Biomechanical simulations, soft tissue phantoms and open data - validating and benchmarking systems for computer assisted minimally invasive surgery

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***Abstract*—Determining the accuracy of computer assisted surgery (CAS) systems is challenging. This is in particular true in the realm of minimally invasive soft tissue interventions. Here, it is very complicated and sometimes even impossible to obtain reliable in vivo ground truth data. For this reason numerical simulations, organ phantoms and animal experiments are used as a means for validating the accuracy of CAS systems. In this paper, we discuss these common evaluation tools in the context of sensor data processing and registration techniques. Furthermore, we present solutions for mechanically accurate soft tissue phantoms and numerical validation tools for endoscopic surgery. It will become apparent that even when using these strategies the acquisition and processing of suitable evaluation data can be very time consuming. We will thus conclude with a discussion of the need for and core requirements of suitable open repositories for ground truth data.**

I. Introduction

The validation of accuracy is a very important step towards a thorough evaluation for computer assisted surgery systems [7]. It is especially important for algorithms, modules and systems that are in a research or prototype state. In order to provide navigational information to the surgeon CAS systems rely on suitable intraoperative sensors such as tracking systems, endoscopic video or ultrasound data. Typically, complex algorithms for sensor processing and registration techniques are used in order to align pre-operative planning data to the patient based on the sensor information. In this context, the first validations step is to assess the accuracy of each individual component before proceeding to validate the whole system. Validation data can be acquired *in silico*, *in vitro* or *in vivo* including numerical simulations, phantoms or clinical data sets [7].

Until now, numerical environments for *in silico* validation of sensor hardware and processing algorithms are usually restricted to simple synthetic data [5]. Even more elaborate approaches to sensor data simulation are often only used as a means for preliminary validation during development [14].

In contrast, phantom data is widely used for sensor processing validation. Models based on Poly(vinyl alcohol) (PVA-C) can reproduce both the sound and the mechanical properties of human tissue and are suitable for validating ultrasound-based techniques [17]. The properties of the material can be tuned by changing the exact composition of the material and the number of cycles of a freeze-thaw process that is applied during manufacturing. Sufficient experience in handling this substance is required in order to accurately adjust its properties. Silicon phantoms are often used in the context of endoscopic image processing. Examples include phantoms of the heart [13], [16] and the liver [12]. Different paints allow to emulate typical optical properties such as specular reflections. However, it is challenging to reproduce realistic texture patterns in this way.

Animal organs *in vitro* can also be used for accurate validation and benchmarking of image processing techniques in the context of endoscopic interventions [11]. Careful planning and time consuming post processing is required in order to obtain ground truth values using this approach.

For the validation of non-rigid registration techniques it is important to obtain a sufficient dense ground truth of the deformation field. This can be achieved by placing small marker balls inside a phantom [2]. Depending on the scenario, many marker balls are required for this purpose. Thus, it is important to set up the configuration in such a way that the processing of the ground truth data (segmentation, spatio-temporal registration) can be done (semi-)automatically. An important aspect in this application area is the accuracy of the phantom's mechanical behaviour. Kerdok et al. performed the first quantitative analysis by means of force measurements and finite element analysis of appropriate silicon material for simple shapes [9]. More recent results show how phantoms for complex organ geometries can be constructed that provide an adequate accuracy in terms of the mechanical properties [6].

For some interventions, intraoperative volumetric imaging such as cone-beam CT can be used to obtain ground truth data from animal experiments or potentially even during real interventions [4].

Due to advances in simulation technology, components for both real-time simulation of the mechanical behaviour of organs [3] and the accurate ultrasound sensor data are already available [10]. However, currently no system exists that can generate different sensor data and ground truth data for the validation of CAS systems.

In this paper we present ongoing work towards an *in silico* evaluation environment for computer assisted minimally

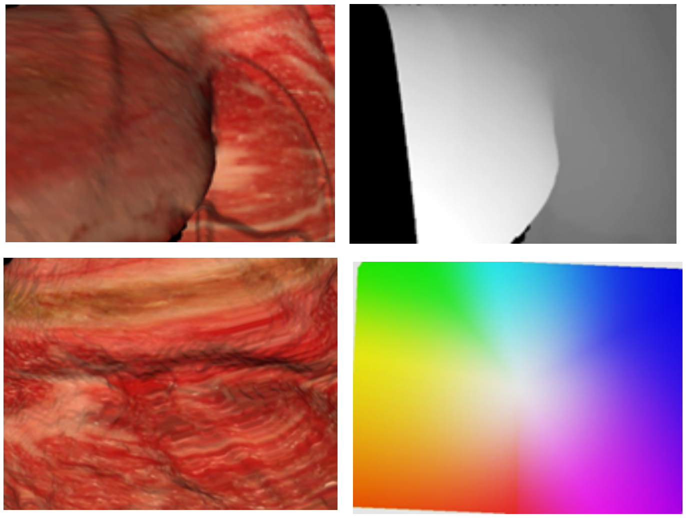

Fig. 1. For each video frame the disparity ground truth between the left and right image is computed (top). Furthermore, the displacement during camera motion or organ deformation is saved and displayed a color coded image (bottom).

invasive surgery. Furthermore, we show how mechanically accurate soft tissue phantoms can be built for validation purposes. Finally, we discuss how such tools and generated data can be made available in open databases.

II. IN SILICO EVALUTION SUITE

We are developing a simulation environment for validating components and systems for computer assisted minimally invasive surgery. The core module of the simulation is an accurate camera model. It can be parameterized to resemble the set-up typically found in different stereo endoscopes. By using realistic organ textures and appropriate lighting models, the optical properties commonly found in endoscopic image sequences (e.g. specular reflections) can be reproduced in sufficient detail for an accurate validation of image processing algorithms. Real-time finite element (FE) techniques are integrated into the model to allow for a realistic deformation of organs in the surgical scene.

The simulation suite generates all necessary ground truth data to validate many image processing (e.g. 3D-reconstructions) and non-rigid registration algorithms. Both the disparity map of the two stereo endoscopic images and the displacement for each pixel in the image over time can be accurately computed using a raycasting algorithm (Fig. 1). Additionally, the deformed organ meshes are saved along with important landmark positions for each timestep in order to evaluate registration results. The numerical simulation is especially useful to assess the sensitivity of algorithms to specific parameters (e.g. camera calibration, noise).

Currently, we are including more relevant sensor data into the simulation tool (e.g. tracking information). In this context we are developing a suitable data format that allows to easily save sensor and ground truth data and to feed the sensor data into the CAS system. Although the simulation runs in real-time, some components for generating and saving ground truth values (e.g. raycasting) do not achieve interactive rates. That's why we are including a tool that allows saving the user

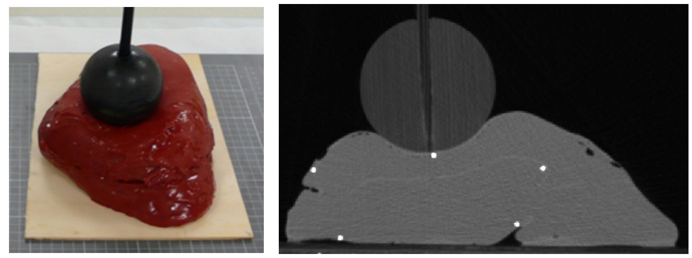

Fig. 2. Liver phantom is deformed in an indentation experiment (left). The deformation can be tracked in CT images using Teflon marker balls (right).

Fig. 3. Upper body phantom build from segmented CT images (left), endoscopic video frame featuring several silicone organs (middle) and corresponding 3D-reconstruction from stereo endoscopic data (right).

interaction (e.g. instrument and camera movement) in order to generate all accurate ground truth computations by re-running the simulation in a non-interactive mode.

III. SOFT TISSUE PHANTOMS

In order to develop mechanically realistic silicon phantoms, we analyzed several different silicon types within an elastometer in order to obtain a database that contains exact material parameters for each silicone. As material models and parameterization for most organs are available in the literature, the database allows selecting suitable silicones for organ phantoms. We use a parameter optimization method on a FE model in order to accurately match different material models. However, silicon exhibits a much more linear behavior than human soft tissue. In order to mimic real tissue behavior over a larger deformation range, the phantoms are equipped with a stiff core and a softer outer region. The stiffness parameters (and thus corresponding silicon types) are again matched using non-linear optimization. More than 100 Teflon balls are inserted into each phantom in order to track the deformation in CT images (Fig. 2).

In order to build a model of the upper body, all major organs were segmented from CT images. A rigid outline of the body as well as bony structures were manufactured using rapid prototyping techniques (Fig, 3). Similarly, molds for each organ were built from the segmented images and silicone organs were cast from these molds. The resulting torso phantom allows simulating more complex deformation pattern and inter-organ interaction. All deformations can be easily tracked in CT images thanks to the markers in the silicone organs. The model thus serves as a very useful validation tool and even offers a cheap, reproducible and accurate alternative to animal experiments for many validation steps.

IV. Discussion

In this paper we presented recent advancements in numerical simulation and accurate organ phantom design for the validation of CAS systems in the realm of minimally invasive surgery. While both techniques have become important tools for CAS validation in the development stage, their design and application is non-trivial and time consuming. Furthermore, the execution and post processing of experimental results from phantom experiments requires not only the access to CT imaging hardware, but also manual effort (e.g. segmentation). Thus we are planning to release an open collection of numerical and experimental phantom data that include accurate ground truth information and are thus suited for accuracy validation.

Having common data sets does not only allow researchers to spend more time on development and less time on validation, but it also allows to benchmark algorithms against each other. In the realm of computer vision, the Middlebury datasets is widely used for that purpose [15]. Although there are few datasets for the validation of CAS components are available (e.g. the Hamlyn Centre endoscopic video datasets [16] and the 3D-IRCAD database [1]), it would be desirable to have a more extensive selection of data. In particular, it would be beneficial to establish a common repository that can serve not only as a central access point for data, but also for benchmark results. As the complexity of the data is growing (e.g. different types of temporally registered sensor data) it is especially important to develop standardized data formats and corresponding processing tools in order to make the data easily accessible.

Naturally, such a repository should not be limited to numerical or phantom data. In the context of image processing (e.g. instrument segmentation) *in vivo* sensor data is often used for qualitative evaluation. In some contexts, manually labeled image data can even serve as a reliable ground truth. Making these kinds of data freely available would significantly speed up the development for many research groups. This is even more true for algorithms that rely on machine learning approaches such as segmentation or situation recognition techniques [8]. In these applications, the acquisition and manual processing of suitable learning and test data often is the most time consuming part of development.

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