FOV of each channel from the simulated setup. The letters refer to the corners. A:Left Top, B:Right Top, C:Right Bottom, D:Left Bottom.

	CH1	CH1	CH1	CH1
A	-16.97|14.31	-16.95|14.32	-16.92|14.35	-16.85|14.23
B	16.85|14.23	16.92|14.35	16.95|14.32	16.97|14.31
C	16.92|-14.35	16.85|-14.23	16.97|-14.31	16.95|-14.32
D	-16.95|-14.32	-16.97|-14.31	-16|85|-14.23	-16.92|-14.35

4 Limits and improvements

The presented setup shows up the limitations of a concept based on a surgical microscope. When trying to record the surgical field with 4 cameras, the clear diameter of the CMO limits the resolution due to the numerical aperture. The calculated resolution limit is a theoretical limit resulting from diffraction. Due to aberrations a real system will suffer from loss of contrast for structures above this size.

To improve the performance of the setup the followings next steps are necessary: To correct the shifts of the single FOVs, a completed setup will include an calibration of each camera. If the application requires a higher resolution it is necessary to increase the size of the prism mount aperture. For a realisation of the setup a next step will be a selection of suitable components. Thereby the calculated characteristics should fit as close as possible for optimal performance. To prove the feasibility of the setup, in a further step tolerances of the optics mounts will be examined. These can alter the position of the optical components and reduce the performance of the system, especially the alignment of the 4 single fields of view. Analysing the tolerances for the system can provide information for a restriction of the accuracy for the 3D reconstruction.

After a selection of components and validation of the setup. It will be installed in a laboratory and connected to image acquisition hardware, to allow imaging of test objects to validate newly developed reconstruction algorithms and processing hardware.

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