

Navigation in Endoscopic Soft Tissue Surgery - Perspectives and Limitations

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Abstract—Despite rapid developments in the research areas medical imaging, medical image processing and robotics, the use of computer assistance in surgical routine is still limited to diagnostics, surgical planning, and interventions on mostly rigid structures. In order to establish a computer aided workflow from diagnosis to surgical treatment and follow-up, several proposals for computer assisted soft tissue interventions have been made in recent years. By means of different pre- and intraoperative information sources, like surgical plannings, intraoperative imaging, and tracking devices, surgical navigation systems aim at supporting surgeons in localizing anatomical targets, observing critical structures, and sparing healthy tissue. Current research in particular addresses the problem of organ shift and tissue deformation, and obstacles in communication between navigation system and surgeon.

In this article, we review computer assisted navigation systems for soft tissue surgery. We concentrate on approaches which can be applied in endoscopic thoracic and abdominal surgery, as endoscopic surgery has special needs for image guidance due to limitations in perception. Furthermore, this article provides the reader with new trends and technologies in the area of computer assisted surgery. Finally, a balancing of key challenges and possible benefits of endoscopic navigation refines the perspectives of this increasingly important discipline of computer aided medical procedures.

I. INTRODUCTION

During the last decade of years, surgical interventions on mostly rigid anatomy have become routinely supported by computer assisted navigation systems. Especially in the disciplines neurosurgery, orthopedics, as well as ear, nose, and throat (ENT) surgery, computer assisted surgery (CAS) has proven its feasibility for precise localization and targeting of anatomical structures. The broad range of applications includes, among others, localization and visualization of tumors and risk structures, guided access to targets using preoperative trajectory planning, navigated biopsy excision, and tissue ablation.

Surgeons performing soft tissue interventions often face similar challenges. Valuable information on whether they work in a safe layer of dissection or whether a structure can be spared or needs to be removed could increase surgical outcome drastically. In contrast to rigid anatomy, however, soft tissue is subject to considerable organ shift and tissue deformation caused by breathing, heartbeat, patient movement, and surgeon's manipulation. Altogether, organ motion is unpredictable, which is not only an aggravating factor for the development of soft tissue navigation systems, but also reduces the value of preoperative imaging data for the surgeon the more an intervention proceeds. Furthermore, endoscopic abdominal and thoracic surgery suffers from little anatomical

reference points, which offer a constant spatial relation to target structures and allow for adequate orientation.

Recently proposed first approaches for computer assisted soft tissue navigation provide information about spatial relation of target and risk structures during an intervention, as they combine information from different sources: High-resolution preoperative imaging can be complemented by the acquisition of miscellaneous intraoperative data. After an individual preoperative intervention planning a patient model can be generated, which incorporates valuable knowledge from all imaging modalities and can be mapped onto the current patient anatomy during an intervention. In order to facilitate this mapping between patient model and anatomy, which is also referred to as (model) registration, intraoperative imaging modalities providing up-to-date information on current anatomical arrangements are well suited. Besides intraoperative imaging, tracking devices such as optical and electromagnetic tracking systems can be used to acquire spatial information during surgery in real time: By attaching small tracking bodies or sensors to objects of interest such as surgical instruments or imaging devices, navigation systems can continuously capture the spatial relation of all tools in an operating room.

Surgical navigation belongs to the broad field of computer assisted surgery. As a subarea of computer aided medical procedures, computer assisted surgery can be seen as a generic term, which includes surgical information devices, surgical robots, surgical tele-assistance, surgical navigation, and other surgical techniques assisted by a computer based system. The terms image guided therapy (IGT) and image guided surgery (IGS) are often used as respective synonyms for computer aided therapy and navigation. However, while the former can be seen as initial names, which stress the systematical use of patient images, the latter terms in contrast underline the use of a virtual patient model, which may include various information sources. Hence, the objective of computer assisted navigation is to process data coming from above mentioned or other information sources, aiming at purification and presentation of relevant information in a way, which is convenient to the surgeon. Therefore, when designing a navigation system, emphasis needs to be placed on its interaction with the surgical team. A seamless collaboration between the system and its users needs to be provided.

Collaboration between the surgical team members themselves is already provided naturally by video endoscopy, which allows everyone to observe the operating site at the same time. The emerging role of endoscopy for thoracic and abdominal surgery is not only revolutionizing therapy, but also reinforces the need and offers new opportunities for soft

tissue navigation: On the one hand, there are well-discussed limitations of perception during endoscopic surgery, as e.g. a restricted field of view and depth perception, little tactile feedback, limited mobility and handling of instruments. On the other hand, endoscopic surgery can provide computer assisted navigation systems with defined access points for more standardized instruments, a limited work space, in which the intervention takes place, and a continuous video stream illustrating all manipulations.

Consequently, computer assistance for endoscopic surgery arose: Starting with tools to (semi-)automatically move the endoscope [114], today, first approaches for computer assisted navigation have been presented, which for instance superimpose hidden anatomical structures or other information directly onto the endoscopic video images.

The objective of this article is to provide the reader with a summary of the current state of the art in soft tissue navigation for endoscopic surgery, and to identify trends and new technologies, which may be of use for navigated surgery in the near future. Furthermore, this paper points out the long term challenges and perspectives of soft tissue navigation. Until now, only Mårvik et al. [82] presented a related article, which is reviewing image-guided laparoscopic surgery. However, this article is rather focused on technical basics and the experiences of the authors' research group. Furthermore, a major part of the published innovations have been introduced recently and is not considered there. Elaborative articles about image-guidance for surgical procedures in general have been given by Peters [94] as well as Yaniv and Cleary [128].

The study selection for this article is based on a literature research in well-established literature databases (Medline, PubMed, IEEEExplore, CiteSeer). The searched keywords comprise the terms "endoscopic navigation", "soft tissue navigation", "augmented reality", and "image guided surgery". Only articles suited to surgical navigation systems with a precise description of methods and outcome have been selected. Furthermore, the selected proposals for computer assistance systems had to be designed - or at least applicable - for endoscopic soft tissue surgery of thoracic and abdominal soft tissue organs.

The paper is organized as follows: After a brief overview about the history of image guided surgery, common system components of rigid organ navigation approaches are presented. In section III, soft tissue navigation systems for endoscopic thoracic and abdominal surgery are reviewed. For the sake of clarity, the systems are separated into four groups based on distinctive system attributes with the following shared characteristics: (i) Intraoperative imaging, (ii) Tracking devices, (iii) Organ shift and tissue deformation, and (iv) User interface. In section IV we elaborate on generic key challenges and new application areas of surgical navigation. Finally, perspectives and limitations of navigated endoscopic surgery are discussed in section V from the observations made.

II. FROM RIGID ORGAN IMAGE GUIDANCE TOWARDS COMPUTER ASSISTED SOFT TISSUE NAVIGATION

A. History of Image Guided Surgery

The increasing use of surgical navigation systems can be attributed to both improved technical possibilities and medical needs. Since subcortical structures can not reliably be localized with the help of osseous cranial landmarks in humans, accurate orientation during brain surgery used to be difficult. Therefore, navigated interventions started with the discipline of neurosurgery and have been routinely performed since more than fifty years: In 1947, Spiegel and Wycis were first to describe the use of a mechanical tool - referred to as stereotactic frame - in human neurosurgery, which was attached to the skull prior to medical image acquisition, and allowed for the establishment of the spatial relationship between medical image space and stereotactic frame space during surgery [37]. Subsequently, frame-based stereotaxy was established as a standard method for supporting various interventions in open [15], [119], [55] and minimally invasive [58], [98] neurosurgery and achieved a reputation as an accurate and reliable way for localizing structures [36], [3], [41]. Although today, there are more sophisticated methods for expressing the location of an object and an image relative to each other, this registration process remains an elementary step in medical image processing and navigation.

With the end of the 1980s, advantages in robotics and computer technology began to change existing technical possibilities again: On the basis of industrial robots, robotic arm systems were constructed, which facilitate accurate positioning of surgical instruments [61], [63]. Additionally, electromagnetic [54] and optical [56], [122] tracking systems, became commercially available in the early nineties. These systems usually provide sub millimeter tracking accuracy based on the detection of small navigation aids, referred to as sensors, fiducials, or markers. In consequence, a relatively simple registration of the different actors of surgery, such as surgical instruments, patient, and imaging modalities could be established. Altogether, these technical advances did not only reduce the cumbersome handling and the restricted access to the surgical field which came along with the stereotactic frame, they also expanded the range of applications for navigation systems to other disciplines. Apart from the discipline of neurosurgery, routinely applied computer assisted navigation emerged in ENT surgery for sinus and skull-base surgery as well as in orthopedics for navigated placement of pedicle screws in spine surgery [91], [77]. Shortly after that, systems for navigated hip [6] and knee [20] replacement followed. Furthermore, in maxillofacial surgery, navigation is used for osteo-synthesis implantation [27]. In dental implant surgery, computer assisted design and manufacturing of implants along with surgical navigation establish a continuous computer assisted treatment workflow [78], [51].

A more detailed discussion of the history of image guided surgery is given separately for the discipline of neurosurgery by Raabe et al. [96], Grunert et al. [39], and Maciunas [70], for orthopedic surgery by Sugano [108], and for maxillofacial surgery by Ewers et al. [27].

B. Common Components of Rigid Navigation Systems

Although today computer assisted navigation is performed in various disciplines of open and minimally invasive surgery, the basic steps of most navigation procedures for rigid organ interventions are similar. In rigid organ navigation, target structures are assumed to be undeformable and have a constant spatial relationship to anatomical landmarks. According to Willems [124], a typical rigid neuronavigation procedure goes through the following steps: Prior to image acquisition, either bone- or skin-applied navigation aids are attached near anatomical regions of interest. A surgical planning step localizes these navigation aids in the imaging data after CT and/or MRI acquisition and optionally performs post processing, which may include the definition of anatomical structures of interest and additional information, as for instance a surgical trajectory or security margins. Immediately prior to surgery, the navigation system is set up in the operating room. During an intraoperatively performed patient-to-image registration, the navigation aids are localized by a tracking device and the mathematical transformation for mapping objects of the image space to the tracking device space is calculated. After checking the system accuracy, the navigation itself starts and - depending on the kind of applied user interface - arbitrary structures in the image data may be visualized in relation to surgical instruments. Especially in interventions at or nearby the head, anatomical features may be used to substitute artificial navigation aids: Either specific anatomical landmarks can be spotted in both, medical image data and tracking device data, or a characteristic surface like the human face enables a surface matching of patient and imaging modality. In both cases, preoperatively attached navigation aids can be omitted.

Alternatively, both imaging device and surgical instruments can be tracked, so intraoperative imaging data and instruments can be localized in the same coordinate frame at the same time. A registration is not needed, as long as the patient does not move. By e.g. tracking a mobile C-arm capable of cone-beam CT, such a system can be useful for joint and spinal surgery [26].

Each of the above mentioned steps can also be seen as a potential source of error for overall navigation system accuracy. Sources of error like improperly navigation aid fixation or distortion of medical images may be recognized during patient-to-image registration. Errors of marker based navigation systems for rigid anatomy can be divided into fiducial localization error (FLE), fiducial registration error (FRE), and target registration error (TRE) [34]. The TRE is the most important error, as it reflects the distance between an arbitrary point (other than the fiducials used for registration) and its corresponding point in the registered space.

However, in soft tissue navigation, all post-imaging changes of surgical anatomy due to organ shift and tissue deformation add up directly in the resulting TRE and its associated target visualization error (TVE). Thus, whenever navigation targets are subject to considerable motion or deformation between preoperative imaging and intraoperative navigation guidance, none of the established rigid navigation approaches, neither applying preoperatively attached navigation aids, nor defining

anatomical reference points or surfaces with a tracked pointer device, proved to be sufficient for reliable navigation.

III. CURRENT APPROACHES FOR SOFT TISSUE NAVIGATION IN ENDOSCOPIC THORACIC, AND ABDOMINAL SURGERY

A. Intraoperative Imaging

1) *Image Acquisition:* The use of intraoperative imaging devices has become popular to counter the effects of organ shift and tissue deformation. As illustrated in table I, many concepts for endoscopic navigation in thoracic and abdominal surgery employ intraoperative ultrasound, since ultrasound is inexpensive, easy to use, and non-invasive [49]. However, these benefits are at the cost of image quality and validity: In addition to speckle noise and echoic reflections, US images may be distorted due to varying velocities of sonic propagation in different kinds of tissue.

Various navigation approaches for laparoscopic liver interventions integrate laparoscopic ultrasound (LUS) for partial liver resection [84], [59], [60] and laparoscopic radio frequency ablation (RFA) [47], [62], [4]. In this context, a flexible laparoscopic 2D ultrasound probe is commonly used, and electromagnetic tracking sensors are utilized to reconstruct a 3D volume dataset [43], [123] or even a 4D volume over time [83] from freehand 2D measurements. This volume reconstruction is not required whenever 3D ultrasound transducers are available. Their increasing popularity may result in more navigation systems applying this imaging modality in the future [29]. Currently, however, only few endoscopic navigation systems for heart interventions [50], [42], [68] or aortic stent implantation [53] acquire volume data directly by 3D ultrasound. Additionally, Baumhauer et al. [7] presented an approach for navigated laparoscopic radical prostatectomy, which is based on the intraoperative processing of 3D transrectal ultrasound volumes.

Apart from ultrasound as intraoperative imaging modality, some efforts have been made to incorporate open MR imaging into laparoscopic procedures [75], [38], [81], [64]. Yasunaga et al. [129] presented a navigation system, which applies open MRI during a laparoscopic liver RFA by use of an MR-compatible endoscope with a distally mounted CCD camera. Although, depending on the utilized surgical instruments, electromagnetic interference (EMI) may cause artifacts in imaging data, experiments showed a successful image guidance with near real-time MR images and 3D visualization. A more elaborative review about future perspectives of intraoperative MR imaging is given by Jolesz [52].

A further development of the well-established mobile C-arm devices, referred to as isocentric C-arm, integrates a flat panel [106] and has the ability to acquire a small 3D volume of $20 \times 20 \times 15 \text{ cm}^3$ in cone-beam CT imaging quality within 32 seconds [31]. Recently, Feuerstein et al. introduced a laparoscopic navigation system, which combines the isocentric C-arm and optical tracking [31]. The system focuses on port placement planning and vessel visualization during resection interventions of liver or kidney. As both the C-arm and the laparoscope are localized by the tracking

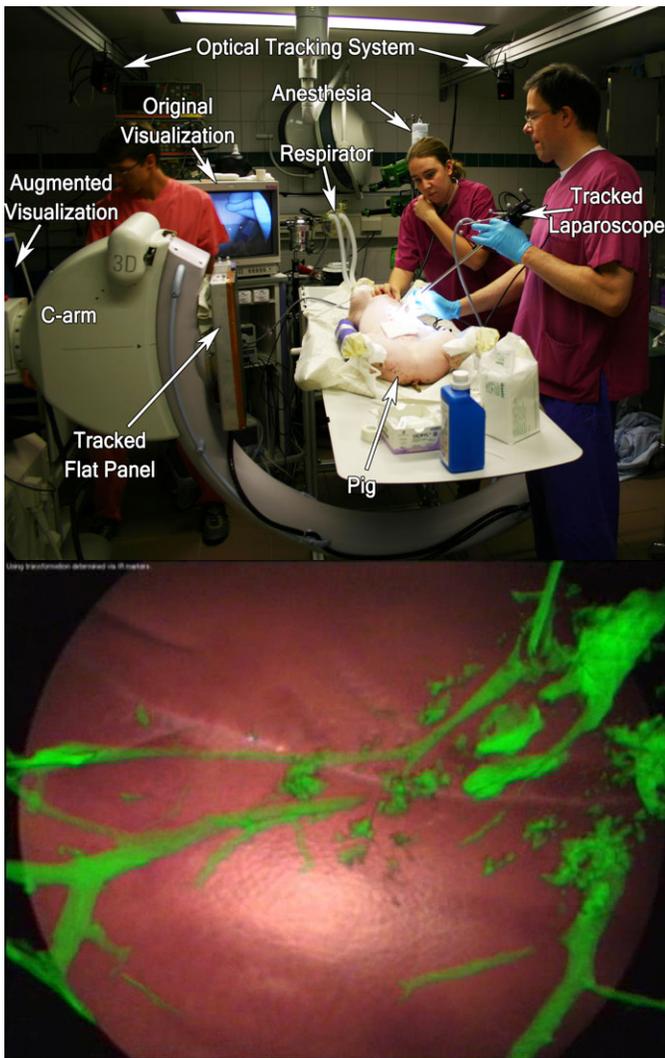


Fig. 1. Augmented reality system for intraoperative liver resection planning in laparoscopic surgery as proposed by Feuerstein et al. [31]. The upper image shows the system setup including an optical tracking system, which localizes both the 3D C-arm and the laparoscope in the same coordinate system. This enables to augment contrasted liver vessel data, which is intraoperatively acquired and reconstructed by the C-arm, on the laparoscope view in real time, as shown in the lower image.

system, an intraoperatively acquired cone-beam CT volume can be augmented on the laparoscope video immediately. Figure 1 shows the system setup and a typical augmentation of contrasted liver vessels.

2) *Image Registration*: To some extent, navigation approaches schedule a preoperative surgical planning before navigated surgery takes place. These surgical plannings may consist of extracted information from different imaging modalities and additional useful information like security margins around tumors or instrument trajectories. A major challenge of soft tissue navigation is the registration of preoperative image data or surgical plannings and intraoperative patient images, because constellation and shape of unconstrained organs changed since intervention planning. A non-rigid image-to-image registration of surgical planning and intraoperative imaging data resolves this issue, as it "warps" a planning until it fits the intraoperative

images of current patient anatomy. Image-to-image registration methods are also used to determine the progression of a disease and postoperative follow up. Most methods perform this registration by finding corresponding groups of points, surfaces, or volumes in both images [72]. Herline et al. [45] introduced a method for surface registration of preoperative CT liver images and laparoscopic 2D US and achieved an overall registration error of 2.9 mm. A point based method for registering liver CT and laparoscopic US was proposed by Bao et al. [5] and resulted in an inferior accuracy of 5-10 mm. Although pre- and intraoperative images of other organs, which are less subject to motion and deformation than liver, may be registered more accurately, these results point out the difficulties of including preoperative plannings into soft tissue navigation concepts. Therefore, many of current soft tissue navigation concepts avoid an image-to-image registration. Instead, they either register the preoperative data directly to the actual patient position, as usually performed in rigid organ navigation, and accept unavoidable errors, or they determine navigation targets during surgery without the surgical planning step. The definition of anatomical structures of interest in imaging data is referred to as image segmentation. An exclusive segmentation of navigation targets during surgery, however, disregards the benefit of preoperative image data for surgery and can hardly be performed manually, as it is time consuming, cumbersome, and prone to errors. Also, an automated segmentation of structures is mostly limited to structures, which are clearly distinguishable in image data, as e.g. vessels by use of a contrast agent.

A survey of segmentation of ultrasound images is given by Noble et al. [90], non-rigid image-to-image registration has been reviewed by Crum et al. [16].

Regardless of whether navigation targets are defined pre- or intraoperatively, a further registration, referred to as image-to-patient registration, is usually performed in order to establish a "connection" of navigation targets and the actual patient position in the OR with regard to a specific reference point, like the coordinate system origin of a tracking device. A straight forward image-to-patient registration has been applied by Marescaux et al. [73], who superimposed a 3D visualization of kidney, adrenal glands, and surrounding tissue on the endoscopic video and manually adjusted the 3D visualization until its boundaries overlapped the organ boundaries in endoscopic video. Since both, endoscopic video and 3D visualization were displayed on a conventional 2D monitor, this manual registration can hardly achieve accurate, reproducible, and measurable results. More common is a registration by means of anatomical landmarks or fiducial markers, as it is performed since the beginning of stereotactic neurosurgery (cf. section II-B). As illustrated in table I, several navigation concepts rely on this point-to-point registration principle. In this context, the registration accuracy is depending on how exact the landmarks can be spotted in both data and, often more significant, if the spatial relation of navigation targets and landmarks changed since target definition.

Other approaches, like Nakamoto et al. [83], Feuerstein et al. [31], [32], and Leven et al. [67], do not require a dedicated registration procedure, instead, they utilize tracking bodies or

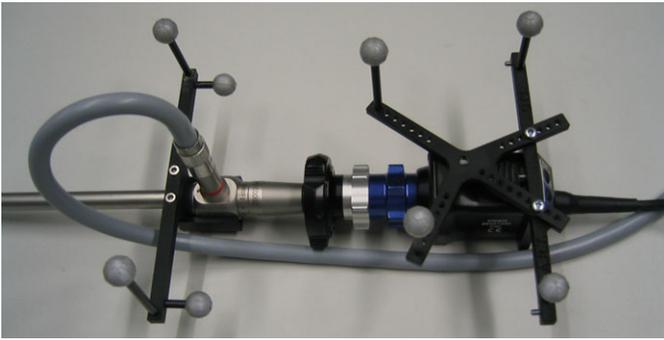


Fig. 2. Retroreflective spherical markers attached to a laparoscope in order to localize them as so-called bodies (each consisting of four markers) by an optical tracking system and estimate the position and orientation of the camera center.

sensors attached to intraoperative imaging devices like US transducers and the endoscope. For this purpose, a calibration procedure has to be performed once, which determines the location of the image volume in space. An evaluation of different calibration methods for 3D ultrasound probes for instance was given by Poon et al. [95] in 2005 and showed a mean calibration error of 1.16 - 5.13 mm depending on the applied method. Also for the reconstruction of 3D US volumes from a series of tracked 2D US images (referred to as freehand 3D US) calibration is an obligatory process, which is important for the accuracy of the reconstructed 3D volume [76].

B. Tracking Devices

An important component of most surgical navigation concepts are tracking systems, sometimes referred to as digitizers, as they link spatial information from various devices like imaging modalities, surgical instruments, or the endoscope by representing these actors in one common coordinate system. To a large extent tracking systems rely on optical or electromagnetic measurements. Each tracking approach has its advantages and shortcomings. Currently, optical tracking is known to ascertain the position of navigation aids with a high accuracy of 0.1 - 0.35 mm [82] by means of triangulation of stereo camera images. However, a direct line-of-sight between stereo camera device and optical marker must be ensured, otherwise tracking becomes impossible. A laparoscope optically tracked by two tracking bodies each consisting of four optical markers can be seen on figure 2.

The strength of electromagnetic tracking, in contrast, lies in the ability to measure the position and orientation of small wired magnetic coils inside the patient, where no direct line-of-sight is possible. For this purpose, a small magnetic field generator has to be installed beside or below the patient. Commercial manufacturers specify the accuracy of these systems with a position mean error of 0.9 - 1.6 mm, and an orientation mean error of 0.8 - 1.7 degrees [87]. However, magnetic tracking is often interfered by ferromagnetic objects like surgical table, instruments, and endoscope, or electrically powered devices. Although a static distortion can be compensated by means of calibration procedures [57], dynamic changes in surgical environment are difficult to compensate.



Fig. 3. Electromagnetic sensor coil glued to the tip of a flexible laparoscopic ultrasound transducer in order to determine the position and orientation of the ultrasound B-scan plane of the transducer.

Therefore, the most common method in addressing magnetic field distortions is to ensure that no ferromagnetic objects are offending the magnetic field [121]. Currently, electromagnetic tracking is often employed for tracking of laparoscopic ultrasound probes or bronchoscopes during lung interventions (cf. table I). An electromagnetic sensor glued to a laparoscopic ultrasound transducer can be seen on figure 3.

Besides systems with electromagnetic or optical tracking, Falk et al. [28] and Leven et al. [67] presented an endoscopic navigation system with mechanical tracking, Fuchs et al. [35] and Baumhauer et al. [7] utilize information of the monocular endoscopic video for tracking.

A trend of recently developed navigation systems is the combined use of optical and magnetic tracking devices within a hybrid magneto-optic tracking configuration, reported first by Birkfellner et al. [9] and later on for laparoscopic interventions by Nakamoto et al. [84], Konishi et al. [60], and Feuerstein et al. [32]. This assembly of tracking methods allows the navigation systems to benefit of the advantages of both techniques. However, it also results in a more complex setup of intraoperative devices and may hamper a smooth integration into the OR. A need for new tracking technologies, which combine flexibility and reliability of current methods, can be constituted from this. A wireless approach, which does not suffer from line-of-sight or distortion constraints, might be the use of radio frequency technology [48]. However, further research must be done, until new feasible tools for the detection of organ movements and deformations are available.

C. Organ Shift & Tissue Deformation

As described in section III-A, many concepts for navigated endoscopic surgery aim to overcome the organ shift and tissue deformation constraints by the application of intraoperative imaging. The one-time use of an intraoperative imaging modality yields an actual snapshot of the anatomical situation. However, as navigation is performed over a certain period of time, a continuous correction of tissue motion and deformation would be required for constant and reliable navigation accuracy.

The application of soft tissue modeling methods is a promising way to enable continuous motion compensation during navigated surgery: Mathematical models, like B-spline, thin-plate splines, and elastic body splines, are able to describe a tissue's behavior during surgery. In contrast to rigid deformation schemes, which can only describe global changes, spline

based approaches can also capture local variances of tissue deformation.

A category of biomechanical models additionally include information about the behavior of the soft tissue. A simplistic assumption for soft tissue characteristics are viscoelastic models, which describe an entire organ as an isotropic linear elastic solid. More sophisticated biomechanical models, as e.g. fluid elastic models, allow for the assignment of different elasticity factors for different regions of an organ in order to model for instance a tumor. A technical elaborative survey about biomechanical modeling for image-guided surgery is given by Carter et al. [11].

Although material deformation modeling is a well-established field of research, its integration into surgical navigation systems is still in infancy. Apart from biomechanical information, which may be implemented into biomechanical models prior to surgery, all modeling methods require permanent intraoperative measurements of organ (sub-)surface displacements to compensate deformations. Until today, the application of biomechanical models in navigated surgery is mainly restricted to open neurosurgery, where they are used for compensation of brain shift [30], [107]. But also for open liver surgery, biomechanical models have been employed along with laser scanners and optical tracking to describe the intraoperative state of the organ [13], [12].

In minimally invasive surgery, only the above mentioned intraoperative imaging and tracking devices can be applied today. Therefore, a remaining challenge is a continuous detection of abdominal tissue constellation before deformation models can be widely incorporated into endoscopic navigation systems. A first approach for monitoring and compensation of organ motion is the implantation or attachment of tracking sensors to organs to continuously capture their motion. This was for instance proposed by Zhang et al. [130], who utilized magnetically tracked needles along with biomechanical models to compensate for respiratory motion of liver. Similar to this, Maier-Hein et al. applied various spline based methods in conjunction with optical tracking data [71] for percutaneous liver RFA. Another limiting factor of all modeling methods is the real time constraint of navigated surgery. As a sophisticated calculation of tissue behavior during motion and deformation is computationally expensive, only simplified models can be used during surgical navigation.

Another type of mathematical methods for tissue deformation modeling have been proposed for the estimation and compensation of motion caused by heart beat and respiration. As these motions can be expected to be recurrent, a prospective approximation of tissue behavior is made. Although investigations mainly focus on the reduction of motion artifacts during image acquisition, similar techniques have also been introduced for interventional navigation. Timinger et al. [111] developed a navigation system for catheter interventions of coronary arteries, which combines magnetic catheter tracking and intraoperative ultrasound imaging of the diaphragm for an elastic compensation of motion caused by heart beat and breathing. For robotic heart surgery, Ortmaier et al. [92] uses a multisensor prediction scheme consisting of the patient's electrocardiogram, a respiration pressure signal, and tracking

data of natural landmarks on the heart surface. Like similar approaches (Trejos et al. [112], Thakral et al. [110], Nakamura et al. [85], and more recently by Cuvillon et al. [17] and Bebek et al. [8]), Ortmaier et al. are aiming at an integration of automatic heart beat compensation into telemanipulator surgery systems.

In treatment of lung cancer, respiratory motion compensation has been intensively investigated for percutaneous radiation therapy [102], [127], [126]. Also in navigated bronchoscopy, motion prediction is applied. Since the bronchoscope always remains inside the tracheobronchial tree, its position can be approximated in a straight forward, non predictive manner, as proposed by Wegner et al. [120]. Mori et al. [79] extended their navigation system by including a predictive Kalman filter [80]. In Deligianni et al. [19], a more sophisticated approach involves shape knowledge of the bronchial tree.

D. User Interface

1) *3D Visualization*: By the time when CT scanners were introduced, a broadly applicable representation of 3D volume data was required. The multi-planar reformatted mode (MPR) displays different, mostly orthogonal, 2D slices of the volume data side by side at the same time, and thus, provides an impression of spatial issues at first glance without presenting the original data in altered way. However, a more detailed comprehension demands a movement of view through several MPR representations, spatial imagination, and user experience.

In contrast to MPR, a visualization of 3D data by means of volume rendering [40] usually requires the definition of a transformation in order to map the source volume information into a color (composed of red, green, and blue) and opacity data representation. The rendering process of this color data can thereon be performed with different approaches. A common method for volume rendering for instance is ray casting, which determines each pixel of an image by emission of a ray into the volume and sampling the ray at regular intervals throughout the volume. All volume rendering methods have in common, that a transfer function (TF) defines the mapping of source volume data into color information and in consequence, which information will be exposed and which will be omitted in the resulting visualization. Since the manual definition of transfer functions is cumbersome and time-consuming, predefined transfer functions can be applied for particular problems. However, an optimization of a TF concerning individual patient anatomy and applied imaging modality protocol yields considerable improved volume rendering. Therefore, the automatic optimization of transfer functions is an ongoing issue in volume visualization research [69]. Latest advanced real-time volume rendering techniques even allow the integration of local and global illumination effects such as lighting, shadowing, and reflection [40], but usually also require the latest graphic card technology.

One benefit of volume rendering is that it can be applied directly after image acquisition as no elaborative preparation is required. However, an inherent shortcoming of volume rendering in medical image visualization should be mentioned here

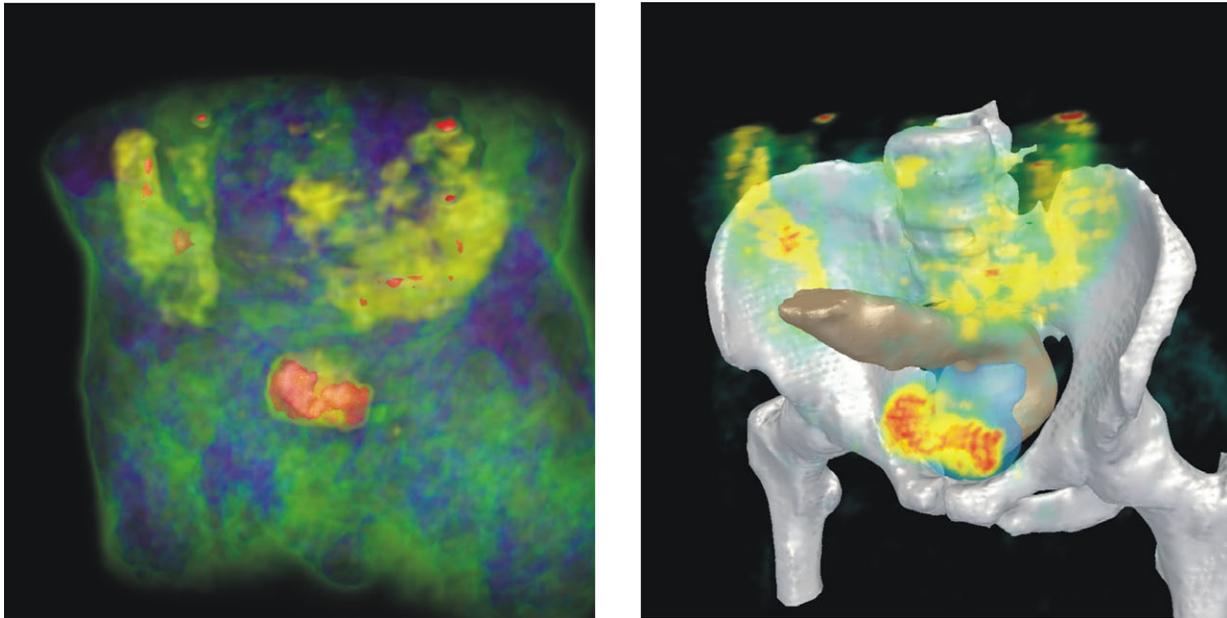


Fig. 4. PET/CT based prostate surgery planning illustrates different computer methods for 3D visualization. *Left side:* The PET data is shown with the volume visualization technique. For this purpose, each PET magnitude value has been assigned with a specific combination of color (red, green, blue) and opacity previously to the planning procedure. *Right side:* Prostate, rectum, and osseous structures have been manually segmented from CT data and are rendered using the surface rendering technique. The PET data is again rendered by means of volume rendering, however, a differing transfer function accentuates a specific range of PET magnitude values.

also: Information in medical image data must be interpreted in an overall context. The transfer function assigns for instance to each Hounsfield unit of a CT scan a certain representation in the visualization. Different materials, however, must not essentially have differing Hounsfield values. This causes a "misinterpretation" of anatomic situation, which often is obviously visible in visualizations, as osseous structures for instance may be rendered like (contrast enhanced) blood vessels. In order to avoid erroneous visualizations during navigated surgery, volume rendering demands a clearly distinguishable value range of anatomical structures of interest in intraoperative imaging data, which may be achieved e.g. by use of a contrast agent (cf. section III-A.2).

Another frequently applied 3D visualization technique is surface rendering. It requires an either manual or (semi-)automatic segmentation of surface contours of all structures to be rendered. As mentioned in section III-A.2, many navigation proposals include a segmentation of surface contours upon preoperative imaging data along with an image-to-image registration for an alignment of preoperative planning and intraoperative imaging data. For visualization, segmentation results are modeled by means of lots of simple geometric primitives (e.g. triangles). Similar to volume rendering, the internal visualization mechanism consists of a virtual camera, which emits rays towards the geometric primitives. On each intersection with a geometric primitive, the ray is sampled and spatial object effects like occlusion and opacity are generated. Additionally, one or more light sources simulate the illumination and thus, brightness, shading, and mirroring effects of objects. In consequence, visualized objects typically appear more clearly and spatial relations can be better comprehended compared to standard real time volume renderings. However,

unlike volume rendering, where no a priori preparation is required, surface rendering can hardly be used in surgical routine due to time restraints, if the visualization is based on intraoperative imaging data. Examples for volume and surface rendering are illustrated in figure 4.

2) *Virtual and Augmented Reality:* The visualization and perception of a computer generated virtual environment in real time is referred to as virtual reality (VR). VR is widely spread for simulation of minimally invasive surgical interventions, since simulators proved to be helpful in training of novices. In a strict sense, a virtual reality system provides the complete immersion of human senses into a virtual world, which usually includes a stereoscopic visualization and the ability to dynamically interact with virtual objects. However, since perception during endoscopic surgery is limited anyway, a virtual simulation of human perception during endoscopic surgery is usually also referred to as virtual reality. Nevertheless, interaction between users and virtual contents remains an important component of VR devices. Therefore, in context of this article, pure virtual 3D visualizations without dynamic tissue interaction are named virtual environments, although the authors may claim their systems to have virtual reality visualizations (cf. table I). In general, pure virtual reality is currently a minor issue for endoscopic navigation systems, as the simulation of surgical perception would cause a loss of information. An overview of virtual reality in clinical application is given by Englmeier et al. [23]

In augmented reality (AR), additional information is superimposed on "real-world" images (endoscopic video, ultrasound, and other imaging) in real time. For augmentation of endoscopic video during surgery, this additional information may consist of anatomical structures like e.g. tumors or ves-

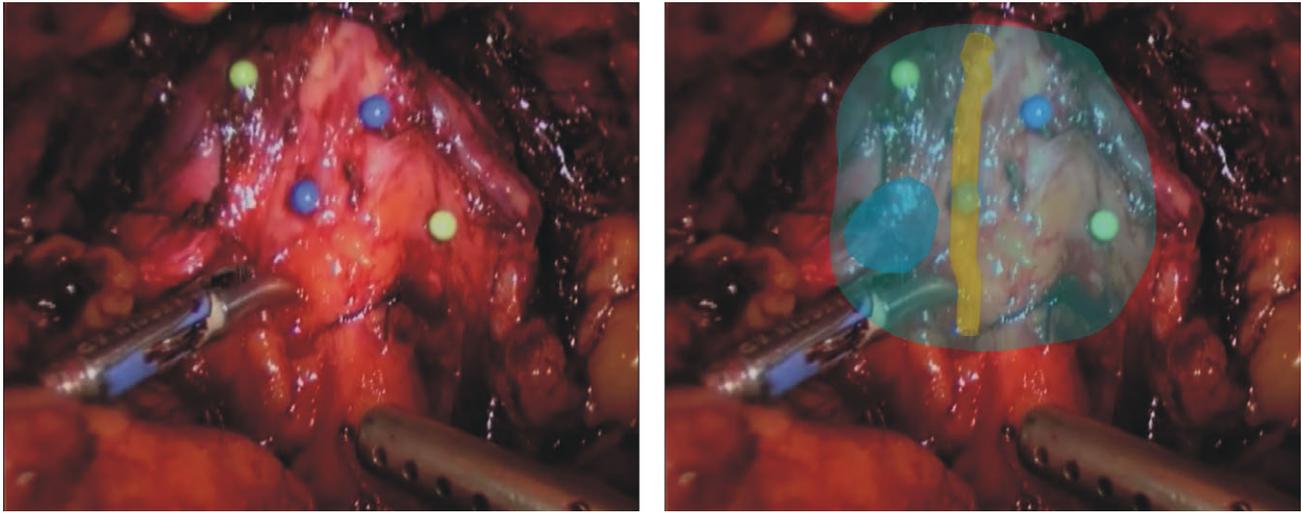


Fig. 5. Experimental trial of navigated LRP using the navigation system described in Baumhauer et al. [7]. *Left side*: Prostate with four needle-shaped navigation aids inserted. *Right side*: Augmented reality visualization of prostate boundaries (green), urethra (orange), biopsy proven tumor nodule (blue). The navigation targets have been manually segmented in transrectal 3D US. (Note that these are static frames of dynamic video sequences, which provide better perception of anatomical structure to the surgeons.)

sels, which are either occluded or invisible in video images. A technical prerequisite for augmented reality during endoscopic surgery is an exact knowledge about the spatial relationship of endoscope and patient. In addition, the structures to be visualized have to be aligned with the patient, too (referred to as image-to-patient registration, cf. section III-A.2). As a last requirement, the intrinsic endoscope parameters have to be determined. For this purpose, a camera calibration is performed before surgery, which usually calculates parameters, like focal length and endoscope distortion, by means of few images showing a known, easily identifiable (e.g. chessboard-like) pattern from arbitrary perspectives. During surgery, when enabling the AR navigation, the computer moves an identical, but virtual camera equivalent to the real endoscope movements within its virtual scene and generates perspective visualizations by means of either volume or surface rendering methods. The resulting visualizations are then superimposed onto the endoscopic video images in real time, which means at least 25 times a second. An augmented reality visualized navigation during laparoscopic radical prostatectomy (LRP) is illustrated in figure 5.

The use of augmented reality during surgery has been initially reported by Roberts et al. [97] in 1986. Today, the majority of published endoscopic navigation proposals (cf. table I) accomplish their visualization with augmented video images. However, not only endoscopic video images are superimposed with additional information, several possible combinations of "real-world" images and augmentation contents are possible. In laparoscopic radio frequency ablation, the navigation systems presented by Bao et al. [4], Kleemann et al. [59], and Hildebrand et al. [47] use augmented ultrasound and superimpose a needle trajectory to guide the RFA needle towards ablation targets. But not only guidance information is used to enrich ultrasound images. Kaspersen et al. [53] utilize preoperative CT segmentations to augmented intraoperative 3D ultrasound data for navigated stent implantation

of the aorta. Linte et al. [68] visualize their navigated mitral valve implantation by an augmented 3D visualization. For this purpose, the valve-insertion tool, the valve fastening device, and a transesophageal 2D US probe are tracked by a magnetic tracking device. During navigation, all devices are visualized with surface rendering methods and additionally, the 2D US images are not superimposed but included into the 3D computer visualization. A review article dedicated to augmented reality in medical applications is given by Tang et al. [109], and a more recent survey of augmented reality in surgery by Shuhaiber [104].

3) *Intraoperative perception*: In general, when referring to 3D computer visualization, the information is often shown as 2D perspective projection, although the computer is internally aware of the 3D scene. Likewise, a monitor during endoscopic surgery displays a two dimensional projection of the three dimensional scene inside a patient, computer visualizations on usual monitors are recognized as two dimensional projections by an observer and thus, depth perception during 3D visualizations, like augmented reality, is limited [105]. In this case, the observer's visual perception reconstructs a 3D scene by use of several 3D features supporting the perception, as for instance an object's color and texture combined with trained knowledge. Furthermore, perspective views, motion, object opacity, object occlusion, and shadows can contribute the three dimensional understanding of 2D projections.

Hence, computer assistance systems for endoscopic surgery, which increase the three dimensional understanding by means of 3D perception supporting features, are subjects of research. Nicolaou et al. [88] developed an approach to improve 3D perception by generation of an artificial shadow of surgical instruments. For this purpose, a further, virtual light emission device is simulated and surgical instruments are tracked by a magnetic tracking system. In Navab et al. [86], the authors propose a laparoscopic virtual mirror, which reflects anatomical structures like blood vessels, tracked surgical instruments,

or other modeled objects. Thus, viewing perspectives, which can not be achieved by the endoscope due to movement restrictions, become visible. Furthermore, the mirror can be moved in real time with the help of a tracked interaction device, which improves depth perception additionally. The virtual mirror has been evaluated along with the navigation system proposed by Feuerstein et al. [31].

In case that specific points of space have to be addressed, like it is necessary during laparoscopic radio frequency ablation, simplified virtual 2D and 3D visualization types can be applied. Seitel et al. [103] evaluated different visualization types for navigated RFA, like e.g. a virtual camera view from the ablation tool tip. The results have shown that there is no optimal visualization for the overall procedure, instead, tip positioning, needle alignment, and needle insertion can be best performed with different types of visualization.

Apart from improvements regarding the contents that are visualized, several technical devices have been invented aiming at the limitations of a 2D monitor. Head-mounted displays (HMD) provide a stereoscopic view, either in form of (optical or video) see-through glasses, on which the contents are superimposed on by augmented reality techniques [35], [117], or in form of pure video displays, which make the HMD virtual reality capable [74]. In addition, specific 3D monitors generate a realistic three dimensional view for a predefined position of the observer. Further devices, like see-through mirrors [33], or projector based systems, which project images onto surfaces [74], have been developed for non endoscopic surgery. However, Herron et al. found no significant advantage in comparison to conventional monitoring in a clinical evaluation of 3D visualization devices [46]. Shortly thereafter, Van Bergen et al. compared 3D visualization and prototype devices of high-resolution endoscopes (HDTV) [115]. They found a tendency to benefit from high-resolution video images, a technique which currently gains momentum in clinical routine.

Not only solutions for visual obstacles of endoscopic surgery are subject of current research, but also deficiencies in haptic perception are addressed. A tactile sensor for surgical instruments has been introduced by Schostek et al. [101]. Similar to a recently presented tactile sensing system for telemanipulator devices [1], the tactile feedback is communicated visually to the surgeon. Ottermo et al. [93] compared a custom built laparoscopic instrument including a sensor array for tactile sensing with haptic perception during open surgery (gloved fingers), and perception with conventional laparoscopic instruments. They found that tactile sensing instruments only slightly increase haptic sensitiveness and called the visual communication of tactile information to account. Further research regarding the representation of tactile information has to be done, however, tactile sensing can add to intraoperative information as well as haptic feedback can be a further opportunity for communication with surgeons in prospective navigation concepts.

IV. PERSPECTIVES AND LIMITATIONS OF ENDOSCOPIC NAVIGATION

Major challenges of image-guided systems in general are widely discussed across academic and industry groups. Two

recently arranged workshops [14], [21] gave special focus on system design, integration into existing workflows, and validation of clinical outcomes. Although the technical progress of surgical navigation systems is varying between medical disciplines, there are several roadblocks, which have been identified to hamper in general a prospective system development and establishment of surgical navigation in clinical routine:

- **Standardization:** The lack of standardized interfaces is a huge obstacle for computer assisted therapy [66]. Although DICOM is an established standard for communication and archiving of medical images, there is no standard for modeling and communication of intraoperative data, as for instance surgical plannings, tracking data, image processing data, protocols and more. The DICOM working group WG24 started in 2005 to define a software standard for surgical information, which is referred to as Surgical DICOM [65]. But not only software interfaces have to be worked out, also operating room hardware has to be designed interoperable. Currently, OR hardware devices are built as standalone systems and do not integrate smoothly into the OR. In consequence, OR devices come along with considerable time effort for the surgeons and many surgeons adopt a critical position regarding additional devices like navigation systems.
- **Data acquisition and fusion:** Today's opportunities for gaining knowledge of the patient's inside during surgery are strongly limited. Imaging technology must be further developed, especially with respect to image quality. Furthermore, new modular imaging devices must be designed, which meet the requirements of surgical use. Furthermore, the medical image processing community is confronted with new challenges, since surgical navigation demands reliable, fast, and automatic methods for determination of anatomical structures within images and fusion of images from different modalities. The integration of pre- and intraoperative image modalities in navigation systems further requires methods to assess the accuracy of displayed information while navigation takes place.
- **Integrated devices:** Information coming from various actors like imaging modalities, tracking devices, tools, and other equipment must be concentrated at one targeted imaging integration system [94]. These systems must include data acquisition, processing, and displaying features and must be able to handle multiple imaging modalities simultaneously. Thus, the development of new navigation systems should be able to rely on a certain basis infrastructure, which enables a fast adaption for new surgical procedures and eliminates a recurring development of base features for surgical navigation. Also, this basis infrastructure eases the evaluation of navigation proposals, as only new modules have to be considered.
- **User interface:** An intuitive and efficient method to display spatial information is required. The intraoperative visualization of 2D slice images demands an in-depth examination of image data and emerged to be distracting for complex spatial information. Also, nowadays visual-

TABLE I
NAVIGATION PROPOSALS FOR ENDOSCOPIC INTERVENTIONS IN THORACIC AND ABDOMINAL SOFT TISSUE SURGERY

Article	Target intervention	Applied Tracking	Additional Intra-operative Devices	Visualization	Registration
Heart					
Handke et al. [42] (2006) Linte et al. [68] (2007) and Huang et al. [50] (2005)	Heart Heart, mitral valve implantation	None Magnetic (Optical in [50])	3D US 2D/3D US	Multi-planar Augmented virtual environment	No designated registration Semi-automatic two step registration between pre-op CT/MRI and intra-op US: pre-op pre-registration and intra-op adjustment
Falk et al. [28] (2005)	Heart, bypass grafting	Mechanical	Da Vinci [®]	Augmented video	Fiducial markers for registration to pre-op CT, intra-op adjustment by clicking on artery bifurcations in endoscope video
Lung					
Wegner et al. [120] (2007)	Lung, bronchoscopy	Magnetic	None	Virtual environment, augmented video	Anatomical landmarks for registration to pre-op CT, lung movement compensation
Hautmann et al. [44] (2005)	Lung, bronchoscopy	Magnetic	None	Multi-planar	Anatomical landmarks for registration to pre-op CT
Anantham et al. [2] (2007)	Lung, fiducial placement	Magnetic	None	Multi-planar	Anatomical landmarks for registration to pre-op CT
Trejos et al. [113] (2007)	Lung, brachytherapy	Magnetic	2D US	Augmented virtual environment	No registration required
Bricault et al. [10] (1998)	Lung, transbronchial biopsy	None	None	Virtual environment, augmented video	Automatic 4 stage algorithm for registration to pre-op CT
Mori et al. [79] (2005)	Lung, bronchoscopy	Magnetic	None	Virtual environment, augmented video	Fiducial markers for registration to pre-op CT, adjustment by image processing
Liver					
Konishi et al. [60] (2007) and Nakamoto et al. [83] (2007)	Liver, resection	Magneto-optic	2D/3D/4D LUS	Augmented video	No registration required for intra-op US, landmarks for registration to pre-op CT/MRI
Kleemann et al. [59] (2006) and Hildebrand et al. [47] (2007) Scheuering et al. [100] (2003)	Liver, laparoscopic resection and RFA Liver, resection	Magnetic Magnetic	2D LUS None	Augmented US Augmented video	No registration required Fiducial markers for registration to pre-op CT
Bao et al. [4] (2007) Krücker et al. [62] (2005)	Liver, laparoscopic RFA Liver, laparoscopic RFA	Optical Magnetic	2D LUS 2D LUS	Augmented US US augmented on CT	No registration required Anatomical landmarks for registration between pre-op CT and intra-op US
Yasunaga et al. [129] (2007) Feuerstein et al. [31] (2007)	Liver, laparoscopic RFA Liver, kidney	None Optical	MRI 3D C-arm	Multi-planar Augmented video	No designated registration Fiducial markers for registration to pre-op CT for port placement, no registration required for resection planning
Various					
Kaspersen et al. [53] (2003)	Aorta, stent implantation	Optical	2D/3D US	Augmented US	Fiducial markers for registration between pre-op CT and intra-op US
Estépar et al. [25]	Transgastric access	Magnetic	2D LUS	Virtual environment, augmented US	Fiducial markers for registration between pre-op CT and intra-op US
Marescaux et al. [73] (2004)	Kidney, adrenalectomy	None	None	Virtual environment, single augmented images	Manual registration to pre-op CT
Baumhauer et al. [7] (2007)	Prostate	Endoscopic video	3D US	Virtual environment, augmented video	Fiducial markers for registration to intra-op US
Vogt [116] (2005)	Gall bladder, cholecystectomy	Mechanical, optical	AESOP [®]	Virtual environment, augmented video	Light field generation and surface based registration to pre-op CT
Saunders et al. [99] (1995)	Colon, colonoscopy	Magnetic	None	Virtual environment	Anatomical landmarks
Applicable to multiple endoscopic interventions					
Leven et al. [67] (2005)	Various	Mechanical, optical	2D/3D LUS, Da Vinci [®]	Augmented video	No registration required
Feuerstein et al. [32] (2007) Ellsmere et al. [22] (2004)	Various Various	Magneto-optic Magnetic	2D LUS LUS	Augmented video Virtual environment	No registration required Anatomical landmarks for registration between pre-op CT and intra-op US
Fuchs et al. [35] (1998)	Abdominal	Endoscopic video, optical	Structured light emitter	Augmented video, Head-mounted display (HMD)	Structured light generation and surface based registration
De Buck et al. [18] (2001)	Various, gynaecological interventions	Optical	None	Augmented video	Fiducial markers for registration to pre-op CT
Nicolau et al. [89] (2005)	Various	Optical	None	Augmented video	Fiducial markers for (automatic) registration to pre-op CT

ization techniques like stereoscopic head mounted devices provide only limited depth perception [105]. Further, new or elementary revised visualization concepts are needed for seamless integration of computer assistance into surgical routine.

These basic deficiencies can also be identified in current concepts for endoscopic navigation: The lack of standards presupposes researchers to develop most components of navigation systems of their own, which increases expense and time effort. As one example, the configuration of markers for optical tracking of an endoscope (as illustrated in figure 2) differs - if applied - among all research groups listed in table I. However, as reported by Feuerstein et al. [31], a sub-optimal marker configuration can have considerable effect for tracking accuracy. Standards have to be defined for purposes like this in order to favor a commercialization of established tools, and, perhaps more important, to make navigation systems better comparable. But also in software development, the public availability of state-of-the-art methods is crucial. Open-Source toolkits for applied research, like the MITK toolkit [125] or the IGSTK toolkit [24], facilitate a rapid application development and contribute to expandability and reusability of previous work. However, latest software algorithms are only limited available to the public community, today.

In contrast to navigation for interventions like orthopedics, the continuous motion and deformation of anatomic structures of abdomen and thorax are a major challenge for navigation system design. Many of today's navigation proposals pay too little attention to this fact and transfer components of rigid navigation to soft tissue procedures, where they do not solve given problems. Furthermore, a one-time registration of surgical planning and patient anatomy is of restricted use for reliable soft tissue navigation, as the validity of presented information during image guidance can hardly be verified. Instead, a recurrent alignment of navigation targets and patient anatomy has to be established. Promising solutions have already been introduced for lung bronchoscopy with the help of additional knowledge of the bronchial tree (e.g. by Mori et al. [80], or Deligianni et al. [19]). Also in navigated liver resection and laparoscopic RFA, organ motion is considered by means of laparoscopic ultrasound, as proposed e.g. by Nakamoto et al. [83]. The real time compensation for tissue motion is becoming more difficult, if motion is non-recurrent and can not be captured continuously by imaging modalities. Although, the use of organ surface adhesive markers as e.g. performed by Feuerstein et al. [31] can not compensate for motion and deformation effects, it can detect the magnitude of tissue shift and allows for a verification of navigation validity. Similar to this, Baumhauer et al. [7] utilize needle shaped navigation aids, which are inserted into the organ and tracked by the endoscope. This inside-out tracking approach enables an inherent correction of tissue motion, and additionally allows for the detection of deformations.

The diversity of published endoscopic navigation concepts during the last few years confirms a vivid interest for computer assisted surgical interventions. This interest may increase to real medical need with further reduction of invasiveness - and a corresponding further loss of conventional intraoper-

ative perception - as it is claimed by new surgical technologies like natural orifice transluminal endoscopic surgery (NOTES) [118]. Obvious upcoming problems in conjunction with NOTES will be a more limited mobility of endoscope and surgical instruments during surgery and a requirement for navigation inside organs, like the stomach. In this context, a first in-vivo study of feasibility for navigated transgastric access to the abdomen has already been presented by Estépar et al. [25].

The increasing use of robots and tele-manipulators in surgical routine is another ongoing process, which influences a further progression of surgical navigation systems. Currently, navigation proposals can benefit from surgical robots, as they may provide a standardized user interface and instruments, and positional information about surgical actors. Falk et al. [28] utilizes the positional data of the Da Vinci[®] system in heart bypass grafting for patient-to-image registration by means of fiducial markers. Similar to this, Vogt employs the positional data from the AESOP[®] system in his PhD thesis to facilitate an augmented reality visualization [116]. Furthermore, Leven et al. [67] extended the Da Vinci[®] system with a laparoscopic US probe and displays the US images in form of US augmented video directly within the surgical console. More combined approaches for navigation along with surgical robots can be expected in the future. In the long term, robotic systems may also benefit of surgical navigation, as an automation of simple surgical tasks requires knowledge a navigation system can provide.

V. DISCUSSION

In this article, publications with regard to computer assisted navigation for endoscopic soft tissue interventions have been reviewed. The recent publication dates of most approaches indicate an early status of development of these technologies. Often, simplifications in system design and technical evaluation experiments complicate an assessment of feasibility for clinical use and negate an objective comparison of overall system accuracies. The probably greatest challenge relates to the intraoperative measurement and modeling of organ shift and tissue deformation of "unconstrained" organs in thoracic and abdominal cavities. Handling these problems requires additional expenses in contrast to rigid organ navigation, which in consequence results in more sophisticated system setups and additional devices for the OR. Therefore, soft tissue navigation is hardly practicable with a single autonomous navigation device, as it is commonly used for rigid organ interventions. Instead, a collaboration of several surgical actors has to be established in a way, which integrates seamlessly into surgical routine. However, as elaborated above, deficiencies in infrastructure and interoperability of OR devices impede this integration and thus, up to now, endoscopic soft tissue navigation is still limited to animal studies or experimental clinical trials.

Nevertheless, endoscopic navigation systems show ways and means to enhance surgeons' perception during minimally invasive and open surgery. Furthermore, nowadays surgical interventions produce a huge amount of patient related data from

different information sources, like technologically improved pre- and intraoperative imaging modalities, surgical planning methods, tracking data, and high-resolution endoscope video images. A separation, analysis, and presentation of valuable information during surgery by means of computer assistance systems can improve the surgeons' knowledge about anatomical situations. The benefit of additional knowledge about the position of surgical instruments may even be indispensable for upcoming intervention techniques, like NOTES, where surgical instruments are not always visible in endoscopy images.

A further progress of soft tissue navigation, however, requires physicians and engineers to collaborate closely. Specific surgical procedures have to be identified, where current technical possibilities provide a valuable benefit. A thorough system design, development, and technical evaluation is necessary in order to provide the surgeons with reliable systems, which demonstrate the feasibility of soft tissue navigation in surgical routine.

VI. ACKNOWLEDGMENT

Part of the present work was conducted within the setting of the "Research group 1126: Intelligent Surgery - Development of new computer-based methods for the future workplace in surgery" founded by the German Research Foundation. The authors would like to thank Tobias Simpfendorfer and Jens Poxleitner for the contribution of figures, and Marco Nolden for technical support.

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