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Exploring object and multi-target instrument tracking for AR-guided interventions

https://doi.org/10.1515/cdbme-2022-0019

Abstract: The rapid development of available hard- and software for computer-assisted or augmented reality (AR) guided interventions creates a need for fast and inexpensive prototyping environments. However, intraoperative tracking systems in particular represent a high cost threshold. Therefore, this work presents a low-cost tracking method based on a conventional RGB camera. Here, a combined approach of multiple image targets and 3D object target recognition is implemented. The system is evaluated with a systematic accuracy assessment analyzing a total of 385 3D positions. On average, a deviation of $15.69 \pm 9.95\ mm$ was measured. In addition, a prototypical AR-based needle navigation visualization was developed using Microsoft HoloLens 2. This system's feasibility and usability was evaluated positively in a pilot study (n=3).

Keywords: Optical instrument tracking, surgical navigation, medical augmented reality, rapid prototyping

1 Introduction

Computer-assistance and surgical navigation has become essential for many interventional procedures but often require specialized hardware. For instance, optical Moiré phase tracking has been proposed to facilitate navigation for percutaneous MR-guided procedures [13]. In addition, augmented reality (AR) is often used to improve visual feedback and ergonomics [11]. Image-guided interventions, and AR in general, are in rapid and constant development, thus increasing the need for rapid prototyping processes [9]. However, the necessary special hardware is often expensive and difficult to acquire. To facilitate the prototyping process for percutaneous interventions, a more cost-effective tracking alternative would be desirable.

Instrument tracking for AR-guided procedures is completed either with inside-out or outside-in methods. The former uses the AR devices' internal sensors to obtain instrument transform data, e.g., the infrared (IR) cameras of Microsoft HoloLens (*HoloLens*) to track fiducial markers [8], or its RGB camera to track image markers [10]. These techniques are limited by the small field of view in front of the viewing direction of the AR glasses. More flexibility can be achieved using outside-in methods with external tracking hardware. These are mostly electromagnetic [7] or IR-based optical systems [4], which enable high accuracy but are also expensive [8].

Therefore, we propose using an outside-in optical image marker tracking based on low-cost RGB cameras for prototyping environments. This method was already shown to be feasible for inside-out tracking using the *HoloLens*. There, the libraries *OpenCV* [2], *ARToolKit* [1] or *Vuforia* [5, 15] were shown to be viable options. Aside from tracking only one image [6, 12], multiple image targets (multi-target) can be combined for increased robustness [14]. In addition, *Vuforia* enables tracking of 3D models using an object scanner [3]. We aim to transfer these findings to outside-in tracking and propose a combination of multi-target tracking and the 3D object itself. This system can be used for the simulation of in-bore percutaneous procedures, even without AR support. In addition, we report a prototypical instrument navigation visualization using the *HoloLens*, an accuracy assessment of the proposed tracking system and initial user feedback.

2 Material and Methods

2.1 Apparatus

Tracking was realized using an external RGB camera (BRIO 4K Pro Webcam, Logitech) and the *Vuforia AR SDK* (PTC). Image markers were created using *Affinity Designer* (Affinity, 2022). The game engine *Unity* (Unity Technologies) was used as the general development environment. Furthermore, the *HoloLens* (2nd generation) AR headset was used to visualize 3D models of segmented anatomical structures. A physical abdominal phantom was used to represent a patient (Triple Modality 3D Abdominal Phantom, CIRS) and a regular biopsy needle was used as an exemplary surgical instrument to puncture specific anatomical targets in that phantom, e.g., tumors. An overview of the system can be seen in Fig. 1.

2.2 Optical instrument tracking

Optical image marker tracking was implemented to determine the position and rotation of a biopsy needle in space and to lo-

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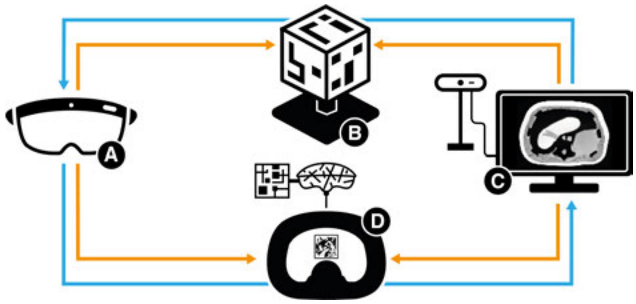

Fig. 1: System Overview. (A) AR headset, (B) world anchor, (C) external camera and PC with image data, (D) phantom and needle with multi-target and image markers. Lines: (blue) data transfer, (orange) tracking.

cate the instrument in relation to potential anatomical targets. This camera-based method detects distinctive patterns that can be identified by unique features. Requirements for the markers include a high detail density, high contrasts, and the avoidance of repetition. *Vuforia* offers different marker types that can be used for tracking:

Image target: A printed 2D image with a fixed size. This is easy to create and saves time and space. However, it is only visible from one side and therefore only offers good tracking up to a certain viewing angle.

Multi-target: A cube with a fixed size and with different image targets on each side. This allows 360° tracking, but requires more space, is more difficult to attach to instruments and is also more elaborate to produce.

Object target: A 3D object captured by a 3D scan (e.g. *Vuforia Object Scanner*). Unfortunately, the side of the object that touches the ground during the scan is not captured. Objects should also have distinctive features, which otherwise have to be compensated for by modification, e.g., with a pattern.

To balance the advantages and disadvantages of the marker types, a combination of multi- and object target was implemented for needle tracking. This ensured a large tracking space even with partial occlusion. A custom 3D-printed cube with image markers on each side was attached to the needle at a known position with respect to the needle tip. These image markers were each 4.5×4.5 cm in size. An easily recognisable pattern created out of high-contrast paper stripes was attached to the instrument because it did not have enough distinctive features for object target tracking. Initial tests revealed that the object target was recognized more precisely and robustly. Therefore, object target tracking was used primarily. The multi-target was used whenever no other tracking data was available. This way, the area of the object target not detected during the scan could be supplemented by the multi-target.

2.3 Registration

To utilize the needle tracking data on the *HoloLens*, the AR glasses needed to be registered with the tracking camera coordinate system. To this end, an additional multi-target marker was created that could be simultaneously detected by both the external camera and a user wearing the *HoloLens* opposite of it. This *world anchor* and an accompanying pedestal were 3D-printed with a side length of 12 cm to be detectable from a larger distance. Custom image markers were attached on each side of the *world anchor*, except for the bottom. In addition, all coordinate systems needed to be spatially aligned with the abdominal phantom representing a patient. Three easily recognizable fish oil capsules and an image marker were attached to that phantom before taking an MRI scan. Because the transform between image and capsules was known, a subsequent segmentation of the fish oil revealed the coordinates of the image in MRI space. Using *Vuforia* image target tracking, the phantom could then be registered to camera or *HoloLens* space. All registration steps were performed automatically upon application start.

2.4 Visualization

Our AR application serves as a conceptual use case to visually support the user when performing a percutaneous image-guided intervention. To this end, the anatomical structures in the abdominal phantom (liver, vessels, tumors), the needle and its virtual extrapolation were visualized as 3D objects in *HoloLens* space. The anatomical 3D models were generated by segmented MRI data. A model of the needle and its extrapolated trajectory facilitated the targeting process. If the instrument path would hit a target (e.g. tumor) but not injure any risk structures, the needle handle and the virtual extrapolation were colored green. Otherwise, a red color indicated a problematic alignment. This visual feedback should support the finding of a suitable insertion point and angle. We also provided an image-guided navigation concept based on automatic alignment of the image plane along the needle tip. Here, we determined the transverse cross-section corresponding to the current position of the needle tip from the MRI data of the abdominal phantom. This slice image was then displayed on a desktop monitor.

2.5 Tracking accuracy estimation

To assess the accuracy of our tracking solution, we recorded a total of 385 tracked needle poses at known positions. We also printed two different uniform grids and positioned the needle orthogonally above it using a metallic arm (see Fig. 3). The

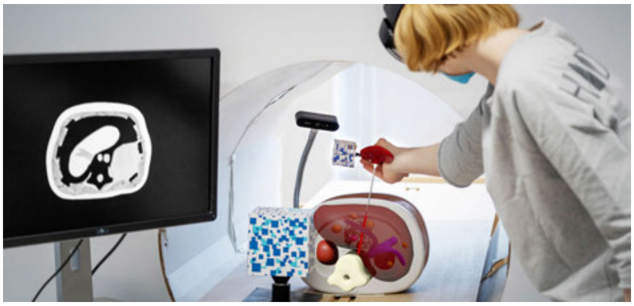

Fig. 2: Feasibility study apparatus. Phantom, world marker, needle with multi marker, RGB camera, monitor with image data, and AR glasses with 3D contents needle, path extension and anatomy.

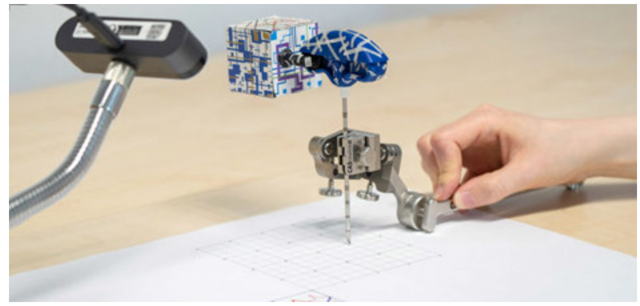

Fig. 3: Validation setup of tracking accuracy. Needle is fixed by metallic arm and placed over grid with image marker.

first grid consisted of 3×3 positions with $2\ cm$ distance. For each point, the needle was positioned at three different heights, each $2\ cm$ apart. Five consecutive tracking poses were measured for each needle position, resulting in a total of 135 data pairs. The second grid consisted of 5×5 points with $3\ cm$ distance. Here, two different height settings with $4\ cm$ distance were evaluated and ten consecutive poses were again measured. This resulted in 250 additional data pairs. The grids and the tracking data were registered by tracking an image marker with known transforms towards the grid positions.

2.6 Pilot AR guidance experiment

To evaluate the feasibility of our tracking approach with our AR concept, a pilot study was conducted (n=3). Fig. 2 shows the experimental setup. All subjects had a computer science background. The study was conducted with a physical mock-up of an MRI to mimic image-guided interventions [9]. This mock-up was specifically designed for ergonomics and usability evaluations and is equipped with video recording and virtual reality hardware, and eliminates the need for MR safe or MR conditional equipment. The phantom was placed inside the mock-up bore so that the participants needed to lean into it to reach the target. The external tracking camera was mounted inside the bore facing towards the subjects. After a verbal introduction, participants were tasked with puncturing three liver tumors with the biopsy needle. The order of targets was randomized. A think-aloud protocol was recorded, encouraging participants to report their experiences and impressions. After one training session, three trials were conducted to measure the *task completion time* (TCT) from the beginning of the puncture (entry of the needle tip into the phantom) until the target structure was reached.

3 Results and discussion

For data analysis, all consecutive pose estimations were first averaged for each grid and height position. Then, ground truth and tracked data were transformed into the same coordinate system, and the Euclidean distance between each corresponding point pair was calculated. The average deviation was then considered as an estimate of tracking accuracy. The result was a deviation of $7.44 \pm 2.67\ mm$ for the smaller grid and $20.13 \pm 9.60\ mm$ for the larger grid ($15.69 \pm 9.95\ mm$ for both combined). Tracking errors seemed to increase with the distance to the camera. Compared to intraoperatively used tracking systems, these deviations are rather large, but seem sufficient for the intended prototyping use. Tracking accuracy is also dependent on the quality of registration. However, this was not analyzed separately in this work. Future work would benefit from a detailed examination. In addition, we only evaluated static positions. A dedicated investigation of dynamic tracking capabilities would also be of interest. All targets could be reached in our AR evaluation. TCT was $14.8\ s$ on average ($SD = 15.2$). No temporal development over the series of trials was identified. However, a clear difference between participants could be observed. Regarding the qualitative feedback, all subjects were particularly positive about the visual concept. The colored indicators helped provide confidence in the execution, and the extrapolation of the needle was a useful aid. It was noted that, for complex tasks, further auditory and visual feedback (e.g. distance to the ideal insertion point) would be helpful. Conducting the study in a mock-up MRI made the performance of the task more realistic, as the body posture had to be the same as during a real image-guided procedure. This posture was perceived as strenuous and unfamiliar. AR glasses and real MR scanners are unlikely to be used conjointly in the near future. However, our prototyping environment was not limited by these restrictions, and both systems could be replaced with compatible but comparable solutions. To optimize the tracking, installing several cameras was suggested to minimize problems with occlusions of the needle and thus to increase the tracking area. Furthermore, desires for a visual display of the tracking volume and the current tracking status were expressed. During the registration of the data, an offset of the virtual needle on the *HoloLens* in relation to the real needle occurred. This varied depending on where the needle is located, although there was an ideal point where both objects aligned perfectly. Since the offset varied in magnitude, it is assumed to be scaling error. This offset was not present on the direct RGB camera stream shown on a PC.

4 Conclusion

This work reported an outside-in needle tracking method based on a low-cost RGB camera setup. *Vuforia* multiple image target recognition was combined with 3D object pose estimation for a robust and inexpensive instrument tracking. The solution was designed for rapid prototyping of computer-assistance for image-guided interventions. A pilot study showed the feasibility of the optical camera tracking and its potential use for AR-guided needle placement. Estimated accuracy of $15.69 \pm 9.95\ mm$ is promising for further development. Future work should investigate a setup with multiple cameras and focus on improving the registration between camera tracking and the *HoloLens*. While performing more complex tasks, further research should introduce complementary auditory and visual needle navigation feedback.

Author Statement

Research funding: This work was funded by the Federal Ministry of Education and Research within the Forschungscampus *STIMULATE* (grant no. 13GW0473A). Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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