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ORIGINAL ARTICLE

Augmented reality haptic (ARH): an approach of electromagnetic tracking in minimally invasive surgery

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Abstract
Purpose Minimally Invasive Surgery (MIS) is a widely used surgical technique that requires a long training process due to its difficulty and complexity. We developed an Augmented Reality Haptic (ARH) System based on electromagnetic tracking devices for use in creation training models (computer-enhanced trainers), in computer-assisted surgery or telemanipulation applications.
Method The ARH system consists currently in a Linux driver and a calibration protocol to acquire the tooltip position of conventional laparoscopic tools in real time. A Polhemus Isotrack® II was used to track surgical endoscopic tooltip movements. The receiver was mounted on the tool handle in order to measure laparoscopic tools positions without complex modifications. Two validation tests were done to guarantee the proper functioning of the ARH system in a MIS environment. The first one checks the driver operation and the second measures the accuracy and reliability of the tooltip pose estimation process.
Results Jitter and orientation errors for the first test were 2.00 ± 0.10 and 2.00 ± 0.09 mm, respectively. Relative position error of 0.25 ± 0.06 cm for a distance of 5 cm was found. Jitter error for the second test was 127 ± 60, 117 ± 40 and 122 ± 39 mm in *Z*, *Y* and *X* rotations, respectively.
Conclusions Results obtained with the ARH system are sufficiently accurate for use in MIS training. A supplementary correction procedure would be necessary to use this ARH system in computer-assisted surgery or telemanipulation.

Keywords Electromagnetic device tracking · Minimally invasive surgery · Surgical assessment · Computer-assisted surgery · Surgical training

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Introduction

Minimally Invasive Surgery (MIS) is a widely used surgical technique that has revolutionized the surgical practice for the last years because of its multiple safety advantages for patients. However, it comprises some complex procedural tasks which need specific training models and devices [1,2]. Surgical training devices are normally classified in three groups: (1) physical trainers which are usually called box-trainers or pelvic-trainers, (2) virtual reality simulators and (3) hybrid or computer-enhanced trainers.

Although some studies show similar results for different types of training devices [3,4], virtual reality training systems are not broadly accepted among surgeons [5–7]. Traditional box-trainers are widely used but do not offer any automatic assessment tools. Finally, hybrid systems or computer-enhanced technologies are more popular [8–10] because they are more similar to box-trainers. These computerized systems provide some objective measures to mentors in order to assess surgical skills of novel surgeons [11].

Tools tracking is one of the main information sources and several techniques can be used for this purpose: image processing-based [12–16], optical-based [17], mechanical-based [18] and magnetic-based [19–21] tracking.

As far as we know, magnetic tracking systems located on the tool handle have not been used before. Receivers located on the tooltip were used in [19,20]. This option is computationally easier than ours but adds a strange element inside the surgical field. Miniaturized magnetic tracking devices can also be used and they are inside the working shaft but they require non-reversible modifications on surgical tools to assembly them. Furthermore, these tiny sensors are usually more expensive. Other solutions are based on optical tracking sensors which present the inherent problem of occlusion. This problem can be solved with different techniques.

Although cost should not be an important point in this first phase, we have selected a relatively cheap device considering the requirements of a future commercial product.

In this paper, we present a new magnetic tracking system with different applications in MIS: training assessment, analysis of surgical gestures, assisted surgery or telemanipulation. The proposed system is simple, with an easy calibration method and less intrusive for surgeons. The final purpose of this study is focused on improving some aspects of surgical learning process: the use of objective metrics to assess surgical skills, the definition of learning curves [22] in different surgical procedures and doing learning curves as short as possible. In order to achieve this final aim, other devices and signal processing will be used to enhance the Augmented Reality Haptic (ARH) system for training in MIS.

Materials and methods

The Augmented Reality Haptic (ARH) System aims to calculate the exact position of the laparoscopic tooltip in real time meanwhile the surgeon accomplishes training tasks using current laparoscopic tools. In this section, we present a Polhemus Isotrack II® driver and a new calibration method in order to use this magnetic tracker in MIS.

Devices and equipments

An Intel Core 2 Quad CPU Q9300 processor with 3 Gb RAM was used to develop and test the ARH System. Two Isotrack II® receivers were placed on the handle of each laparoscopic tool and were carefully held on to prevent relative motions.

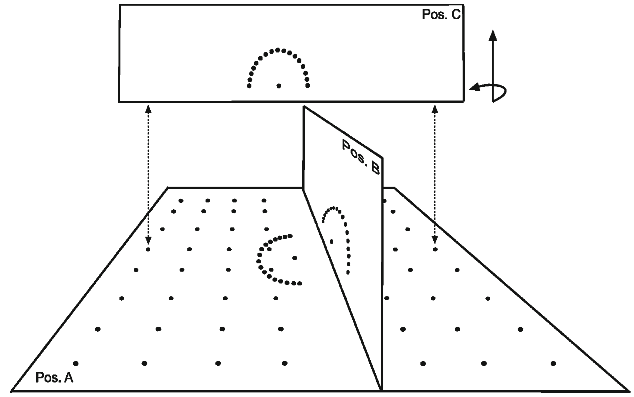

Fig. 1 The wood measurement plate is a modification of polycarbonate plate described in [2]. A new configurable additional plate with 16 holes hemispherically place (11.25° separation) was made in order to measure accuracy of ARH system over different rotation axis. The "calibration system" measure *Z* axis rotation (Pos. A), *X* axis rotation (Pos. B) and *Y* axis rotation (Pos. C)

The calibration protocols were performed in a non-metallic platform as shown in Fig. 1. All tests were carried out in laboratory conditions.

Driver programming

A linux driver was developed as the ARH system core. It was developed in C/C++ using a callback function, with the gcc 4.4.1 compiler and a 2.6.31 kernel version. RS-232 port communication was used to connect the Polhemus Isotrack® II and the computer.

The callback function allows non-polling communication with the polhemus library (polhemus.h).

Calibration protocol

The calibration protocol was designed to obtain the tooltip coordinates within the local coordinates system of the receiver (local tooltip) by means of a set of controlled movements. This is a necessary step before calculating the tooltip coordinates within the global coordinate system (global tooltip) centered in the transmitter. For this purpose, the laparoscopic tool was vertically placed and three positions of the receiver were recorded while rotating the tool on its working shaft. Considering the Second Tales Theorem and using these three points, the local tooltip is obtained. Figure 2 shows global and local coordinate systems of the ARH System. It is important to remark that the relative position of the tooltip with respect to the receiver placed on the handle never changes, i.e. local tooltip is always the same.

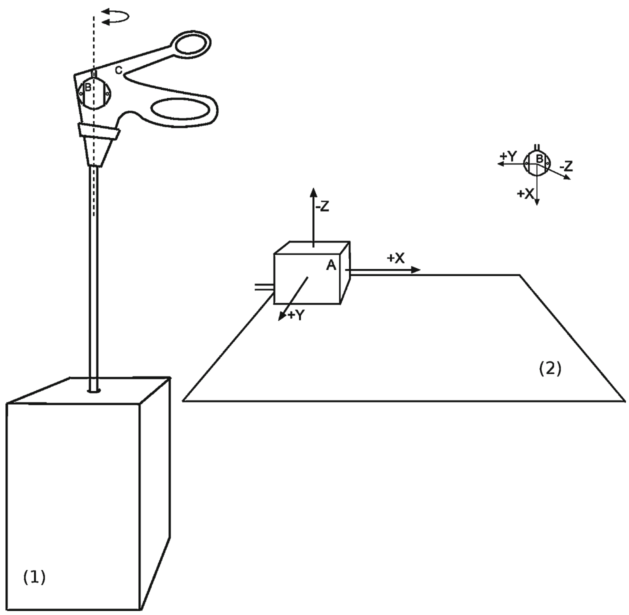

Fig. 2 (**1**) Polhemus Isotrack® receiver **B** was fixed to laparoscopic tool handle **C** in order to make possible a joint rotation. The magnetic receiver describes a spherical movement over the laparoscopic tool stick. (**2**) Global and local coordinate systems (transmitter and receiver, A and B respectively) are showed above

With all this information, the global tooltip can be calculated. The following transformation matrix was applied for coordinates transformation:

$$M = \begin{bmatrix} \cos(\beta)\cos(\alpha) & \cos(\beta)\sin(\alpha) & -\sin(\beta) \\ \sin(\gamma)\sin(\beta)\cos(\alpha) - \cos(\gamma)\sin(\alpha) & \sin(\gamma)\sin(\beta)\sin(\alpha) + \cos(\gamma)\cos(\alpha) & \sin(\gamma)\cos(\beta) \\ \cos(\gamma)\sin(\beta)\cos(\alpha) + \cos(\gamma)\sin(\alpha) & \cos(\gamma)\sin(\beta)\sin(\alpha) - \sin(\gamma)\cos(\alpha) & \cos(\gamma)\cos(\beta) \end{bmatrix} \quad (1)$$

where α, β and γ are azimuth, elevation and roll angles, respectively. Finally, the equation that transforms the local tooltip into the global tooltip is:

$$x = M^{-1} \cdot y + t \quad (2)$$

Where

x is the global tooltip
M^{-1} is the inverse matrix of M.
y is the local tooltip previously calculated
t is the current position of the receiver

M and t are continuously changing when moving the laparoscopic tool but y is constant as previously explained. Therefore, this equation transforms the receiver location to the global laparoscopic tooltip. The transpose matrix can be used instead of inverse because above matrix is orthonormal.

$$M^{-1} = M^t \quad (3)$$

Similar calibration methods were described as "stylus calibration" for other surgical fields such as ultrasonography [23,24].

Validation process

Ideal performance of magnetic trackers is not the goal of this study. Although the developed driver was checked with a first calibration test, this validation process is focused on different technical parameters of the developed system. According to Jannin and Korb [25], this validation corresponds with the first assessment level.

Two validation tests were designed: the first one checks whether the driver works properly and the second one demonstrates accuracy of the tooltip calculation method. The former has been depicted as "developed driver test" and the latter as "laparoscopic tool test".

Other works present specialized fixture for performance assessments [27,28]. A jig was used to measure position errors and a special fixative box was needed in order to work with laparoscopic tools. The validation process was focused on static error analysis.

Driver test

According to the specification of the manufacturer, the Isotrack II® system can offer in normal mode a static accuracy of 0.24 cm RMS for the X, Y and Z receiver position. On the other hand, it can offer 0.75° RMS for azimuth, elevation and roll receiver orientation angles. This first experiment assessed the correct work of the developed driver. A measurement plate similar to the one described by Hummel et al. [26] was used. The measurement plate had a set of 5 cm-spaced holes disposed in 8 rows and 7 columns. The parameters described by Hummel et al. [26] were used in our experiments: *jitter error* and *relative error*. Both errors were acquired with a sample frequency of 60 Hz and only one receiver was used in this test. The *jitter error* describes the deviation of the electromagnetic measurements at a defined position over a period of time. The *relative error* was calculated considering the measure errors obtained in all possible combinations of holes which are separated 5, 10, 15, 20, 25 and 30 cm.

Laparoscopic tool test

This experiment was focused on checking the calculation of the laparoscopic tooltip position using the transformation

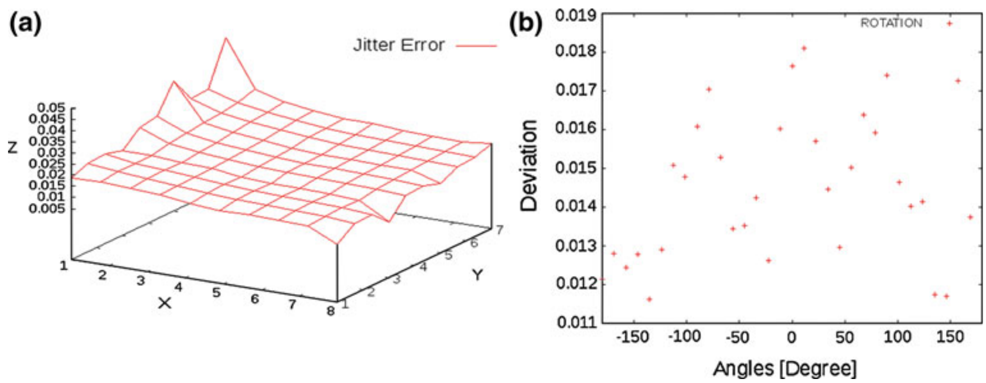

Fig. 3 **a** Position jitter error vs grid position. *X* and *Y* label position of the sensor on the measurement plate, *Z* indicates the resulting jitter in cm. **b** Deviation vs *Z* axis rotation angle

Table 1 Jitter error and standard deviation in mm

	1	2	3	4	5	6	7
1	1.87 ± 0.86	2.87 ± 1.46	2.02 ± 0.92	5.40 ± 2.87	4.03 ± 2.32	4.59 ± 2.67	4.85 ± 2.63
2	1.74 ± 0.80	2.01 ± 0.90	1.79 ± 0.79	1.99 ± 0.95	2.52 ± 1.22	3.16 ± 1.60	3.67 ± 2.14
3	1.66 ± 0.74	1.71 ± 0.74	1.77 ± 0.84	1.77 ± 0.80	1.90 ± 0.94	2.39 ± 1.16	2.66 ± 1.44
4	1.34 ± 0.78	1.29 ± 0.73	1.38 ± 0.79	1.59 ± 0.74	1.78 ± 0.90	2.17 ± 0.98	2.11 ± 1.00
5	1.13 ± 0.51	1.24 ± 0.67	1.31 ± 0.72	1.52 ± 0.76	1.64 ± 0.84	1.86 ± 0.84	2.23 ± 1.08
6	1.02 ± 0.35	1.03 ± 0.54	1.14 ± 0.67	1.39 ± 0.77	1.67 ± 0.81	1.89 ± 0.82	2.19 ± 1.04
7	1.03 ± 0.49	1.11 ± 0.49	1.08 ± 0.46	1.39 ± 0.65	1.64 ± 0.77	1.97 ± 0.88	1.92 ± 0.89
8	0.81 ± 0.32	0.81 ± 0.36	0.70 ± 0.46	1.27 ± 0.59	1.33 ± 0.64	1.61 ± 0.71	2.07 ± 1.04

Rows and columns show the *X* and *Y* labelled positions of the sensor on the measurement plate, respectively

matrix previously described. A special fixation box and a vertical measurement plate were developed in order to assess the accuracy and reliability of the ARH system. These two new calibration equipments were designed to be used together with the measurement plate used in the driver test.

The special fixation box allowed grasping the laparoscopic tool in a set of specific orientations and positions. It kept the tooltip in the same point all the time. The vertical measurement plate had a set of 16 holes which are placed in a 9 cm-radius semisphere and separated 11.25°. This vertical plate can be placed parallel to XZ and YZ planes.

Values in the three different rotation axes *X*, *Y* and *Z* were taken in order to calculate the *jitter error*. Values in the *Z* axis were taken just placing the fixation box on the measurement plate (Fig. 1. Position A). For values in the *X* and *Y* axis, the fixation box was placed on the vertical measurement plate (Fig. 1. Positions B and C).

Results

Developed driver test

As a result of the first experiment test, a jitter error was obtained for each one of the 56 holes. Figure 3a and Table 1 show E_{rms} and deviation as function of sensor position on the measurement plate. *X* and *Y* indicate the position of the hole on the measurement plate and *Z* indicates the jitter error value. These values were more stable in the central area of the measurement plate, but they had some peak values in the external holes. Considering all the values, a mean jitter error E_{rms} of 2.00 ± 0.10 mm was obtained. Figure 3b shows E_{rms} and deviation as a function of *Z* axis rotation. The mean orientation jitter error was 2.00 ± 0.09 mm. The driver jitter errors are similar to the ones obtained by Hummel et al. [26].

Results for the relative error are shown in Table 2. For each distance, all possible combinations of holes in the measurement plate which are separated that length have been considered. The values of the relative error increase with the separation of the holes.

Laparoscopic tool test

Jitter error was measured for each one of the 16 holes semi-spherically placed both in the measurement plate and the vertical measurement plate. Table 3 shows the jitter error for some of the defined angles in each one of the rotation axes. The largest errors were obtained for −90° in *Z* rotations and −180 in *X* and *Y* rotations. These values can be related to the electromagnetic receiver position within the system working

Table 2 Relative position error in cm

Distance (cm)	Mean	SD	Minimum	Maximum
5	0.25	0.06	−0.04	0.24
10	0.34	0.07	−0.03	0.29
15	0.39	0.08	−0.04	0.34
20	0.45	0.10	0.01	0.39
25	0.51	0.11	0.07	0.47
30	0.56	0.11	0.14	0.50

Table 3 Jitter error E_{rms} in mm

Rotation angle	*Z* rotations	*Y* rotations	*X* rotations
0°	154.52 ± 1.15	198.56 ± 2.43	164.82 ± 1.17
−45°	159.10 ± 1.50	95.12 ± 2.67	103.43 ± 1.54
−90°	305.54 ± 1.81	138.33 ± 1.36	121.08 ± 2.47
−135°	134.86 ± 2.81	198.97 ± 2.07	203.01 ± 2.26
−180°	100.65 ± 1.84	231.54 ± 3.15	247.99 ± 2.17
Total	127 ± 60	117 ± 40	122 ± 39

area (see error of the system in Fig. 3a). If the receiver has a higher electromagnetic error, this value can be propagated in the calculations to obtain the tooltip position.

Mean jitter error E_{rms} was 127.38 ± 59.97 mm in *Z* rotation axis; 117.43 ± 40.39 mm in *Y* rotation axis and 122.03 ± 39.37 mm in *X* rotation axis.

Discussion

This study presents an Augmented Reality Haptic (ARH) system that enhances conventional laparoscopic tools. As the tooltip is calculated in real time, the ARH system can maintain the interactivity and realism of the physical box-trainers meanwhile including the advantages of virtual reality simulators: an objective assessment and customization of training. Our main objective has been developing and assessing a module for a hybrid trainer but the ARH system could be used in other applications such as ergonomics and surgical gestures analysis, computer-assisted surgery or telemanipulation.

Results show that the linux driver works properly [26] and the calibration protocol achieves an approximate tooltip position. Hummel et al. define an assessment protocol for electromagnetic tracking systems in [26]. Comparing their results with the ones obtained with this proposed method, it can be said the linux driver works properly and that the tooltip position can be approximated by using the calibration protocol.

Measure surgical dexterity is an important assessment task in the surgical training process as Young et al. [11] or Xeroulis et al. [29] state. Therefore, a useful objective method for evaluating surgical skills would be provided by using the ARH system within a training curricula. Although interesting results can be found in [29–31] where an Isotrack II device is used in different surgical procedures, the ARH system could achieve better results in the assessment of laparoscopic procedures since it directly measure the movements of the surgical tools instead of hand motion.

Grober et al. [32] validate hand motion analysis (HMA) as an objective measure of surgical skill on real patients. With the ARH system, this analysis could be changed into a tooltip motion analysis (TMA) which would provide further information of the behavior of the instrumental inside the surgical field. Metrics such as average and peak speed or acceleration could be calculated and used to assess the gentleness of surgeons.

Metrics used by ProMIS [11] in processing the physical data in educational settings are path length, economy of movements and total time. The ICSAD device measures number of movements and speed [33] but the sensor is placed on the back of the hand and do not assess the tooltip motion. Other simulator (LTS3e) uses the validated McGill Metrics [4]. These objective values are used by all of them in order to make the training curricula [34] of the trainee. Path length, total time, number of movements and speed could also be obtained with the ARH system and will be included in future works.

As far as we know, motion analysis focused on the rotation of the laparoscopic tooltip has never been studied. Placing the sensor on the handle could detect just the tooltip rotation. This new metric could be used to assess ergonomic criterion as well as to compare different surgical procedures.

Some authors [5–7] states that surgeons prefer box-trainers and hybrid simulators rather than virtual simulators because lack of realism of the latter. Therefore, Virtual reality simulators focus great efforts on improving collision detection and response [35–37]. Considering that the ARH system is based on a physical simulator, it can provide good interactivity and realism because collisions between surgical tools and between tool and elements inside the simulator are real. This fact would reduce complexity of collision detection modules in hybrid simulators. Nevertheless, the ARH system needs to be improved in future to detect the opening and closing of the tip of the surgical tool. Thanks to this added value, the ARH system could be a different option to current virtual reality haptics.

Feng et al. [19] and Diaz et al. [20] have already used electromagnetic receivers for tracking in a surgical field. The sensors were placed on the tip of surgical tools limiting its use only in training systems. Our assembly of the ARH system allows the transfer to the operating room because it does not add foreign items in the surgical field as the sensors are placed on the handle. Placing the sensor in this area should not disturb surgeons as it is out of the surgical field and surgical tools are not usually introduced until the handle. This affirmation has to be confirmed with a face validity questionnaire which is included in further studies.

The price of training systems is normally an important factor in order to achieve quality training for surgeons [38] around the world. For this reason, the Isotrack II electromagnetic tracking device was selected in the ARH system design. This kind of devices is usually between three and five times cheaper than optical systems and miniaturized electromagnetic systems. Optical tracking markers or rigid bodies need to be attached to the tools and may undergo occlusions with the surgeon's movements. Moreover, the assembly of miniature electromagnetic sensors need to remove the surgical tool, made adjustments in the tool parts and finally re-assembled the tool [39]. The ARH system presents a simple and relative inexpensive solution that can be used in the training phase and also used in real procedures in the OR.

Conclusions

The Augmented Reality Haptic (ARH) system has some advantages over other tracking-systems tools such as simplicity of construction, lower-cost system (compared to optical or miniature magnetic systems) and more accuracy and higher frequency than image processing techniques. As other hybrid systems, the ARH combines the best of the physical simulators: interactivity and realism; with the best of virtual simulators: objective assessment and customized training.

The ARH system is an important part of a computer-enhanced training system which will be composed by the EDEST® electronic device [40], an image processing module and the ARH system.

The obtained results are accurate enough considering similar works [26] and could be used in training models. Some correction techniques would be necessary in future works to use this ARH system in computer-assisted surgery or telemanipulation.

Detection of the opening and closing of the tooltip is one of the necessary improvements that the image processing module would add. Image processing systems could be good solutions in the future but they cannot provide the same exactitude and frequency as magnetic and optical tracking.

Additional experiments to obtain a construct and face validity will be carried out. A group of experiment and novice surgeons should perform basic laparoscopic tasks. The subjects will be grouped depending on their skill level and they will use surgical instruments equipped with the ARH device.

Once the training value is provided, the ARH system could be used in the operating room in order to classify surgical procedures. Objective criteria could be used to compare the advantages and drawbacks of different surgical procedures.

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