Laparoscopic Quantitative 3D Endoscopy for Image Guided Surgery

Jochen Penne[1], Christian Schaller[1], Rainer Engelbrecht[3], Lena Maier-Hein[2],
Bernd Schmauss[3], Hans-Peter Meinzer[2], Joachim Hornegger[1]

[1]Pattern Recognition Lab and Erlangen Graduate School in Advanced Optical Technologies (SAOT), Friedrich-Alexander-University Erlangen-Nuremberg, Germany
[2]Division of Biological and Medical Informatics, German Cancer Research Center, Heidelberg, Germany
[3]Chair of Microwave Engineering and High Frequency Technology, Friedrich-Alexander-University Erlangen-Nuremberg, Germany
`Jochen.Penne@informatik.uni-erlangen.de`

Abstract. Image-guided surgery aims at relating data of an on-going intervention to preoperative information about important anatomical structures or tumor localizations. Using intra-operatively acquired 3D information of the operation area has been proven to be the right starting point for accomplishing this task, but is leading to technical challenges especially in the field of minimally invasive surgery. A novel laparoscopic 3D surface scan device providing >3000 3D surface points at 20 fps was utilized to exemplarily accomplish a) the fusion of 3D surface scans and color information at 20 fps and b) the fusion of 3D surface scans and CT data with a mean error of 1.68 mm. Experiments were on one hand accomplished in-vitro using a porcine stomach and on the other hand using a liver phantom. The results verify the proof of concept of the utilized system and lead to clear directions for future research.

1 Introduction

Segmental liver resections as well as ablative therapies require accurate and precise tumor localization. In the preoperative setting the anatomic location of hepatic tumors is commonly determined using tomographic imaging techniques, computed tomography (CT) and magnetic resonance imaging (MRI). Transferring this information to the intra-operative setting poses a technical challenge as the peritoneal cavity is subject to deformations caused by respiration as well as topologic changes of the operation site during the intervention. Therefore, mapping the intra-operative position of utilized instruments onto preoperative, high-resolution, tomographic data sets, will enhance the tumor localization and resection.

As the intra-abdominal application of traditional frameless stereotaxy approaches is facing few stationary landmarks and considerable intra-operative deformation, current research has successfully focused on acquiring 3D surface scans of the operation area even in minimally invasive interventions [1]. The registration of these 3D surface scans to preoperative tomographic data relates the on-going resection to the tumor and surrounding anatomical structures. The registration has to take into account organ deformations. The accuracy of locating intra-parenchymal targets is comparable for traditional fiducial-based registrations and the rather new surface-based registrations [2].

The contribution of this paper is two-fold: a) A novel 3D surface scanning device for minimally invasive interventions is described and b) initial results for the registration of the 3D surface scans with color information and CT data are provided.

2 Materials and Methods

For acquiring 3D surface scans a rather novel scanning device was utilized. The used Time-of-Flight-based (ToF based) 10 mm laparoscope acquires 3072 3D surface points at 20 fps with an average precision of 0.89 mm [3]. The operation area is scanned with a spatial and temporal resolution which is comparable if not superior to alternative techniques like laser range scanners while only utilizing off-the-shelf technology components.

Fig. 1. The utilized endoscope system: To the upper laparoscope a conventional color sensor (768×576 px) was proximally mounted; to the lower laparoscope a ToF sensor for acquiring 3D surface scans and gray-value images was proximally mounted. By actively illuminating the operation area via the laparoscope with an optical reference signal and the pixel-wise measurement of the phase-delay between emitted and received reference signal in a proximally mounted ToF sensor the length of the propagation path of the light is estimated in each pixel of the 64×48 pixel (model 3 kS from PMDTechnologies GmbH) ToF sensor matrix [4]. Additionally, a gray-value image of the field-of-view is provided by the ToF sensor. Depth map and gray-value image provided by the ToF sensor are registered by construction.

After accomplishing a calibration of the projective properties [5] of the endoscope optic 3D Cartesian coordinates can be computed from the measured depth maps [6]. In order to express these 3D coordinates in a Euclidean coordinate system whose origin coincides with the endoscope tip and whose z-axis is aligned with the optical axis of the endoscope the measured distances have to expressed relative to the endoscope tip. This requires an additional distance calibration step. In contrast to the distance calibration proposed in [3] a more extensive distance calibration which also takes into account systematic integration-time related distance measurement errors of the ToF sensor [7] was accomplished.

For correcting lens distortions in the depth map it is advisable to compute the inverse distortion correction numerically [8] instead of warping the image and interpolate undistorted pixel values.

For the experiments a second laparoscope was mounted fixed to the ToF laparoscope and the relative transformation between the two optics was determined by a calibration routine, which provides the extrinsic and intrinsic camera parameters. A color image sensor was proximally mounted to the additional laparoscope. By projecting the 3D points of the surface onto the image plane of the additional laparoscope using the computed relative transformation the fusion of color and ToF data was accomplished. During the projection lens distortions were taken into account, too.

Two experiments were accomplished using the described dual-laparoscope device:

1. A manually insufflated porcine stomach was inspected in order to acquire in-vitro data and accomplish the fusion of ToF laparoscope and color laparoscope data.
2. A liver phantom was inspected. The 3D surface scans were registered with the liver surface phantom data available from a CT image volume using the iterative closest point (ICP) algorithm [9].

3 Results

Fig. 2 shows the checker-board overlay of the fusion of the gray-value image of the ToF sensor and the color image which was computed by projecting the 3D surface scan onto the color image plane. Additionally, a 3D surface scan textured with the registered color information is displayed. The data was acquired during experiment 1 (inspection of the porcine stomach). On a dual-core CPU (2.4 GHz, 2 GB RAM) the computation of the fusion took 47 ms, where all computations

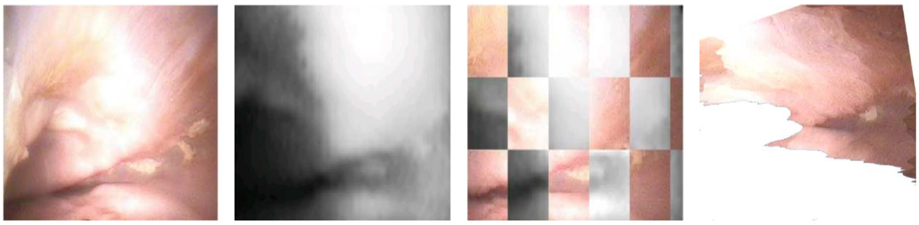
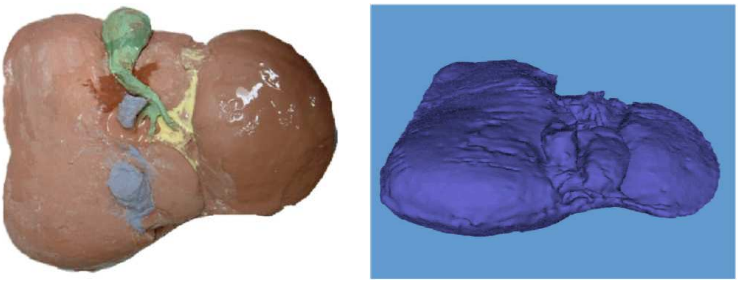

(a) Color image (b) Intensity image (c) Fusion (d) Color texture

Fig. 2. Results of porcine stomach in-vitro experiments. Two endoscope optics were utilized: One with a proximally mounted color sensor and one with a proximally mounted ToF sensor for 3D surface scans. An occlusion detection was omitted. (a): color data; (b): gray-value image which is provided in addition to the 3D surface scan from the ToF sensor; (c): checker-board overlay of registered color and 3D surface scan data; (d): 3D surface scan data which was textured by the registered color data.

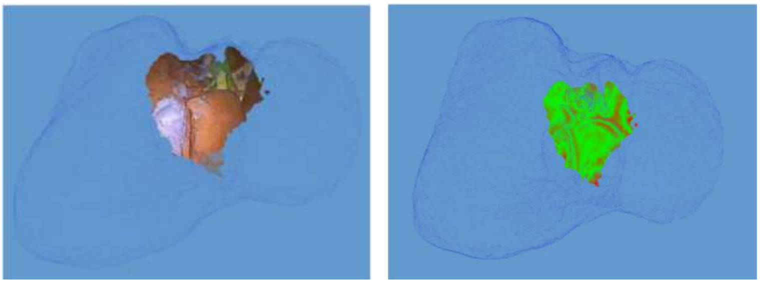
regarding the ToF data were accomplished on an increased lateral resolution of 320×240 pixels compared to the original 64x48 pixels of the ToF sensors. Increasing the lateral resolution by bicubical interpolation leads to a denser sampling of the color image when projecting the ToF 3D points onto the color image plane. Fig. 3 shows the fusion of the laparoscopic 3D surface scans of the liver phantom (experiment 2) with the 3D point cloud extracted from the CT data. As the 3D surface scan was registered before with color information, it is textured with this color information. Computing the average value of the closest distance between a 3D point from the ToF data and its nearest neighbor from the 3D point cloud of the CT data yielded a value of 1.68 mm.

4 Discussion

The obviously well overlay of gray-value and color data in Fig. 2 verifies that the calibration of the projective properties as well as the distance calibration lead to a sufficient measurement accuracy as well as a correct 3D modeling of the scene: Any error in the estimation of the projective properties or the distance



(a) Liver phantom (b) 3D point cloud



(c) Fusion of color (d) Error map

Fig. 3. Results of multimodal fusion. (a): utilized liver phantom; (b): 3D point cloud which was extracted from a CT data set; (c): fusion of 3D surface scan with color and the 3D CT data set point cloud; (d): color-encoded distance error between a 3D point of the 3D surface scan and its closest point from the CT 3D point cloud (bright/green: 0.04 mm, dark/red: 7.65 mm; average error: 1.68 mm).

calibration would lead to a mismatch between color and ToF laparoscope and a misalignment.

The fusion of 3D surface scans and CT data yields a mean point-to-closest-point Euclidean distance error of 1.68 mm. The initial ICP transformation was computed based on nine manually selected corresponding landmarks in CT and 3D surface scans. This can be accomplished intra-operatively under sterile conditions, for example, by using a ToF based gesture control as proposed in [10] and is no issue decreasing the practical feasibility of the approach. The authors of this paper envision a system where this intra-operative registration is done once and the future fusion of 3D surface scans and CT data is based on the tracking of the endoscope optics.

The presented results are preliminary: Experiments involving surface fiducials are subject to current research and will lead to an additional validation of the fusion of 3D surface scans and color information as well as 3D surface scans and CT data. The last mentioned data fusion does currently not involve any deformation compensation: This is the focus of future work.

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