Time-of-Flight

Dr Lena Maier-Hein has been investigating computer-based methods for gentle and safe cancer therapy. Here, she explains the Time-of-Flight camera technology and its potential for real-time imaging during surgery

© DKFZ, TOBIAS SCHWERDT

To begin, what has influenced your decision to investigate this topic in particular? How have your interests in the field evolved?

One of the main challenges in computer-assisted interventions is the fast, accurate and robust acquisition of the anatomy during surgery. Fusion of this intraoperative data with preoperative images allows for augmented reality (AR) visualisation of subsurface anatomical detail, overlaid, for example, on laparoscopic video images.

While diagnostic imaging has undergone significant improvements in the past decades, interventional imaging systems do not yet meet the specific requirements imposed by surgery. In this context, Time-of-Flight (ToF) cameras caught my attention a couple of years ago. As they allow capturing positional data in real-time, I figured they could emerge as an interesting alternative to conventional medical imaging modalities in the context of patient localisation and tracking.

What are the advantages of ToF cameras compared to other range-imaging devices such as structured light systems or stereoscopic systems?

The main advantage of ToF cameras, is that they deliver dense depth datasets in real-time independent of the scene. As they require no correspondence search across images, they work well in the absence of salient features and do not need much computational power. While other approaches require two cameras or a camera and projector setup in a certain distance relative to each other, ToF cameras are based on a single chip. This makes them very compact devices that can be miniaturised to meet the size requirements of endoscopic procedures.

What are the benefits of ToF cameras compared to conventional medical imaging modalities, such as X-ray, computed tomography (CT) or ultrasound?

ToF cameras are compact devices that can be integrated well into interventional workflows. Unlike most conventional medical imaging modalities, they are low-cost, real-time and do not expose the patient or physician to harmful radiation. Furthermore, they do not require contact with the patient, unlike ultrasound devices.

You are currently investigating possible applications for range-imaging devices in medicine. Can you provide some examples?

There are many potential applications for range imaging devices, including medical staff tracking for operation room monitoring and workflow analysis, hands-free interaction, as well as prevention and support in elderly care and rehabilitation. In our group, we focus on patient localisation and organ tracking as well as mobile AR for intuitive on-patient visualisation of medical data.

How close to reality will AR images come?

In the context of computer-assisted medical interventions, the term AR typically refers to the enhancement of the physician's view by the display of subsurface anatomical detail. These data may be obtained from tomographic planning images and can, for example, be displayed on transparent mirrors, head-mounted displays or be overlaid on laparoscopic video data.

The main challenge in this context is the robust and fast intraoperative registration of the planning data with current patient anatomy in the presence of patient movement and organ deformation. The accuracy of the visualisation depends on the quality of this registration, which, in turn, is increasingly challenging with an increasing degree of organ deformation.

Will you use CT or magnetic resonance imaging (MRI) to obtain data of internal anatomy? If so, how will these dat be transformed?

We can use any types of 3D data for our purposes. During surgical planning, the surface of the target organ is extracted via medical image segmentation. During the procedure, the partial surfaces of that organ, acquired with the range-imaging device, are continuously registered to the corresponding surface extracted from planning data.

How do you foresee the future of technological innovation in healthcare? To what extent do you work with industry to shorten the transition from bench to bedside?

Clinical translation is a major challenge in the context of computer-assisted interventions. Often, clinical studies tend to favour a computer-based assistance system over conventional procedures in terms of accuracy or radiation exposure, but the majority of systems have not yet entered clinical practice.

We aim to form multidisciplinary partnerships between scientific, industrial and clinical personnel at very early stages of our projects. Furthermore, I hope that national funding agencies bridge the financial gap between initial feasibility studies and industrial prototypes.

Precision technology

Time-of-Flight technology is paving the way to advanced surgical precision in healthcare. Ongoing research at the **German Cancer Research Center** is making this application in the future likely

TIME-OF-FLIGHT (ToF) camera technology, initially developed in the 1990s to benefit engineering, robotics and surveillance, creates a 3D image by measuring the time it takes for light emitted from a device to travel to an object and reflect back to a sensor. For over a decade it has been the role of the research community to investigate ToF potential and reduce the large fluctuations in precision and accuracy so typical of untried technology. In doing so, new avenues have been opened for other scientific disciplines. For medicine in particular, ToF presents a number of advantages, which are currently under investigation. Specifically, it offers improved capabilities for intuitive data visualisation as well as augmented reality (AR) during surgery.

Currently, visualisation for surgical planning and procedure uses computed tomography (CT) or magnetic resonance imaging (MRI) techniques to build up static 3D images which are subsequently manipulated on a computer. Surgeons can use these images to then decide the best way to enter a patient during a surgical procedure. While these tools have made large contributions to medicine, there are limitations. Prone to failures which can have real consequences for patients and are often premeditative, the physician has to mentally transfer the virtual image to the reality of the patient. ToF cameras and other range imaging techniques, however, allow real-time imaging of patient anatomy. By mapping the real-time image onto the 3D virtual object, they remove the need to make this transfer.

Based at the German Cancer Research Center (DKFZ), Dr Lena Maier-Hein and her Junior Group Computer-Assisted Interventions are leading the way in the field of computer-assisted medical interventions,. Forming part of a wider international research initiative, she is collaborating with Imperial College London and University College London, UK; Friedrich-Alexander University Erlangen-Nuremberg, Karlsruhe Institute of Technology, the University of Heidelberg, Germany; and the University of Auvergne, France. Maier-Hein and her colleagues have focused on ToF cameras application and development for intuitive on-patient visualisation of data. They have actively been involved in a great deal of research to try and overcome some of the current issues with the ToF technology, to establish its advantages and to make it more suited to a clinical setting.

IMPROVING AND TESTING THE TECHNOLOGY

One key problem with the ToF technology is a high measurement uncertainty of the ToF camera in viewing direction. This can lead to errors in surface registration, which is a prerequisite for AR visualisation based on ToF. To combat this, the team extended the well-known iterative closest point (ICP) algorithm for shape matching. Maier-Hein explains: "We proposed a generalisation of this popular method that keeps the main advantages of the original algorithm, namely, the guaranteed convergence, the general applicability in various fields and the straightforward implementation, while targeting one of the key issues: the assumption of isotropic localisation errors in the input data". Reassuringly, with this revised algorithm, they found a >50 per cent improvement in surface registration accuracy on a large dataset.

A large international consortium has been established to assess and compare the quality of the surfaces reconstructed with ToF cameras and other range imaging techniques. They used surface data acquired from different organs with different shapes and textures, and robustness was investigated in the presence of blood and smoke. The study is ongoing but initial results suggest that stereoscopy-based approaches performed best in terms of accuracy and precision but displayed low robustness. ToF techniques require no baseline, provide high point density independent of the scene and require no image processing, but they currently fail to reconstruct some fine surface structures. Maier-Hein expounds: "The study suggests complementary advantages of the different techniques with respect to accuracy, robustness, point density, hardware complexity and computation times".

The same study conducted an *in vitro* evaluation of the quality of ToF surfaces acquired with the first mobile ToF-based endoscope. The prototype was developed by the company Richard Wolf GmbH (Knittlingen, Germany). So far it has been found that the surfaces reconstructed with the ToF endoscope prototype are subject to quite severe systematic errors and noise. However, there is a lot of scope for further development and improvement of the hardware and, in contrast to other techniques, ToF can guarantee a range value for all pixels. The study has confirmed the potential of ToF camera technology for fast and low cost imaging but shown that for the technology to be viable future work must focus on calibration of systemic distance errors and sensor fusion.

MOBILE AUGMENTED REALITY

ToF has been advantageous to physicians, capable of transferring images to the patient through augmented reality. Using portable devices such as a tablet PC or iPad with a mounted ToF (Figure 1), the physician can see the internal anatomical structure of the patient which, over time, becomes more intuitive.

FIGURE 1. Concept of mobile Augmented Reality (Dr Lena Maier-Hein and Dr Alexander Seitel).

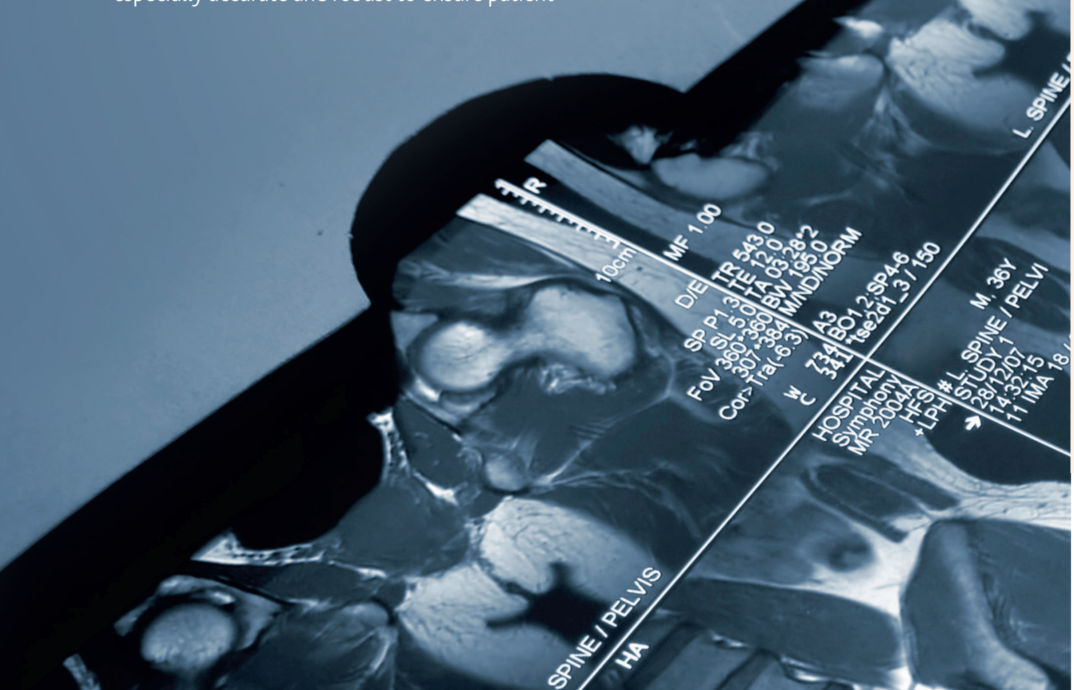
Junior group Computer-assisted Interventions; from **left** to **right**: Dr Lena Maier-Hein, Thomas Kilgus, Anja Groch, Eric Heim, Dr Alexander Seitel, Sebastian Wirkert, Keno März, Justin Iszatt, Alfred M Franz, Sven Mersmann.

Maier-Hein and her colleagues are particularly excited about this advancement as it has proved to be a relatively accurate method for lightweight, markerless visualisation. "In an initial feasibility study, we applied our new surface matching methods for camera pose estimation. The position of the display relative to the static 3D dataset is continuously obtained through registration of the partial ToF surfaces to the surface extracted from the static set," she adds. Capable of performing anistropic iterative closest point (A-ICP, the registration method designed by Maier-Hein) registration, compared to ICP, A-ICP can decrease target registration error significantly. Again, robustness and run-time need to be fine-tuned, but the technology holds great promise. "By moving the device along the body of the patient, the physician is given an impression of looking directly into the human body. The proposed concept, which yielded promising results in initial feasibility studies, can be used for intervention planning, as a teaching aide and various other applications that require intuitive visualisation of 3D data," enthuses Maier-Hein.

CONTINUING CHALLENGES

ToF cameras show great potential for healthcare and for some applications, including touchless interactions, the technology is now marketable. The precise and critical nature of surgical intervention, means new techniques must be especially accurate and robust to ensure patient safety. Severe systematic distance errors and noise must be resolved before ToF cameras can be certified for clinical use and the current warm up period addressed to compensate for temperature-related errors, which disrupt clinical workflow. Maier-Hein is determined to overcome these barriers through continued study. Yet beyond these, acceptance from the physician community is a hurdle that may need further work. To reduce reluctance to change established behaviours, systems must not add time, be obtrusive or complicate a procedure and should be simple to use with an ergonomic interface. And finally, for the benefits to reach the patients, a company must be found to invest in the technology.

These are all realistic concerns that need additional study. Over the next few years the working group on Computer-Assisted Interventions will refine their algorithms to refine ToF cameras so that they can be implemented in surgeries throughout Europe. With a working model, range-imaging technology could pave the way for precision procedures and ultimately, life-saving treatment.



INTELLIGENCE

DEVELOPMENT OF BASIC PROCEDURES FOR USING THE TIME-OF-FLIGHT CAMERA TECHNOLOGY IN OPEN AND LAPAROSCOPIC SURGERY

OBJECTIVES

Fusion of medical and technological advances for gentle cancer diagnosis and treatment.

KEY COLLABORATORS

Professor Adrien Bartoli, the Advanced Laparoscopy and Computer Vision group, University of Auvergne and French National Centre for Scientific Research (CNRS), France • **Dr Neil Clancy; Professor Daniel Elson**, the Department of Surgery and Cancer, Imperial College London, UK • **Professor Emeritus J Michael Fitzpatrick**, Department of Electrical Engineering and Computer Science, Vanderbilt University, USA • **Professor Joachim Hornegger**, Pattern Recognition Lab, Friedrich-Alexander University Erlangen-Nuremberg, Germany • **Dr Hannes Kenngott; Dr Beat Müller-Stich**, Department of General and Visceral Surgery, University of Heidelberg, Germany • **Dr Stefanie Speidel**, the Institute for Anthropomatics, Karlsruhe Institute of Technology, Germany • **Dr Dan Stoyanov**, Centre for Medical Image Computing and Department of Computer Science, University College London, UK • **Dr Boris Radeleff**; **Dr Nadine Bellemann**, Department of Diagnostic and Interventional Radiology, University of Heidelberg, Germany

FUNDING

The German Research Foundation (DFG) supports the ToF-related research including:

DFG project: Time-of-Flight camera technique for navigated visceral surgery

DFG Research Training Group 1126: Intelligent Surgery

CONTACT

Dr Lena Maier-Hein
Principal Investigator

Junior Group Computer-Assisted Interventions
Division of Medical and Biological Informatics
German Cancer Research Center
Im Neuenheimer Feld 280
D-69120 Heidelberg
Germany

T +49 6221 42 2341
E l.maier-hein@dkfz-heidelberg.de

LENA MAIER-HEIN received a diploma degree in computer science with distinction from Karlsruhe Institute of Technolgy (KIT) in 2005 and PhD with distinction in 2009. As a junior group leader at the German Cancer Research Center, she now works in the field of computer-assisted medical interventions. For her scientific contributions, Maier-Hein received several awards, including the Waltraud-Lewenz Prize 2008, the Ingrid-zu-Solms Prize for Natural Sciences 2009/2010 and the Heinz Maier-Leibnitz Prize 2013.