Extending MITK by a real-time online video overlay navigation system for minimally invasive surgery

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Abstract

The purpose of this paper is to present our extension of the *MITK* toolkit by a real-time navigation system for computer assisted surgery. The system was developed with laparoscopic partial nephrectomies as a first application scenario. The main goal of the application is to enable tracking of the tumor position and orientation during the surgery. Our system is based on ultrasound to CT registration and electromagnetic tracking. The basic idea is to process tracking information to generate an augmented reality (AR) visualization of a tumor model in the camera image of a laparoscopic camera. Our system will enhance the surgeon's view on the current scene and therefore facilitates higher safety during the surgery. A key intention of the development was to use only open source toolkits such as *VTK*, *MITK* and *OpenCV* in order to implement the desired functionality. So far we have applied our system in vitro in two phantom trials with a surgeon which yielded promising results.

Contents

1 Introduction

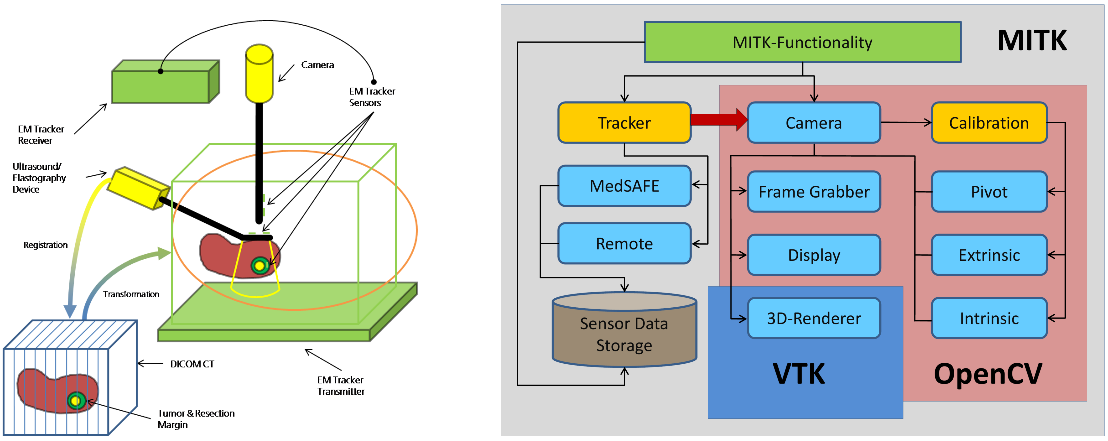
In recent years, an increasing number of kidney tumors were treated by minimally invasive resection. During these so called laparoscopic partial nephrectomies the surgeon suffers from several limitations such as a limited field of view and a lack of depth information. Therefore surgeons could benefit from computer and hardware assistance. This leads to the emerging field of computer assisted surgery. However, for navigation in minimally invasive surgery many challenges have to be addressed.

An important challenge is to distinguish between healthy and diseased tissue. The separation line between the two tissue types forms the boundary where the surgeon excises the tumor from the organ after adding a safety margin. In most cases this boundary cannot be identified solely through visual observation of the intraoperative camera image. Therefore, surgeons study preoperative CT or intraoperative ultrasound images closely. But even after planning, the risk of cutting into the tumor tissue or cutting away too much healthy tissue is relatively high. The reason for this risk is the inaccurate cognitive transfer process from imaging modality to the organ, which mostly depends on the experience of the surgeon. We think that by extending the planning process with the generation of a tumor model that will be automatically superimposed to the laparoscopic camera image during the surgery, the inaccuracy of the cutting process can be reduced significantly. To enable this augmentation two working steps are necessary. At first an automatic or semi-automatic system to register preoperative CT images with intraoperative ultrasound has to be created. Secondly the camera and tumor positions as well as their orientations need to be tracked to enable an anatomically correct video overlay.

Literature shows great progress in tracking the tools, camera and intraoperative imaging modalities in use. However, tumor tracking is a very important step and still one of the biggest challenges on the way to enable assistance throughout the surgical procedure. The two commonly employed tracking methods are optical (with optical targets and feature based) and electromagnetic tracking. Optical tracking of target frames offers fast tracking with high accuracy. It is mainly used for tracking rigid tools by attaching the optical frame to the proximal part of the tool. Examples for the medical application of this technique can be found in [10]. This approach suffers from the need for a direct line of sight between camera and frame as well as the limitation to rigid tools. The group at DKFZ (German Cancer Research Center) has developed a navigation system based on optical tracking of small markers that are attached to the organ surface [2]. This enables the tracking of the organ position and orientation and allows for an augmented reality video overlay of internal structures [16]. Both optical tracking approaches based on markers do not allow for tracking of flexible tools and the tumor itself, which is the target of the procedure. Therefore the navigation assistance using optical tracking with markers is limited to an orientation at the beginning of the procedure and loses reliability during the resection process. A group at Johns Hopkins University has presented an optical tracking system based on a stereoscopic camera system and feature extraction [15]. Unfortunately such systems suffer from so called drift due to error accumulation over time [1].

Unlike optical tracking, electromagnetic tracking systems do not require a direct line of sight and any optical markers or features to track objects. Especially in minimally invasive surgery, where the available space inside the abdominal cavity is limited, distinguishable landmarks are rare and a direct line of sight is not given at any time, electromagnetic tracking systems clearly have an advantage. Furthermore our electromagnetic tracking approach allows tracking of the tumor troughout the whole surgery. Birkfellner et al. have shown the applicability of electromagnetic tracking in the surgical environment in [3] and [4].

In the remainder of this paper we describe the system setup in section 2. The required camera calibration steps are specified in section 3. We are going to conclude the paper and give an outlook into future research fields in section 6.



(a) (b)

Figure 1: The subfigure (a) shows schematic drawing of the hardware components of our navigation system and their interconnectivity. Subfigure (b) shows the software components and their integration into the toolkits.

2 System Overview

Similar system designs using both optical and electromagnetic tracking systems are proposed in the literature. Our system in figure 1a is similar to the system introduced in [12]. Nevertheless there are three key differences. Our system differs from [12] by the electromagnetic tracking system and camera being used. The last and most important difference however is, that contrary to the retrospective system described in [12], our system can generate the video overlay online and in real-time.

The components of our navigation system that are shown in 1b. It is implemented using the three open source toolkits *MITK*, *VTK* and *OpenCV* with *MITK* being the development basis [19]. The user interface elements and functions for receiving and storing electromagnetic tracking data inside our functionality are extending the *MITK-IGT* components. The *OpenCV* toolkit offers state-of-the art and well tested methods for camera calibration which are important to ensure the accuracy of the navigation system. All accumulated and processed data is then used to generate an accurate rendering scene of the tracking system with the *VTK* toolkit. Using the rendering scene it is possible to obtain rendering images that are superimposed to the camera live video feed, providing the desired augmented reality visualization. More detailed information on the imaging and registration components of our navigation system can be found in [13].

Registration

One of the key steps in the proposed system is the registration of a pre-operative CT and its previously segmented tumor model to the intra-operative situation. This means that the CT and planning data have to be aligned to the patient position and orientation in the operating room which might differ from the situation during the CT scan. During the surgery two three dimensional ultrasound volumes are generated using tracked freehand ultrasound. With our system we are generating B-Mode and Elastography Imaging (EI) ultrasound volumes, with EI being a simple imaging modality sensitive to relevant features. We are using a version of the *MITK* rigid registration functionality which we have enhanced according to our needs and already given back to the community. A rigid six degree of freedom (DOF) registration of the translation and rotation parameters is performed. In the registration step a variety of difficulties related to ultrasound might impede the achievement of high quality registration results. Apart from the need to track the probe, the field-of-view as well as the amount of discernible features is limited. As the region-based stiffness values of EI data are related to CT density information, an information-based metric (Mattes Mutual Information in this case) is used for registration [8]. The result of the registration step is a transformation of the CT volume and the corresponding tumor model into the reference coordinate system formed by the tracking system.

Tracking

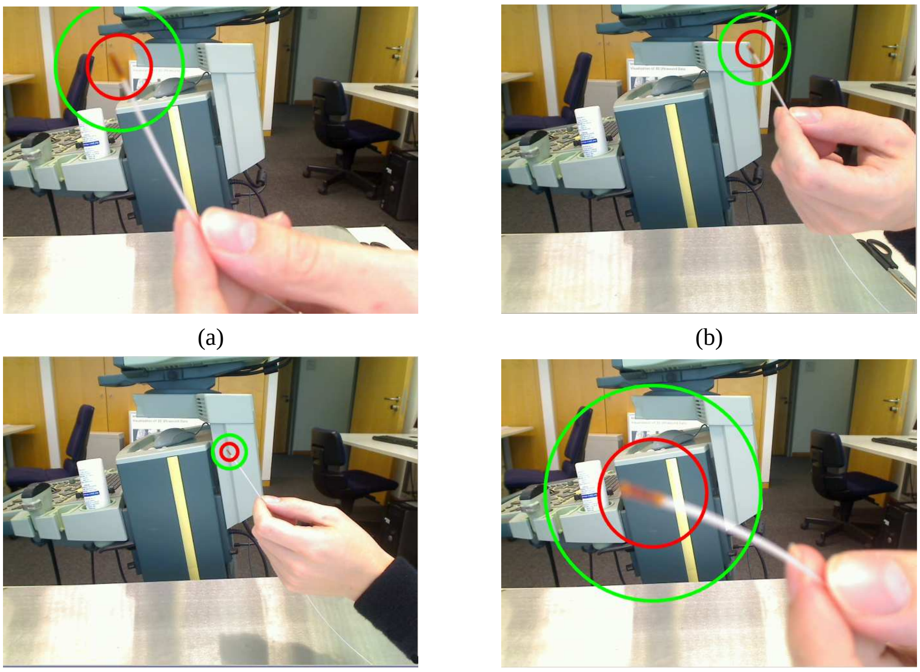
Wired electromagnetic tracking systems have been used to track surgical instruments like ultrasound probes, bronchoscopes or catheters [9] and [11]. We propose to use the 3D Guidance medSAFE tracking system from Ascension Technology Inc., USA for tracking camera and tumor movement. We extended the *MITK-IGT* components to support this new tracking device as well as a remote tracking client that allows for reading tracking information via a TCP/IP network. The medSAFE tracking system has no need for an additional optical tracking system (cf. the optical and electromagnetic hybrid tracking system from Calypso Medical which was proposed by [12]), which eliminates the additional source of inaccuracy and reduces calibration efforts. Furthermore the absence of the optical tracking system eliminates the line of sight problem. Compared to the Calypso system, we are tracking the tumor movement using a single miniaturized sensor. With this single sensor we have 6 degrees of freedom and sub-millimeter precision whereas the Calypso system needs three larger beacons to achieve similar accuracy. This limits the applicability of the Calypso system on small tumors, where the amount of healthy tissue that is needed for placing the beacons next to the tumor would be too high compared to the advantage of such a navigation system. Furthermore using our tracking technique we are able to track tumors by placing the sensor into the safety margin without cutting into the tumor tissue which should be avoided at any cost. Passing the necessary wires of the tumor sensor into the body can be easily solved by utilizing the 4th trocar, which is placed but not used in our scenario. The system we present in this paper requires a tracking system with at least two active sensors. The first sensor is implanted next to the tumor under ultrasound control. We are using a Tuloc marker wire from Somatex Medical Technologies GmbH, Germany and attach the sensor to this wire with Medi Cure biocompatible glue from DYMAX Europe GmbH, Germany so that the sensor cannot change its relative position to the tumor. The second sensor is attached to the tip of the optical instrument that allows the surgeon to see the operating field.

Camera

Currently a Logitech QuickCam camera provides the 640-by-480 pixel live video footage. In future system designs the video source will be replaced by a laparoscope and therefore it will meet the requirements for minimally invasive surgery. For a smooth and real-time experience of the video navigation we are calculating at least 25 augmented video images per second. The much higher rate of position information from the tracking system enables outlier correction which will be implemented in future system stages.

3 Calibration

Since each of the employed devices has its own characteristics and coordinate system, they have to be calibrated to enable a projection of a given tracking coordinate into the camera image (cf. figure 2). In order to set up the navigation system, it is sufficient to calibrate the camera, as mentioned in section 1. One distinctive feature of the proposed system is that only intrinsic and extrinsic camera calibration are required.



(a) (b) (c) (d)

Figure 2: The sufigures (a)-(d) show cirles around the projection position of the tumor sensor in the image plane. Please note that the size of the circles is chosen according to the tumor size (red) and the resection margin (green) based on the distance between tumor and camera.

The intrinsic parameters consist of an intrinsic camera matrix (or projection matrix) and five distortion parameters. They are the projective transformation part of a homography H that describes the 3D to 2D image plane transformation. Using the calibration methods described in [7], [17] and [21] all intrinsic parameters can be obtained by solving linear equation systems. Advancing the video source to an endoscope, the intrinsic calibration should be done as described in [20] or [18] depending on the endoscope type in use. These calibrations will be more accurate as they are specifically created to deal with endoscope characteristics, e.g. very short focal length that creates highly distorted images or oblique-viewing capability (cf. [14]).

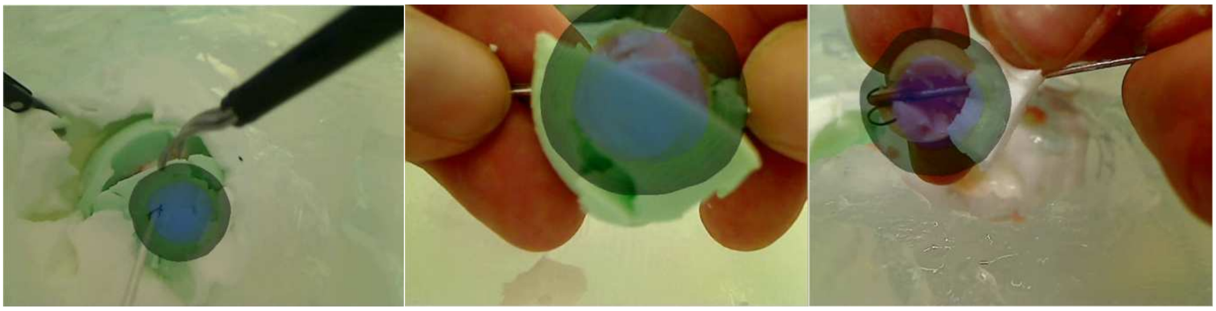
The extrinsic parameters consist of a rotation matrix R and a translation vector t. They are the physical transformation part of the homography that describes the 3D to 2D image plane transformation, which essentially specifies the relation between the viewing plane in the tracking coordinate frame and image plane in the camera coordinate frame. Further information on extrinsic calibration can be found in, [21] and [22]. The equation:

$$p = HP = MWP \tag{1}$$

represents the homography between the points p in the camera plane and the points P in the tracking space. M is the projection matrix of the intrinsic parameters.

$$W = [R, t] \tag{2}$$

describes the calibration between the camera and the electromagnetic tracking system and is a 3-by-4 com-



(a) (b) (c)

Figure 3: Placing a tumor model around the calculated center of the tumor relative to the sensor position. Please note that the physical tumor representation in (a) is different from the tumor in (b) and (c) in a way that the red tissue represents the tumor including the resection margin whereas in the other two figures the tumor is the red tiussue only and the resection margin is represented be the green tissue.

ponent matrix composed of the 3-by-3 rotation matrix R and the translation vector t. We need a set of related points in camera and tracking space to calculate H and therefore R and t. For detailed information on how to calculate R and t see [6] and [5].

4 Navigation

After a successful camera calibration the intrinsic and extrinsic camera parameters are available. Together with the position and orientation information obtained during the movement of any employed sensor, these parameters can be utilized to describe the surgical manipulation process and enable an intraoperative navigation using video overlay in real-time.

The navigation process works as follows. The tumor model as well as the safety margin that were previously segmented are loaded into our *MITK* navigation functionality. Each model's position and orientation, that are known due to the registration process described in section 2, are stored in a transformation matrix. With each movement the sensors attached to the camera and tumor generate position and orientation data that is stored in a *MITK* filter based sensor data queue and used to calculate new relative transformation matrices that can be applied to the loaded models.

To generate a 3D rendering scene of the models, a *VTK* 3D render window is created offering powerful 3D processing functions. An image that shows the transformed models is now rendered and superimposed to the life video feed, hence creating an augmented reality visualization (cf. figure 3).

Due to the previously described necessity for camera calibration the current camera position and orientation obtained through the tracking process has to be transformed back to calibration state in order to make the projection to the altered camera plane possible. The following transformation matrix $T_{movement}$ describes this transformation and is the key component for camera movement:

$$T_{movement} = T_{calibration} * T_{current}^{-1}. \qquad (3)$$

Also, if each laparoscopic tool would be equipped with a sensor, it would be possible to track and display the position of the instruments leading-edges, even if they are currently hidden behind organs or other tools.

Additionally the trajectory of the surgical tool could be displayed. This could also improve the surgeon's ability to resect a tumor. Combining the camera movement transformation and the projection we receive a new function that is applied during tracking and therefore is essential for the navigation:

$$p = MWT_{movement}P. \tag{4}$$

5 Testing

Together with a surgeon from the Johns Hopkins University we have evaluated our system in a trial on 2 custom made artificial kidney phantoms from CIRS Inc.. Each phantom had 2 lesions which were segmented, registered using *MITK* functionalities and resected using our navigation system. The tumors in each phantom were of different sizes and tissue properties including color, echogeneity for ultrasound imaging and CT Hounsfield units. We placed the sensor inside the tumor as can be seen in figure 3c using laparoscopic ultrasound guidance. A laparoscopic trainer was used to obstruct the surgeons view on the scene and to allow for a more realistic surgical environment. Therefore the surgeon was limited to the camera video image and our navigtion aids based on augmented reality visualization. Although we were facing problems with the phantoms and there physical properties during the resection process, the surgeon stated that the navigation was helpful and enabled him to estimate a good access path to the tumor. Furthermore the fact that the tumor visualization moved along with the tumor itself helped him to stay inside the resection margin and close to the tumor without cutting into the tumor itself.

6 Conclusion

In this paper we presented a new real-time navigation system for minimally invasive surgery. By using an electromagnetic tracking system with wired sensors, our technique has several advantages over systems that can be found in literature. At first, we eliminated the line of sight problem that appears when using optical or hybrid tracking systems. Secondly we are able to use the same tracking system for US Volume generation as well as tumor and camera tracking. This reduces the amount of calibration between different imaging systems and the tracking system. Last but not least the biggest benefit of our system is that the augmentation of the planning model over the real-time video can be done online instead of retrospectively as described in the literature so far. Although our results are still preliminary we think that our approach seems very promising and should be further investigated using improved phantoms.

References

[1] Iigo Barandiaran, Cline Paloc, and Manuel Graa. Real-time optical markerless tracking for augmented reality applications. *Journal of Real-Time Image Processing*, 5(2):129–138, June 2010. 1

[2] M. Baumhauer, T. Simpfendörfer, B. Müller-Stich, D. Teber, C. Gutt, J. Rassweiler, H. Meinzer, and I. Wolf. Soft tissue navigation for laparoscopic partial nephrectomy. *International Journal of Computer Assisted Radiology and Surgery*, 3(3):307–314, September 2008. 1

[3] W. Birkfellner, F. Watzinger, F. Wanschitz, R. Ewers, and H. Bergmann. Calibration of tracking systems in a surgical environment. *IEEE Transactions on Medical Imaging*, 17(5):737 –742, oct. 1998. 1

[4] Wolfgang Birkfellner, Franz Watzinger, Felix Wanschitz, Georg Enislidis, Michael Truppe, Rolf Ewers, and Helmar Bergmann. Concepts and results in the development of a hybrid tracking system for cas. *Medical Image Computing and Computer-Assisted Interventation MICCAI 98*, 1496/1998:343–351, 1998. 1

[5] Gary Bradski and Adrian Kaehler. *Learning OpenCV: Computer Vision with the OpenCV Library*. O'Reilly, Cambridge, MA, 2008. 3

[6] Richard Hartley and Andrew Zisserman. *Multiple View Geometry in Computer Vision*. Cambridge University Press, March 2004. 3

[7] Janne Heikkila and Olli Silven. A four-step camera calibration procedure with implicit image correction. *IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, 0:1106, 1997. 3

[8] Matthias Keil, Philipp J. Stolka, Marion Wiebel, Georgios Sakas, Elliot R. McVeigh, Russell H. Taylor, and Emad Boctor. Ultrasound and ct registration quality: Elastography vs. classical b-mode. In *IEEE International Symposium on Biomedical Imaging: From Nano to Macro, 2009. ISBI '09.*, pages 967–970, 28 2009-July 1 2009. 2

[9] Sascha Krueger, Holger Timinger, Ruediger Grewer, and Joern Borgert. Modality-integrated magnetic catheter tracking for x-ray vascular interventions. *Physics in Medicine and Biology*, 50(4):581+, February 2005. 2

[10] Giuseppe Megali, Vincenzo Ferrari, Cinzia Freschi, Bruno Morabito, Filippo Cavallo, Giuseppe Turini, Elena Troia, Carla Cappelli, Andrea Pietrabissa, Oliver Tonet, Alfred Cuschieri, Paolo Dario, and Franco Mosca. Endocas navigator platform: a common platform for computer and robotic assistance in minimally invasive surgery. *International Journal of Medical Robotics and Computer Assisted Surgery*, 4(3):242–251, Sep 2008. 1

[11] Kensaku Mori, Daisuke Deguchi, Kenta Akiyama, Kenta Kitasaka, Calvin R. Maurer, Yasuhito Suenaga, Hirotsugu Takabatake, Masaki Mori, and Hiroshi Natori. Hybrid bronchoscope tracking using a magnetic tracking sensor and image registration. *Medical Image Computing and Computer-Assisted Intervention*, 3750/2005:543–550, 2005. 2

[12] Masahiko Nakamoto, Osamu Ukimura, Inderbir S. Gill, Arul Mahadevan, Tsuneharu Miki, Makoto Hashizume, and Yoshinobu Sato. Realtime organ tracking for endoscopic augmented reality visualization using miniature wireless magnetic tracker. In *MIAR '08: Proceedings of the 4th international workshop on Medical Imaging and Augmented Reality*, pages 359–366, Berlin, Heidelberg, 2008. Springer-Verlag. 2, 2

[13] Philipp J. Stolka, Matthias Keil, Georgios Sakas, Elliot McVeigh, Mohamad E. Allaf, Russell H. Taylor, and Emad M. Boctor. A 3d-elastography-guided system for laparoscopic partial nephrectomies. volume 7625, page 76251I. SPIE, 2010. 2

[14] P.F. Sturm and S.J. Maybank. On plane-based camera calibration: A general algorithm, singularities, applications. In *Computer Vision and Pattern Recognition, 1999. IEEE Computer Society Conference on.*, volume 1, page 437 Vol. 1, 1999. 3

[15] Li-Ming Su, Balazs P Vagvolgyi, Rahul Agarwal, Carol E Reiley, Russell H Taylor, and Gregory D Hager. Augmented reality during robot-assisted laparoscopic partial nephrectomy: toward real-time 3d-ct to stereoscopic video registration. *Urology*, 73(4):896–900, April 2009. 1

[16] Dogu Teber, Selcuk Guven, Tobias Simpfendörfer, Mathias Baumhauer, Esref Oguz Gven, Faruk Yencilek, Ali Serdar Gözen, and Jens Rassweiler. Augmented reality: A new tool to improve surgical accuracy during laparoscopic partial nephrectomy? preliminary in vitro and in vivo results. *European Urology*, 56(2):332 – 338, 2009. 1

[17] R. Tsai. A versatile camera calibration technique for high-accuracy 3d machine vision metrology using off-the-shelf tv cameras and lenses. *IEEE Journal of Robotics and Automation*, 3(4):323–344, 1987. 3

[18] Christian Wengert, Mireille Reeff, Philippe C. Cattin, and Gábor Székely. Fully automatic endoscope calibration for intraoperative use. In *Bildverarbeitung für die Medizin*, pages 419–423, 2006. 3

[19] I. Wolf, M. Nolden, T. Boettger, I. Wegner, M. Schoebinger, M. Hastenteufel, T. Heimann, H. Meinzer, and M. Vetter. The mitk approach. *The Insight Journal*, MICCAI Open-Source Workshop, 2005. 2

[20] Tetsuzo Yamaguchi, Masahiko Nakamoto, Yoshinobu Sato, Kozo Konishi, Makoto Hashizume, Nobuhiko Sugano, Hideki Yoshikawa, and Shinichi Tamura. Development of a camera model and calibration procedure for oblique-viewing endoscopes. *Comput Aided Surg*, 9(5):203–214, 2004. 3

[21] Zhengyou Zhang. Flexible camera calibration by viewing a plane from unknown orientations. In *in ICCV*, pages 666–673, 1999. 3

[22] Zhengyou Zhang. A flexible new technique for camera calibration. *IEEE Trans. Pattern Anal. Mach. Intell.*, 22(11):1330–1334, 2000. 3