A Review of Augmented Reality in Robotic Surgeries

Zhang Yedi

1 Introduction

1.1 Background

Surgical robot, represented by da Vinci, is developing rapidly in the last decade. Compared with conventional open surgery, robotic surgery has many distinguishing advantages, such as improving the accuracy, conforming to the ergonomics and so on. However, because doctors perform operations indirectly in robotic surgeries, robotic surgery also suffers from a lack of intuitive depth perception and tactile perception. At the same time, augmented reality is becoming a maturer technology. Hence, applying AR into robotic surgeries renders possible solutions to further improve robotic surgeries. In specific, AR can provide surgeons with helpful information (3D model, instruments, annotations, etc.) superimposed on the operator's view.

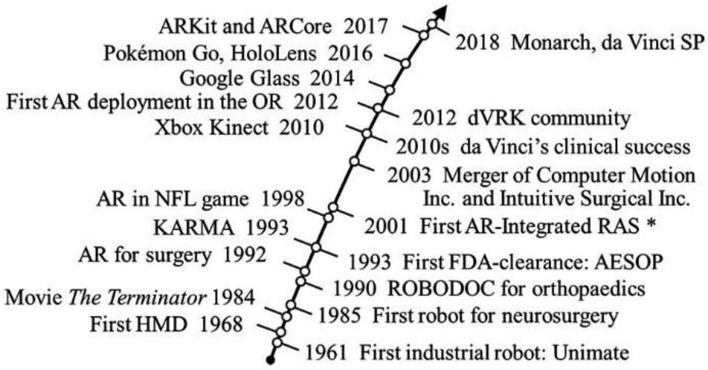

Fig.1 Timeline of the commercialization of AR and robotic surgeries [1]

The picture [1] shown above presents the timeline marking each milestone during the commercialization of AR and robotic surgeries.

1.2 Purpose

This work is done to investigate the developments concerning AR in robotic surgeries in the last 5 years. The main focus is to understand the diversity and generality of application paradigms. In addition, we are also interested in the research that gives better algorithms to improve the AR rendering.

1.3 Our work

48 research articles and 6 review articles are gathered and read. While reading, I record the research articles by filling in an Excel table. The table consists of 4 sections, being basic *information*, *overview*, *methodology*, and *evaluation*; in and these 4 parts include 17 separate items. After that, referring to my records and review articles, a flow chart and a mindmap is made to summarize the recent research.

2 Methods

2.1 Searching method

The collected articles are obtained from two sources. The first is the references in a review article[1]. The second is the searching results in *Web of Science*. The search entry terms are (augmented reality OR mixed reality) AND (medical robot OR surgical robot OR medical robotics OR da Vinci OR surgical robotics OR robot assisted OR robotic assisted OR robotic aided OR robot aided OR robotic surgery); and augmented reality AND (laparoscopy OR surgery OR intervention). The articles are selected manually through browsing the title and abstract.

While collecting, I try choosing the papers to include more application paradigms. Considering the timeliness, relevance and citations, the selected papers are published after 2015 (>2015) with only 6 exceptions.

2.2 Recording method

The recording table contains 4 major sections.

The first section is the *basic information*, including the title, first author, journal and citation, which are simply transcribed from the paper.

The second section is the *overview*, which records the target problems, main solutions, innovations and application. The target problems are where a paper aims for improvements; namely, the present drawbacks like lack of spatial and tactile perception and technical difficulties like the intraoperative tissue deformation. Main solutions record the procedures that the paper gives a detailed description. Typical answers are registration, tracking, reconstruction, AR visualization, etc. Innovations are the novel methods first purposed or the new contributions first achieved. Application specifies the kind of surgeries that the system is intended to apply to; the major category is laparoscopy.

Methodology is the third section, including prior data, runtime data, robotic platform, display, augmentation, algorithms. In a typical research, the surgery is done on a robotic platform (mainly da Vinci); the prior data (mainly CT and MRI) and the runtime data (mainly binocular/monocular endoscopy) are utilized to generate augmentation, which is displayed in real-time. Algorithms mentioned in papers are recorded, being annotated with their usage.

The fourth and last section is the *evaluation*, which records error and time of purposed systems. The root mean square (RMS) error is recorded, if the paper mentions it. As for the time, I find that different papers present the performance with regard to time in different ways; there are also papers whose results do not include data concerning time. Hence, time is recorded in various terms, such as the time for reconstruction, frames per second, etc.

3 Results

3.1 Application in surgeries

AR is currently applied to a variety of surgeries, among which there is a preponderance of laparoscopic surgeries. Representative laparoscopic surgeries are partial nephrectomy and prostatectomy. Other than laparoscopy, there are also applications in orthopedic surgeries [2], transoral surgeries [3], thyroidectomy [4], neurosurgical oncology [5], ear surgeries, lymphadenectomy [6], stereoelectroencephalography [7] etc.

When being applied, AR usually assist surgeons by superimposing helpful contents during the surgery. This real-time augmentation can enhance depth, substitute tactile sensory [8], provide more intuitive human-machine interface [9],expand field of view [10] and annotate helpful cues [3, 11]. Moreover, AR can also be employed for interactive surgical planning [7, 9] and surgical skill training [12].

3.2 Implementation paradigms

In a variety of implementations, AR is applied to robotic surgeries following a relatively similar process. For instance, Qian *et al.* [13] developed a system that integrated multiple runtime data to generate instruments and endoscopy rendering, which are visualized in Hololens.

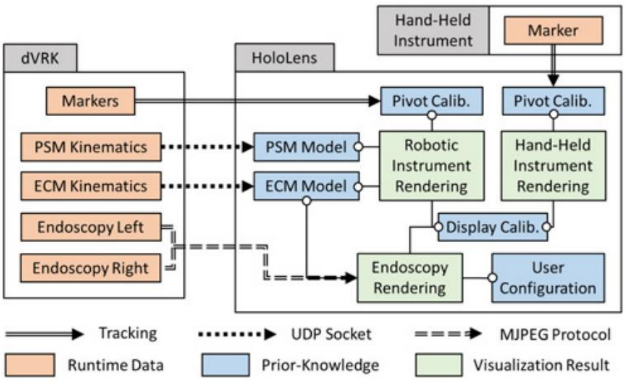

Fig.2 Date flow in ARssist purposed by Qian *et al.* [13]

Chen *et al.* [14] purposed a framework that tracks the monocular endoscopy and simultaneously reconstructs a dense geometric mesh of the surgical scene without referring to preoperative scan.

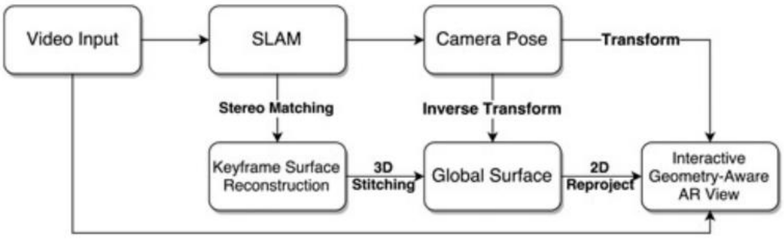

Fig.3 Workflow in the system purposed by Chen *et al.* [14]

To summarize, I make a flow chart that applies to all the research articles I have reviewed. In an implementation paradigm, the system utilizes one or several kinds of intraoperative data. The preoperative data is sometimes but not always needed. The majority of preoperative data is CT and MRI, which are usually processed to obtain a model. Afterwards, the preoperative model is registered with the intraoperative data, giving various sorts of augmentation. Ultimately, the surgical scene and augmentation are displayed for surgeons.

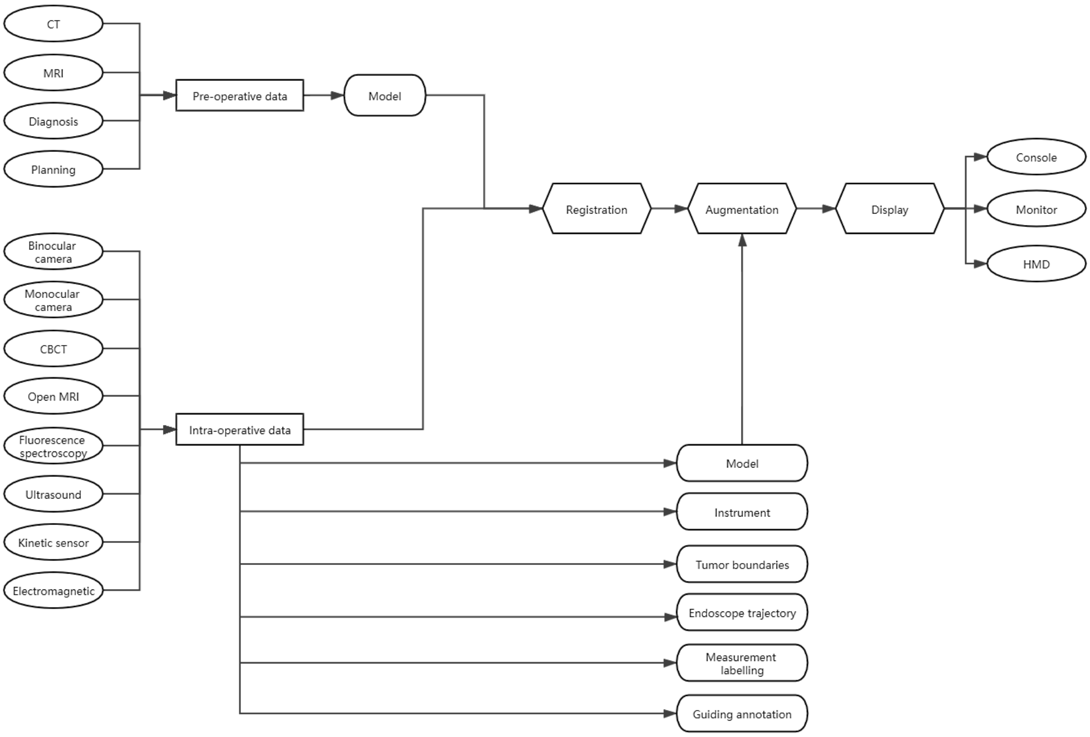

Fig.4 Flowchart of general paradigms

3.3 Display

Two most common media for displaying is the da Vinci console and the computer monitor. Other methods include the projector [15], tablet [9] and head-mounted-display (HMD) [2, 5, 11, 13, 16]. HMD is the third most common method; it can be classified as optical see-through HMD and video see-through HMD [1]. Through an optical see-through HMD, the user can see the augmentation and real environment through its optical combiner. Hololens is a kind of optical see-through HMD, which is the majority of HMD used in intraoperative guidance. Video see-through HMD, such as Sony HMZ-T2, is only reported being used for surgical training.

3.4 Algorithms

Researchers apply previous and self-purposed algorithms for reconstruction the 3D model, tracking the endoscopy, registering the preoperative model with intraoperative data and in other data automatic procedures.

- **Reconstruction algorithms**

Reconstruction may be the procedure that involves the most important and diverse algorithms. Reconstruction algorithms can be categorized into two kinds [17]: active and passive. Active methods require controlled light to be projected into the environment, while passive methods only require images [18]. Among the reviewed papers, active algorithms include SL (Structure Light), SfP (Shape from Polarization) and ToF (Time of Flight). Passive algorithms include SfM (Structure from Motion), DSfM (Deformable Shape from Motion), SfS (Shape from Shading), SLAM (Simultaneous Localization and Mapping) [14, 19-23], stereovision.

- **Registration algorithms (methods)**

While registering the preoperative model with intraoperative data, manual registration [4] or automatic registration is applied. Automatic registration methods include fiducial marker-based registration [24, 25], picture-in-picture visualization [3] and point cloud-based registration [26]. In the systems equipped with particular intraoperative data input, registration can also base on kinematics [27], electromagnetics [28], etc.

3.5 Innovation highlights

- **AR contents**

In most cases, the 3D model is superimposed on the real scence; there are both surface and subsurface models. Surface models can be either rigid or elastic. Generally, elastic models are considered better, because they can adapt to deformable tissues which are common in a surgery. Porpiglia *et al* [29] purposed a system that can reconstruct and superimpose a 3D elastic model. The model is stretched and bent according to the traction exercised on the prostate by robotic arms, allowing dynamic tracking of prostate deformation during surgeries.

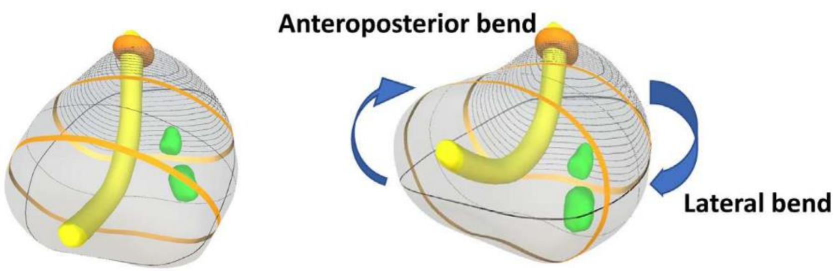

Fig.5 Rigid (left) and elastic (right) model [29]

Haouchine *et al* [30] developed a monocular 3D reconstruction method that generates AR on elastic objects with self-occlusions handling. The elastic model is reconstructed using Saint Venant-Kirchhoff model. As reported, the augmentation is effective even when the deformation generated by the instrument forces the lobe of the liver to fold.

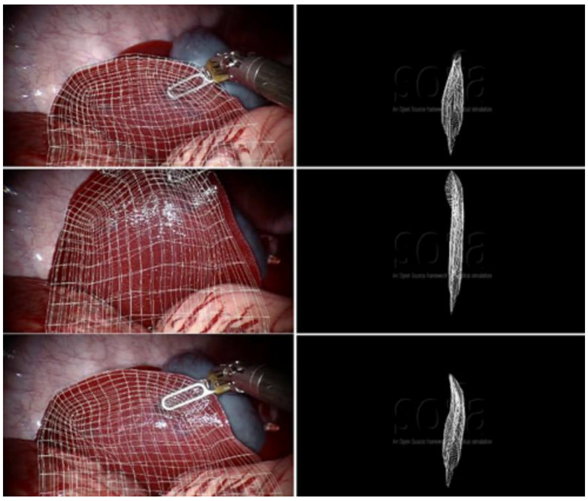

Fig.6 3D elastic augmentation of the mechanical model on monocular laparoscopic images [30]

Other than augmenting models, instruments are also displayed in some cases to help surgeons understand the geometric relationship between instruments and tissues. Qian *et al* [13] purposed ARssist that renders real-time 3D robotic instruments, hand-held instruments and stereo endoscopy, assisting instrument insertion and tool manipulation.

Various annotations are also developed by researchers to suit specific demand. Autofluorescence lifetime AR purposed by Penza *et al* [31] allows surgeons to self-define a safety volume and augment a graphical representation of the distance between the instruments and the reconstructed surface when an instrument approaches the safety volume.

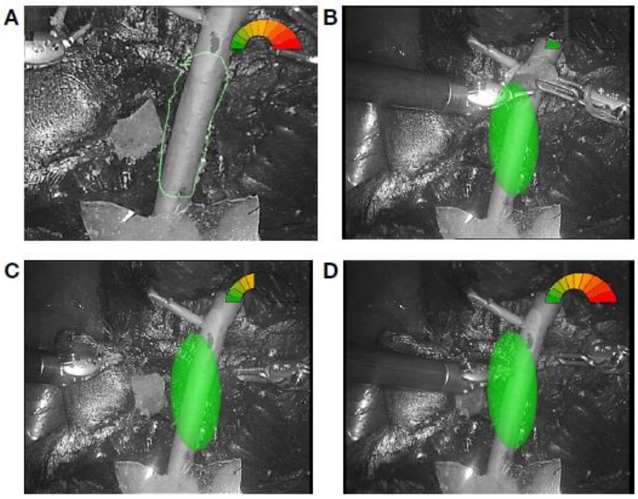

Fig.7 Example of AR visualization. (A) The view of the SA definition; three different situations showing. (B) The instruments performing the surgery in the safe green range. (C) The right instrument approaching the delicate area. (D) The left instrument almost touching the vessel surface and the gage completely red. [31]

Liu *et al* [11] proposed an AR based navigation system for hip resurfacing. The AR guidance for hole drilling was generated according to a preoperative plan. During drilling, the planned position and orientation of the holes are displayed in Hololens.

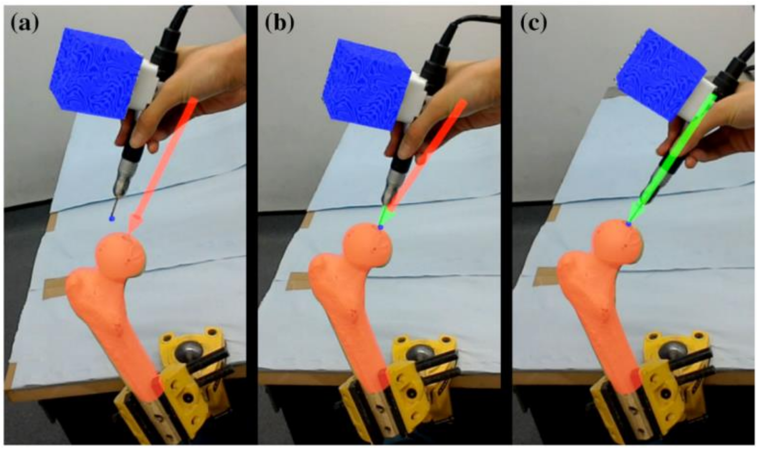

Fig.8 Visual guidance through HoloLens for guide hole drilling. This was recorded from the user's view. (a) Inaccurate position and direction. (b) Accurate position but inaccurate direction. (c) Accurate position and direction. [11]

A novel system developed by Zevallos *et al* [8] utilizes kinetic sensors to produce a stiffness distribution map to be augmented on the registered model. According to the stiffness map, surgeons can better determine the location and shape of the tumor.

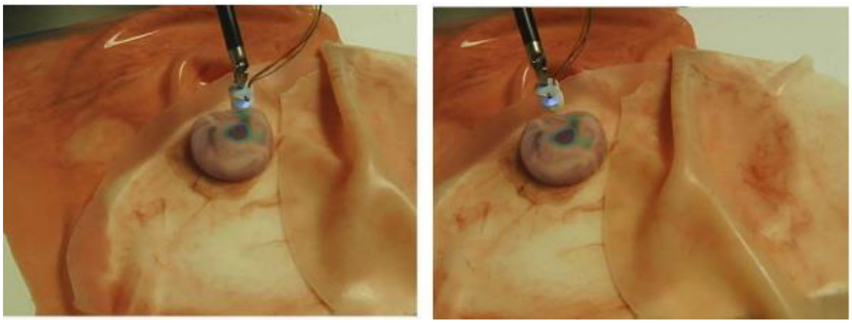

Fig.9 Estimated stiffness map augmented on the registered model. Dark blue regions show high stiffness. Note that the stiffness map reveals the location and shape of the tumor. [8]

- **Intraoperative data input**

Binocular endoscopy is the most widely used intraoperative data. However, some systems only rely on monocular endoscopy data during a surgery. These systems [14, 22, 23, 32] usually apply the SLAM algorithms to reconstruct the model and track the endoscopy. Also, Nosrati *et al* [33] reported that they can utilize multiple (up to 14) endoscopy positioned at different viewpoints to generate segmentation and pose estimation more precisely.

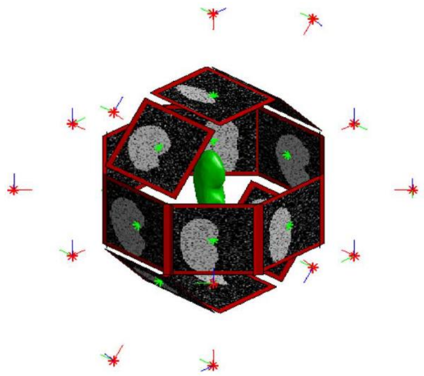

Fig.10 Multiple views of a synthetic kidney [33]

Other than endoscopic images, researchers have also succeeded integrating other intraoperative data input to improve the AR systems in robotic surgeries. Bardosi *et al* [34] used Rhinospider sensors and a microscope camera in mastoidectomy, integrating intraoperative magnetic and optical data for more precise structure localization. There are also reported usage of Cone beam CT [2], ultrasound [27, 35-37], SPECT [6, 24], fluorescence camera [24], etc.

- Human-machine interaction

To render more intuitive human-machine interaction, researchers have tried to equipped the surgical systems with additional functions. Rong *et al* [9] developed a system providing interactive surgical guidance. The system enables the surgeons to make intraoperative planning, such as selecting insertion ports and marking specific operation zones. Surgeons can also toggle the AR display between 2D medical images (e.g., CT and MRI) and 3D models. These operations can be done using hand gestures and the touch screen of the tablet.

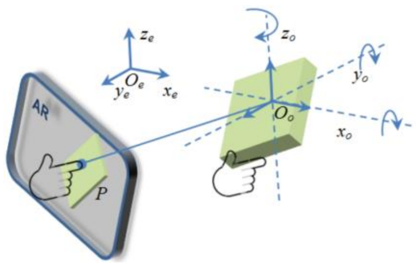

Fig.11 3D touch interaction with an AR object [9]

Bowei *et al* [7] purposed to use AR interface to aid stereoelectroencephalography electrode implantation. The interface intuitively verifies implantation accuracy by displaying the electrode entry points on the patient's head with a projector-camera system.

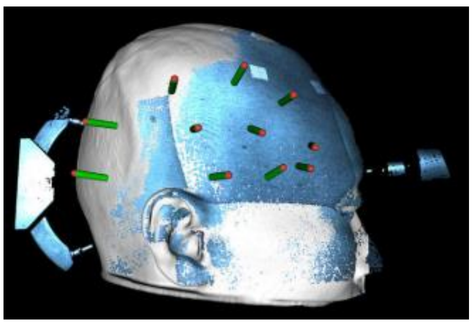

Fig.12 The planned electrode trajectories, intraoperative point clouds and phantom preoperative model [7]

4 Discussion

4.1 Current challenges

Surgical AR systems are typically evaluated by accuracy and time. To meet the clinical standard, the distance error should be less than 2mm. To render AR, the system should operate in real-time. Achieving the high accuracy and real-time rendering is a main challenge of AR systems in robotic surgeries.

More technically, recent AR systems usually face several other challenges. Some systems try solving the challenges; while some systems have drawbacks due to the challenges. The first challenge is that human tissues are usually deformable; therefore, preoperative model may fail to register with the intraoperative tissue. Some researchers tackle the deformation issue by developing elastic models [29, 30]. Other researchers assume the tissue remains rigid during the surgery; consequently, those systems possibly suffer from adaptability problems when encountering severe deformation. Secondly, specular reflection is another challenge; because specular reflection causes the intraoperative images to have abnormal colors, making registration and tracking harder. Turan *et al* [38] purposed a non-rigid map fusion-based direct SLAM method for endoscopic capsule robots. This method handles specularities by preprocessing: the preprocessing module first detects reflection and then preforms suppression by inpainting to remove reflection.

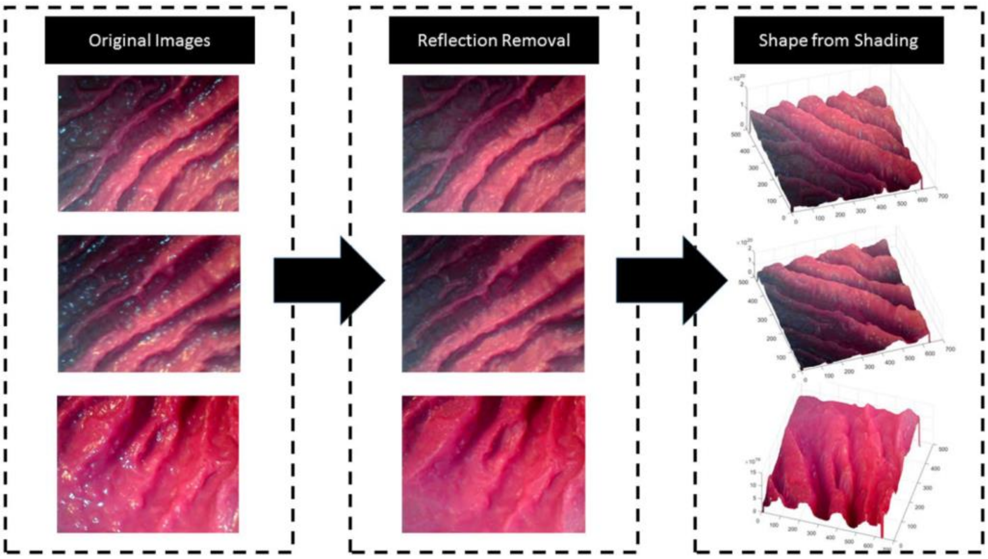

Fig.13 Reflection suppression and shading-based depth image creation

Other technical challenges include abrupt camera motion, occluding surgical tools and etc. Some challenges especially perplex the systems based on feature tracking. Since features may be discontinuous due to occlusion, sudden camera motion, and motion blur [22]. As a consequence, feature tracking suffers from drift and drop-off.

4.2 Future perspectives

By reviewing the previous research papers, especially some of the latest work, AR is expected to expand its usage in robotic surgeries in the future.

Firstly, AR applications in robotic surgeries will continue taking the advantage of the progress in relevant hardware and software platforms. For example, with the commercialization of Hololens, more systems use HMD to display. The SLAM algorithm enables researchers to conduct dense reconstruction with a handheld monocular camera [32]. Self-supervised learning is also reported being used to augment depth to monocular endoscopy [10, 39].

There may be more integration of AR from other robotic surgeries. Previously, there is a distinct preponderance of laparoscope in the applied cases. Hussain *et al* [40] applied AR to middle ear surgery where the surgery is done through a microscope (Zoom Pro). Bárdosi *et al* [34] integrated AR into microscopic lateral skull based surgery. Because these surgical interventions involve intraoperative videos, AR can be introduced to provide image guidance.

With the development and popularization of novel biophotonic and sensory methods, more integration of diverse preoperative and intraoperative data input may appear in the future. Autofluorescence [3], SPECT [24, 33], and Kinect [9] are already applied to make improvements.

Last but not the least, more clinical trials are also expected in the future. There are used to be animal experiments and a limited amount of human trials. At present, robotic surgeries and AR technologies become more common; also, the systems that use optical see-through HMD are fail-safe [41]. Expectedly, more clinical trials and applications are probably to happen. Some engineers and doctors have cooperated to test usability and reliability of existing robotic surgery systems with AR [42, 43].

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