# Spatial and Temporal Registration of Asynchronous Multi-Sensors for Minimally Invasive Surgery Application

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***Abstract*— Current Minimally Invasive Surgery (MIS) technology, although advantageous compared to open cavity surgery in many aspects, has limitations that prevent its use for general purpose MIS. This is due to reduced dexterity, cost, and required complex training of the currently practiced technology. The main challenge in reducing the cost and amount of training is to have an accurate inner body navigation advisory system. As a first step in making minimally invasive surgery affordable and more user-friendly, quality images inside the patient as well as the surgical tool location should be provided automatically and accurately in real-time. The second step will be to provide the surgeon with an inner body Global Positioning System (GPS) like an advisory navigation system. This paper focuses on the first step: providing real-time information needed by the surgeon. This consists of real-time temporal and spatial calibration of heterogeneous asynchronous sensors that provide enough information needed to safely carry out MIS. The real-time asynchronous sensors registration algorithm has been successfully tested in the lab using a mannequin. The experimental temporal and spatial registration showed promising success for real-time tracking of the surgical tool as well as real-time display of the 2D information provided by the videoscope.**

***Keywords-Sensors registration, Spatio-temporal calibration, Computer-assisted surgery, Multisensor System.***

## I. INTRODUCTION

MIS has distinct merits of faster recovery, shorter hospital stays, less pain, and decreased scarring. However, restricted visualization of the operative site, minimal accessibility, and reduced dexterity has increased the challenges of its implementation. Image Guided Surgery (IGS) during MIS will help solve such problems and improve safety and accuracy to a significant level [1]. Da Vinci surgical robot is the first surgical robot approved by FDA for commercial use in hospitals. This sophisticated high-end system has high procurement cost, and specialized training requirements for the surgeon [2].

Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) provide high quality preoperative images of the inside of the patient body. Once the surgery starts, preoperative images can no longer be relied on because the intraoperative environment changes continuously due to manipulation by surgeon or organ movement. Therefore, the surgeon needs to rely on inner body real time images. An Inner Body GPS (IGPS) is also needed to safely and accurately help the surgeon guide the surgical tool to its desired surgery location. The IGPS requires pre-operative CT/MRI, real-time image from videoscope, and navigation sensor(s). The navigation sensors locate the position of the surgical tool, and the videoscope helps the surgeon maneuver around body organs along the path predetermined using preoperative CT/MRI images. Since the videoscope and navigation sensors are heterogeneous, they have different data rate, and provide measurement/information in their local coordinate frame using their local time clock. Spatial and temporal registrations of such sensors are needed as a prerequisite to the success of MIS. The spatial registration represents the spatial coordinates of all the sensors in an absolute coordinate frame while the temporal registration represents all the sensors data in a common time reference.

Hybrid spatial calibration uses fusion of spatial information from more than one sensor to assist the surgeon during MIS operation. While implementing two heterogeneous sensors, researchers leveraged fused information from intraoperative images (Laparoscopic Ultrasound (LUS)/Endoscope) and either preoperative images (CT/MRI) [3] or navigation system (Electromagnetic Tracking System (EMTS)/Optical Tracking System (OTS)) coordinates [4] - [6], [10]. The information gathered from two sensors is not enough for MIS. Preoperative images are the only reference imaging technique to visualize the complete patient body. Surgeon always needs to have a visualization of where he/she is heading inside the patient body along with the position and orientation of the endoscope. On the other hand, it is necessary to have a navigation system connected to intraoperative imaging system to guide the endoscope in CT/MRI coordinate reference frame.

From an information point of view, MIS requires at least three heterogeneous sensors: Two for imaging (pre-operative and intra-operative) and one for navigation. Fakhfakh et. al. proposed an automatic registration of pre- and intra-operative images with OTS embedded ultrasound probe, and preoperative CT scan [7]. The reconstructed 3D image from 2D ultrasound slices was registered with the preoperative CT using principle axes of inertia and the Iterative Closest Point robust (ICPr) algorithm. ICP suffers from being trapped in local minima unless a good initial guess is provided. The use of Hand-Eye calibration for rigid registration among robotic arm, tracking devices (EMTS/OTS), and imaging devices (Endoscope/Laparoscopic camera) was reported in [6], [8]. Reference [8] implemented network time protocol (NTP) for

 ISBN: 978-1-68558-017-9 

temporal data synchronization. In order to calculate the optimum spatial and temporal transformation, [9]-[11] integrated LUS, rigid oblique viewing endoscope, OTS, EMTS, and MRI using linear least square and Levenberg-Marquardt iterative algorithm. Since the whole distortion correction from the metallic objects in EMTS was based on OTS, the magnetic distortion correction mechanism may provide false correction vector when the line of sight (LOS) for OTS is blocked [11]. Furthermore, the system was modeled for static distortion [10], [11]. Hence, the correction vector would be redundant if the distortion in the vicinity changes during surgery. Intraoperative imaging with LUS suffers from shadowing, multiple reflections, low signal-to-noise ratio, and the requirement of expertise and training of surgeon [12]. For temporal calibration, it is assumed that the tracker with higher measurement rate has acquisition frequency multiple of lower one and the data is processed at the measurement speed of slower tracking device. Although, [6], [7], [13] used multiple asynchronous sensors, synchronization of data from such sensors has been overlooked. This inhibits the correct and effective use of asynchronous sensors in high accuracy demanding MIS system in real-time.

In addition to MIS, the use of heterogeneous sensors is desirable in different areas including robotics and automation where additional data complement and enhance the available information and assist to make more informed decisions. Such sensor systems may involve different imaging and navigation sensors such as cameras, Inertial Measurement Units (IMUs), LIDAR for robotic navigation, and object detection and tracking [14] - [16]. However heterogeneous sensors may use different data acquisition systems and may have a different data acquisition rate and use a dedicated local processor clock when reporting the measurements. A prerequisite for correct sensor fusion is the temporal alignment of different sensor data such that the data provided by the different asynchronous sensors are recorded using the same time reference.

The main contribution of this paper is providing a real-time spatial and temporal registrations of heterogeneous asynchronous sensors in an absolute spatial coordinate frame and a common time reference. The process will be called spatiotemporal registration. Performing temporal sensor registration is crucial given the dynamic changes of the surgery path to account for body organs movements in order to navigate safely toward the surgery location. In prior work, the authors performed offline spatial calibration between Laser Range Scanner (LRS), EMTS, and Camera with promising accuracy [17], [18]. LRS was used to emulate CT/MRI images. LRS-EMTS calibration was performed using Horn's absolute orientation method [19], while the camera calibration was achieved using normalized Direct Linear Transform (DLT) algorithm [20]. These registrations are crucial for real time path planning.

This paper is organized as follows. Section II discusses the proposed real-time spatial and temporal heterogeneous and asynchronous sensors registration. Section III discusses the accuracy obtained using experiments conducted in the lab. Section IV contains conclusions and discusses future work.

## II. Proposed Spatial and Temporal Calibration

The preoperative CT/MRI provides 3D images of the patient to determine the inner body 3D location where the surgery is to take place (desired destination). The preoperative images can also be used for 3D path planning to reach the desired destination using the shortest path that has minimal number of obstacles such as bones or body organs. In this work, LRS [21] provides preoperative 3D scan , the videoscope provides real time high quality images, and the EMTS provides pose (position and orientation)of the surgical tool/videoscope inside the human body as shown in Figure 1. The navigation sensor used was NDI Type-2 6DOF sensor for Aurora EMTS with a measurement frequency of 40Hz [22]. According to NDI, the accuracy is 0.8 mm for position and 0.7degree for orientation [22]. The EMTS has been thoroughly tested and it has been found that 300 series stainless steel, aluminum, and titanium does not affect EMTS performance [12]. The third sensor was the Go 5000C series color camera from JAI Corporation [23], with 5 amegapixel resolution and an image acquisition rate of 61.2 frames/sec.

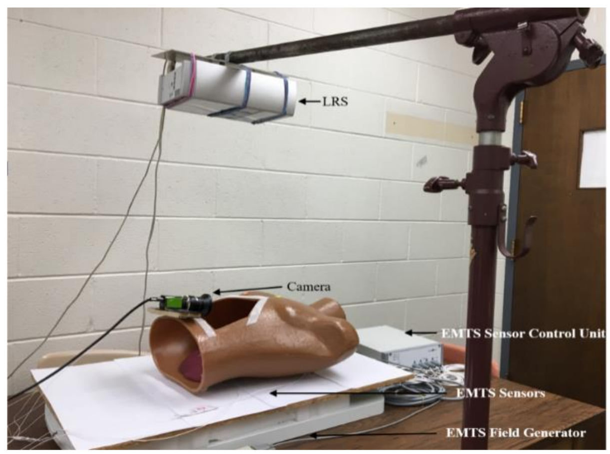


Figure 1. Heterogeneous Asynchronous Sensors Used for Inner Body Navigation

In this paper, the LRS coordinate frame was selected as the absolute coordinate reference frame so that spatial information from camera and EMTS can be transformed and analyzed in LRS coordinate system, as shown in Figure 1. The location of the videoscope in EMTS coordinate reference frame can be determined using the camera registration procedure [20]. The real time position of the camera, planned path, and the desired inner body destination location are represented in the LRS coordinate reference frame. The surgical tool can be moved to the destination correctly using real time feedback from the EMTS attached to the camera. It is worth noting that in clinical applications, a much smaller camera will be used instead of the Go 5000C. However, the proposed sensors registration technique can be applied to accommodate any camera. All information that is needed is their intrinsic and extrinsic parameters. While conducting the experiments it is assumed that the EMTS pose measurement was not interfered with by metallic objects in the room, camera system, or mount for the LRS system. It is also assumed that the relative position of the camera, EMTS, and LRS system was not changed during offline calibration.

### A. *Online Spatial Registration*

The fusion of real-time information from LRS, Camera, and EMTS should be able to guide the surgeon from the initial insertion point to the destination point inside human body. This was achieved by using the online sensors registration. In the spatial registration, all the spatial sensors data was represented in the LRS (CT/MRI) coordinate reference frame. In the temporal registration, incoming data was timestamped based on arrival time to the surgical PC processor. We developed a virtual camera model which replicates the position and orientation of the real camera in LRS coordinate frame and provides real-time image inside human body.

Online spatial calibration accommodates the changes in registration parameters once the sensors start to move. Changing transformations between EMTS and camera coordinate frame can be computed by attaching an Electromagnetic Sensor (EMS) to the videoscope body, and calculation of fixed offset transformation parameters between EMS measurement and the camera center obtained from the camera calibration, as shown in Figure 2. Offline camera calibration provides the position and orientation of the camera in EMTS coordinate frame. The offset transformation between the computed camera center in EMTS coordinate frame and the EMTS sensor can be computed as

$$T_{offset} = T_{calibration} * \left( {}^{CAM}T_{EMTS} \right)^{-1} \quad (1)$$

where, $T_{offset}$ is the Offset transformation between EMS and camera frames, $T_{calibration}$ is the Position and Orientation of Camera obtained from Camera Calibration[27] and ${}^{CAM}T_{EMTS}$ is the transformation from the EMTS coordinate frame to the camera coordinate frame. The transformation between LRS and camera coordinate frames uses the transformation form the EMTS to LRS frames and is given by

$${}^{LRS}T_{cam} = {}^{LRS}T_{EMTS} * T_{offset} \quad (2)$$

Where, ${}^{LRS}T_{cam}$ is the Transformation from camera to LRS coordinate frame; ${}^{LRS}T_{EMTS}$ is the Transformation from EMTS to LRS coordinate frame; $T_{offset}$ is the Offset transformation of the camera center to the EMTS coordinate frame.

The guidance system consists of two separate display units inside single screen, as shown in Figure3. First display unit consists of plot of 3D LRS data, preoperative planned path, current path followed by real-time camera, and position and orientation of camera. Second unit displays real-time video feed from camera. First, 3D LRS data is displayed along with the preoperative planned path, start and destination point, as shown in Figure 3. Before real time processing, the command asks user to put camera at the specified start location of the preplanned path. The user is

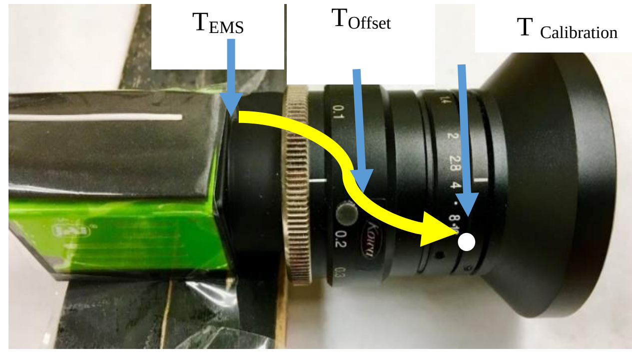


Figure. 2: Offset between EMS and Camera Center

guided in real-time to follow the preplanned path without exceeding the user specified threshold deviation from the planned path. If an obstacle appears in real-time in the preplanned path, the surgeon can use their intelligence to avoid the real-time obstacle. During avoidance of obstacle, it is evident that the path followed by real-time camera may deviate from preplanned path. In such case, the system is

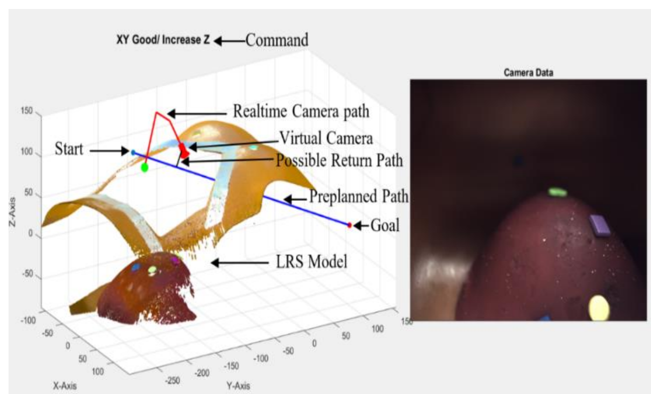


Figure 3: Developed real-time guidance system.

designed in such a way that the processor searches for a shortest path for the camera to return to the original path. The point within the preoperative planned path having minimum distance from current camera location is called immediate goal for camera. The command system guides the user to take the necessary steps to reach the immediate goal. This provides infrastructure that can be used by surgeon such that the path can be automatically followed in real-time.

One of the major challenges in implementation of minimally invasive surgery is to reach to the destination inside human body by minimally damaging the organs along the path. Previously we have designed an intrinsically actuated flexible robotic arm to be used for MIS [24]. To use flexible manipulators, one requires accompanying shortest path with minimum obstacle to reach to the destination. In addition to avoiding the obstacle, the planned path should be enough to accommodate the width of the manipulator. In this work, assuming the availability of preoperative planned path, we developed a semi-automatic system to guide surgeon in real time to reach to the destination inside human body. The preplanned path and the possible return path are just the straight line connecting start and goal position in LRS coordinate frame. Rapidly Exploring Random Tree(RRT), RRT*, Probabilistic Roadmap(PRM), A* [25] are widely used sampling based path planning algorithms that can be implemented for path planning

### B. *Temporal Calibration*

Temporal Calibration is necessary for time synchronization of real-time data obtained from the camera and EMTS. EMTS and camera use different clock and report measurements at a rate of 40Hz and 61.2 Hz, respectively. A prerequisite for time synchronization of measurement is to timestamp the measurement with respect to the clock of a common processor clock. In this application, the common processor clock is the clock of the computer, called here surgical PC, that is used by the surgeon to display the real time camera images and the location of the surgical tool(s) as shown in Figure 4. The PC processor is responsible for controlling, communicating, acquiring, and time stamping of the data from the camera and EMTS in real-time. Hence, instead of processing data with reference to the clocks of sensors themselves, they are processed on the basis of their arrival in the host PC. As soon as data arrive from EMTS and camera, they are timestamped and placed in a circular buffer. With the implementation of the circular buffer, the oldest measurement from the devices are overwritten by the most recently arrived data. This effectively solves the problem of memory leakage during real-time operation. The timestamped data are polled every 30 milliseconds. Polling measurement at every 30 milliseconds provide enough time for data processing without loss of information, as shown in Figure 4.

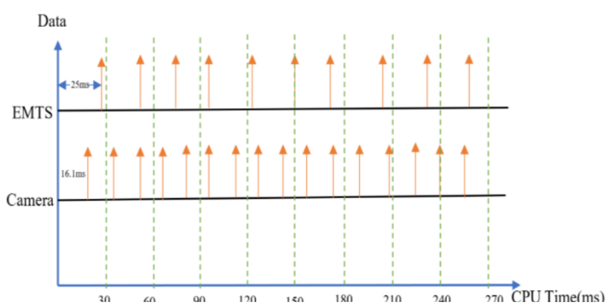


Figure 4: Polling of Timestamped Data in PC

## III. PERFORMANCE EVALUATION

The performance of the proposed sensor fusion system was evaluated in two-fold. First, the information from the 3D LRS was transformed into the EMTS coordinate frame followed by transformation to the camera coordinate frame. The transformation error was computed as an absolute difference between the computed coordinates obtained from the transformation and those extracted from the processed camera images. The sensors calibration and the accuracy evaluation were performed in an environment free of ferromagnetic material near the EM field generator. Tracking in the electromagnetic field generator is unaffected by the medical-grade stainless steel (300 series), titanium, and aluminum [12], [22]. The tabletop field generator also minimizes distortions produced from the patient table or materials located below it [22]. The artificial liver was placed inside the mannequin and attached with different colored objects on the top surface, as shown in Figure 5. The colored objects representing the liver tumor were used for accuracy evaluation.

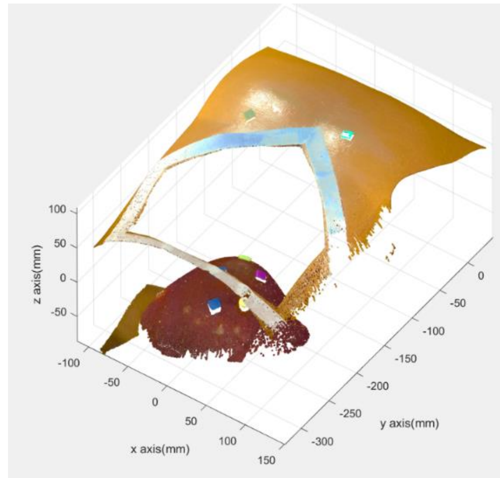


Figure 5: Setup for accuracy evaluation for spatio-temporal calibration system

Given the start and goal position in LRS coordinate frame, the videoscope was navigated to reach to the destination points, Section II. For accuracy evaluation purpose, the destination points are the colored objects attached to the liver. Once the camera reaches to the vicinity of the accuracy evaluation points. The colored objects were extracted, and their centroids were calculated in LRS (see Figure 6), EMTS, and Camera coordinate frames.

The extracted centroids were first transformed from LRS to EMTS coordinate frame. Once the set of points were transformed from LRS to EMTS they were projected to distortion corrected camera image.

$$P_{cam} = {}^{cam}T_{LRS} P_{LRS}$$
$${}^{cam}T_{LRS} = \left({}^{LRS}T_{cam}\right)^{-1} = \left({}^{LRS}T_{EMTS} * T_{offset} * X_{EMS}\right)^{-1} \quad (3)$$

where, $P_{LRS}$ is the accuracy evaluation point in LRS coordinate frame and $P_{cam}$ is the projected accuracy evaluation point in camera coordinate frame.

As the transformation of the centroids were carried out in two phases, accuracy was also evaluated for LRS to EMTS coordinate transformation, and EMTS to camera transformation. The experiment was performed at least 12inch from the top surface of EMTS field generator to provide the room for placement of patient table.

TABLE I. ERROR ANALYSIS OF ONLINE CALIBRATION FROM LRS TO EMTS TO 2D IMAGE

| | **LRS to EMTS** | | | **EMTS to Image** | |
|---|---|---|---|---|---|
| | ***X*** | ***Y*** | ***Z*** | ***X*** | ***Y*** |
| **Mean(mm)** | 1.6315 | 3.0157 | 1.9214 | 0.4154 | 0.1845 |

| | | | | | |
|---|---|---|---|---|---|
| **S. D.(mm)** | 0.8765 | 1.5239 | 0.8912 | 0.1435 | 0.0656 |
| **Range(mm)** | 4.9123 | 5.1455 | 4.3190 | 0.2675 | 0.1265 |

Table I summarizes the absolute positional error for the coordinate transformation from LRS to EMTS as well as EMTS to camera coordinate frame. Similar to our observation in offline calibration, the average error for LRS to EMTS coordinate transformation is minimum along the X, and Z axis while the Y coordinate is most affected by error with maximum standard deviation and range. There are two possible reasons for the error: the varying ability of LRS to correctly scan and replicate the scanned object at varying distance, and the error during data collection because of the non-planar surface of the liver. Previously it has been found that the performance accuracy of LRS significantly improved while scanning planner objects compared to non-planar objects [17]. The experimental error could further be minimized by taking multi-view scans from the LRS and fusing the 3D scans data together. The transformation parameters between EMTS and LRS is constant during the online and offline calibration. The evaluated accuracy for online calibration closely resembles to the offline calibration accuracy of 1.35±0.93mm, 2.60±1.52mm, 1.1325±0.9285mm along x, y, and z axis respectively.

The transformation from EMTS to camera is the overall error associated with the hybrid tracking system. Although the error is in millimeter range, the is mainly due to the propagation of error associated with LRS to EMTS transformation, offset calculation, and EMTS to camera transformation. Compared to the offline calibration with the average error of 0.1081mm and 0.0872mm along x and y axis, the calibration error increased noticeably along both x and y direction. This might be because of the additional error introduced during offset calculation, and the motion of the camera-EMTS system.

## IV. CONCLUSION

In this work, spatio-temporal registration of three heterogeneous sensors to assist minimally invasive surgical applications was proposed. Laboratory testing showed that data fusion from three heterogenous and asynchronous sensors provide enough information to help the surgeon navigate to the surgery location by providing real-time surgical tool position and displaying quality images of the inner body. Accuracy evaluation using a mannequin and an artificial liver sample points localization showed promising accuracy for designing an inner body navigation system (IBNS). A low-cost camera was used to prove the concept. The spatial and temporal registration can be extended to any arbitrarily small size camera as long as the camera intrinsic and extrinsic parameters are provided.

Currently, the real-time display consists of two display units: one for 3D scan and another for 2D images. Future efforts include the development of an augmented reality system to display an augmented view of human organs on the top of 3D scan for real-time simplified navigation. Furthermore, the outcome of this research will be used as a foundation to develop a comprehensive inner-body navigation advisory system.

## REFERENCES


[1] T. Peters and K. Cleary, *Image-guided interventions: technology and applications*. Springer Science & Business Media, 2008.

[2] G. Aston, "Surgical robots: worth the investment?" *Hospitals & Health Networks*, vol. 86, no. 4, pp. 38–40, 2012.

[3] B. Marami, S. Sirouspour, A. Fenster, and D. W. Capson, "Dynamic tracking of a deformable tissue based on 3d-2d mr-us image registration," in *Medical Imaging 2014: Image-Guided Procedures, Robotic Interventions, and Modeling*, vol. 9036. SPIE, 2014, pp. 214–220.

[4] D. Sindram, I. H. McKillop, J. B. Martinie, and D. A. Iannitti, "Novel 3d laparoscopic magnetic ultrasound image guidance for lesion targeting," *Hpb*, vol. 12, no. 10, pp. 709–716, 2010.

[5] C. S. Ng, S. C. Yu, R. W. Lau, and A. P. Yim, "Hybrid dynact-guided electromagnetic navigational bronchoscopic biopsy," *European Journal of Cardio-Thoracic Surgery*, vol. 49, no. suppl 1, pp. i87–i88, 2016.

[6] C. Wengert, L. Bossard, A. Haberling, C. Baur, G. Székely, and P. C. Cattin, "Endoscopic navigation for minimally invasive suturing," in *International Conference on Medical Image Computing and ComputerAssisted Intervention*. Springer, 2007, pp. 620–627.

[7] H. E. Fakhfakh, G. Llort-Pujol, C. Hamitouche, and E. Stindel, "Automatic registration of pre-and intraoperative data for long bones in minimally invasive surgery," in *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, 2014, pp. 5575–5578.

[8] M. Feuerstein, T. Reichl, J. Vogel, J. Traub, and N. Navab, "Magnetooptical tracking of flexible laparoscopic ultrasound: model-based online detection and correction of magnetic tracking errors," *IEEE Transactions on Medical Imaging*, vol. 28, no. 6, pp. 951–967, 2009.

[9] M. Nakamoto, K. Nakada, Y. Sato, K. Konishi, M. Hashizume, and S. Tamura, "Intraoperative magnetic tracker calibration using a magnetooptic hybrid tracker for 3-d ultrasound-based navigation in laparoscopic surgery," *IEEE transactions on medical imaging*, vol. 27, no. 2, pp. 255–270, 2008.

[10] K. Konishi *et al.*, "A real-time navigation system for laparoscopic surgery based on three-dimensional ultrasound using magneto-optic hybrid tracking configuration," *International Journal of Computer Assisted Radiology and Surgery*, vol. 2, no. 1, pp. 1–10, 2007.

[11] K. Nakada, M. Nakamoto, Y. Sato, K. Konishi, M. Hashizume, and S. Tamura, "A rapid method for magnetic tracker calibration using a magneto-optic hybrid tracker," in *International Conference on Medical Image Computing and Computer-Assisted Intervention*. Springer, 2003, pp. 285–293.

[12] W. Birkfellner, J. Hummel, E. Wilson, and K. Cleary, "Tracking devices," in *Image-guided interventions*. Springer, 2008, pp. 23–44.

[13] R. S. J. Estépar, N. Stylopoulos, R. Ellis, E. Samset, C.-F. Westin, C. Thompson, and K. Vosburgh, "Towards scarless surgery: an endoscopic ultrasound navigation system for transgastric access procedures," *Computer aided surgery*, vol. 12, no. 6, pp. 311–324, 2007.

[14] E. Mair, M. Fleps, M. Suppa, and D. Burschka, "Spatio-temporal initialization for imu to camera registration," in *2011 IEEE International Conference on Robotics and Biomimetics*. IEEE, 2011, pp. 557–564.

[15] M. Liang, B. Yang, S. Wang, and R. Urtasun, "Deep continuous fusion for multi-sensor 3d object detection," in

*Proceedings of the European conference on computer vision (ECCV)*, 2018, pp. 641–656.

[16] J. Marr and J. Kelly, "Unified spatiotemporal calibration of monocular cameras and planar lidars," in *International Symposium on Experimental Robotics*. Springer, 2018, pp. 781–790.

[17] D. E. Ruehling, "Development and testing of a hybrid medical tracking system for surgical use," Ph.D. dissertation, Tennessee Technological University, 2015.

[18] U. Bhattarai and A. T. Alouani, "Hybrid navigation information system for minimally invasive surgery: Offline sensors registration," in *Science and Information Conference*. Springer, 2019, pp. 205–219.

[19] B. K. Horn, "Closed-form solution of absolute orientation using unit quaternions," *Josa a*, vol. 4, no. 4, pp. 629–642, 1987.

[20] R. Hartley and A. Zisserman, Multiple View Geometry in Computer Vision. 2003.

[21] Next Engine Inc., "Next engine 3d laser scanner." Available at http:// http://www.nextengine.com/products/scanner/specs (2022/06/21).

[22] Northern Digital Inc., "Aurora,"Available at http:// https://www.ndigital.com/electromagnetic-tracking-technology/aurora/ (2022/06/21).

[23] Jai Inc., "Go series go-5000c-usb compact 5 mp area scan camera," Available at http:// https://www.jai.com/products/go-5000c-usb (2022/06/21).

[24] U. Bhattarai and A. T. Alouani, "Flexible semi-automatic arm design for minimally invasive surgery," in *2017 25th International Conference on Systems Engineering (ICSEng)*. IEEE, 2017, pp. 207–211.

[25] K. Karur, N. Sharma, C. Dharmatti, and J. E. Siegel, "A survey of path planning algorithms for mobile robots," *Vehicles*, vol. 3, no. 3, pp. 448– 468, 2021.