A Review of Augmented Reality in Robotic Surgery

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1 Introduction

1.1 Background

Surgical robots, represented by da Vinci Surgical System, is developing rapidly in the last decade. Compared with conventional open surgery, robotic surgery has many distinguishing advantages, such as improving accuracy, conforming to the ergonomics and so on. However, robotic surgery also suffers from a lack of intuitive depth perception and tactile perception, because surgeons perform operations indirectly in robotic surgery. Meanwhile, augmented reality (AR) is commercialized and becoming extensively utilized in various areas; applying AR to robotic surgery brings plausible solutions to further advance robotic surgery. In specific, AR can provide surgeons with helpful information (3D model, instruments, annotations, etc.) superimposed on the surgeon's view.

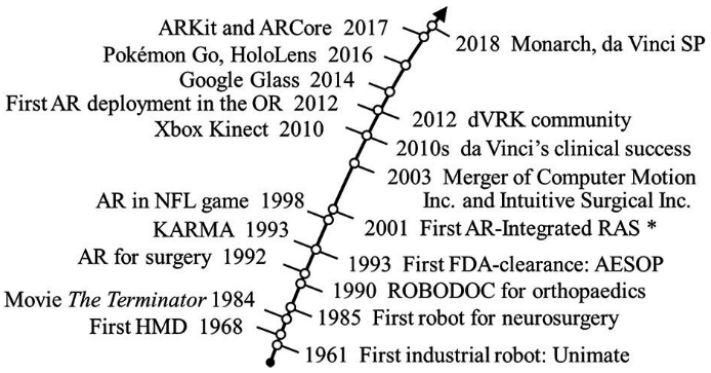

Fig.1 Timeline of the commercialization of AR and robotic surgery [1]

Fig.1 presents the timeline marking each milestone during the commercialization of AR and robotic surgery[1].

1.2 Purpose

This work is done to investigate the development concerning AR in robotic surgery in the last 5 years. The purpose is to understand the diversity and generality of application paradigms. In addition, we are also interested in the research that proposes novel algorithms to improve AR for robotic surgery.

1.3 Our work

48 research papers and 6 review papers are collected and reviewed. While reviewing, I record the research articles by filling in a table, which consists of 4 sections. The 4 sections are *information*, *overview*, *methodology*, and *evaluation*; the 4 sections further include 17 separate items. Afterwards, by referring to the papers and my records, a flow chart and a mindmap are drawn to summarize them.

2 Methods

2.1 Searching method

The collected articles are collected 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 selecting 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 surgery 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 case, the surgery is done on a robotic platform (mainly da Vinci); the prior data (mainly CT and MRI) and the runtime data (mainly binocular or 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 information concerning time. Hence, time is recorded in various terms, such as the time for reconstruction and frames per second.

3 Results

3.1 Application in surgery

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

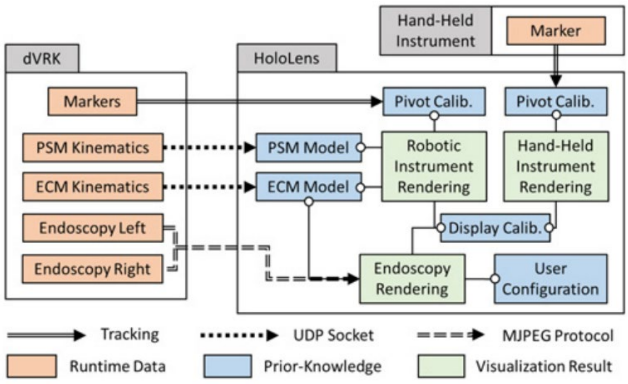

Fig.2 Date flow in ARssist purposed by Qian *et al.* [13]

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.

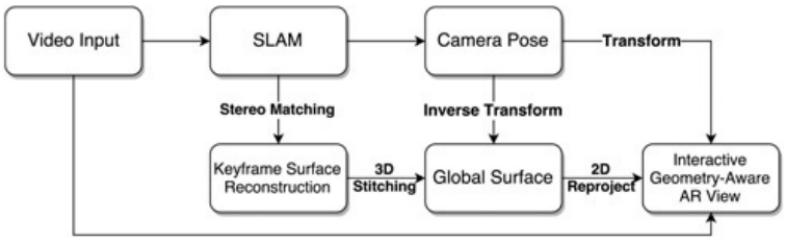

Fig.3 Workflow in the system purposed by Chen *et al.* [14]

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, generating various sorts of augmentation. Ultimately, the surgical scene and augmentation are displayed for surgeons.

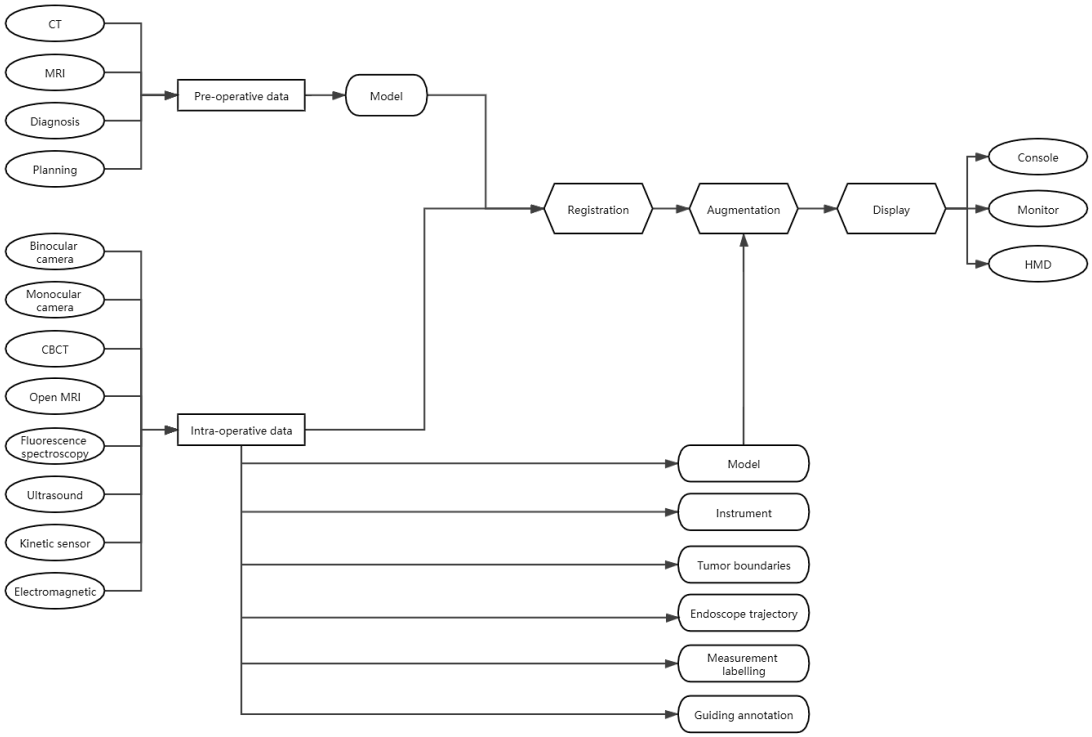

Fig.4 Flowchart of general paradigms

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 is 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 Structure 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 surgical 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 surgery.

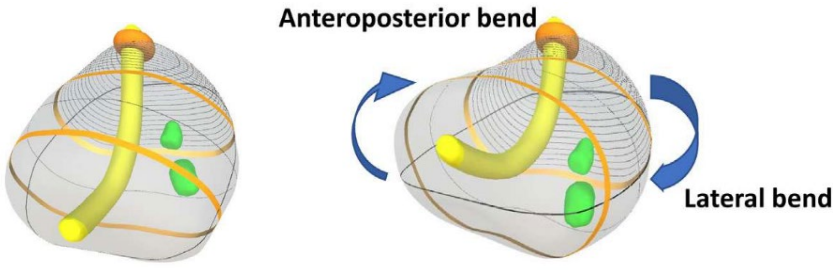

Fig.5 Rigid (left) and elastic (right) model [29]

Haouchine *et al* [30] developed a monocular 3D reconstruction method that generates augmentation 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.

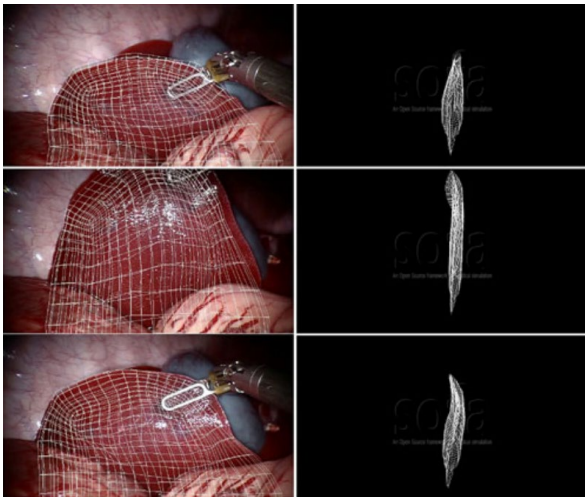

Fig.6 3D elastic augmentation of the mechanical model on monocular laparoscopic images [30]

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.

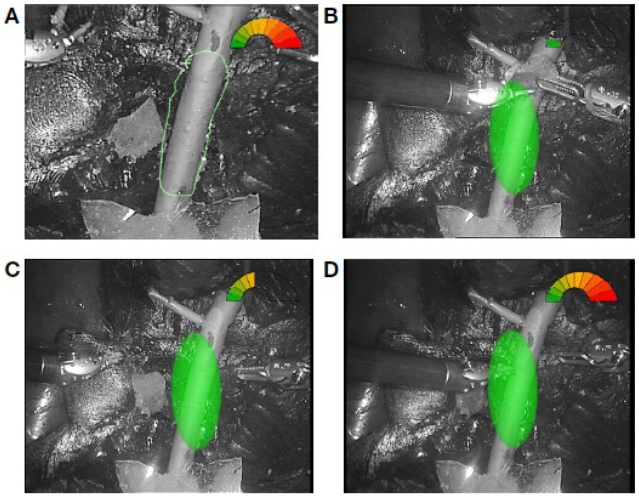

Fig.7 Example of AR visualization. (A) The view of the SA definition; three different situations showing. (B) The instruments performing the surgery in the safe green range. (C) The right instrument approaching the delicate area. (D) The left instrument almost touching the vessel surface and the gage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

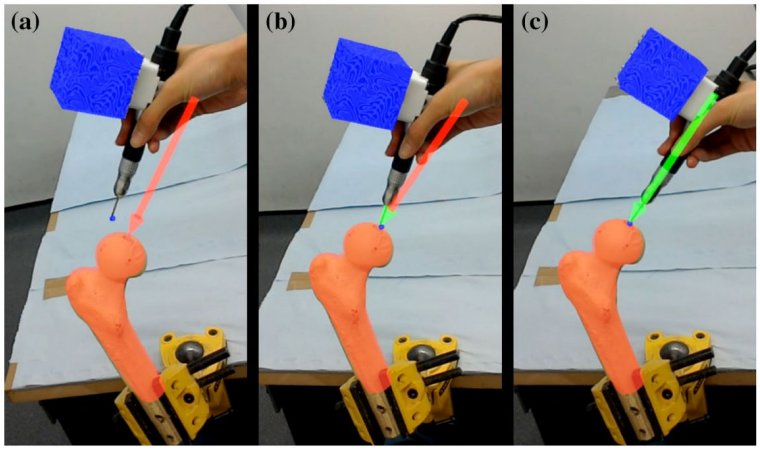

Fig.8 Visual guidance through HoloLens for guide hole drilling. This was recorded from the user's view. (a) Inaccurate position and direction. (b) Accurate position but inaccurate direction. (c) Accurate position and direction. [11]

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.

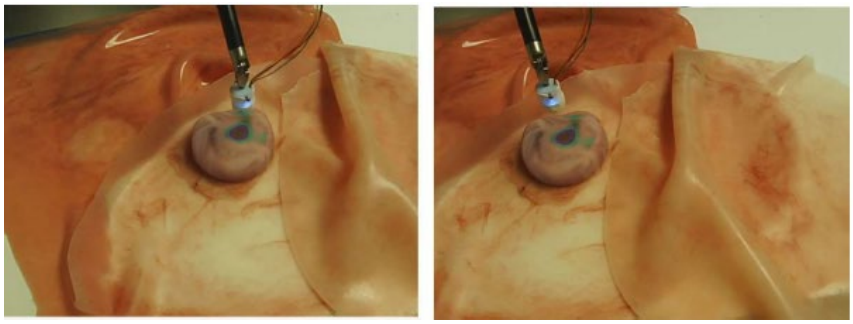

Fig.9 Estimated stiffness map augmented on the registered model. Dark blue regions show high stiffness. Note that the stiffness map reveals the location and shape of the tumor. [8]

- **Intraoperative data input**

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

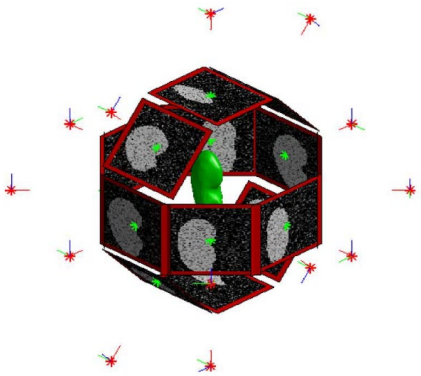

Fig.10 Multiple views of a synthetic kidney [33]

Other than endoscopic images, researchers have also succeeded integrating other intraoperative data format to improve the AR systems in robotic surgery. 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 provide more intuitive human-machine interaction, researchers have tried to equip 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.

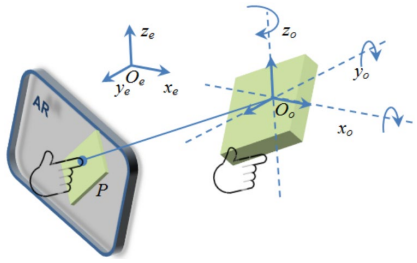

Fig.11 3D touch interaction with an AR object [9]

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.

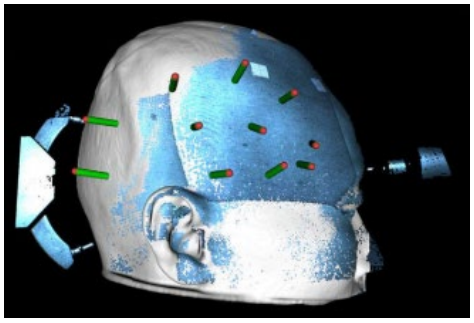

Fig.12 The planned electrode trajectories, intraoperative point clouds and phantom preoperative model [7]

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 augmentations, the system should operate in real-time. Achieving high accuracy and real-time rendering is the major challenge of AR-integrated robotic surgery.

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, another challenge is the specular reflection. Because specular reflection causes the intraoperative images to have abnormal color value, thus making registration and tracking harder. Turan *et al* [38] purposed a non-rigid map fusion-based direct SLAM method for endoscopic capsule robots. Their method handles specularities by preprocessing: the preprocessing module first detects reflection and then preforms suppression by inpainting to remove reflection.

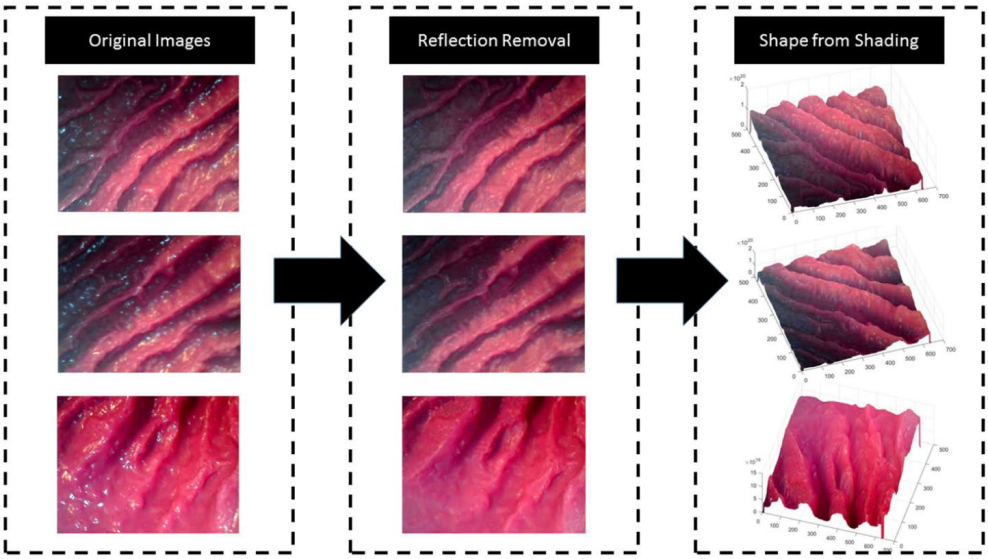

Fig.13 Reflection suppression and shading-based depth image creation

Other technical challenges include abrupt camera motion and occluding surgical tools. Some challenges especially hinder the systems based on feature tracking. Since feature descriptors can be discontinuous due to occlusion and motion blur [22]. Consequence, feature tracking suffers from drift and drop-off.

4.2 Future perspectives

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

Firstly, the application of AR to robotic surgery will continue to take 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 can be more integration of AR from other robotic surgery. 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 techniques, more integration of diverse preoperative and intraoperative data will 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 surgery and AR technologies are becoming more common; moreover, the AR systems that use optical see-through HMD are fail-safe [41]. Some engineers and doctors have cooperated to test the usability and reliability of existing robotic surgery systems with AR [42, 43].

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