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Registration Technology of Augmented Reality in Oral Medicine: A Review

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ABSTRACT Augmented reality (AR) technology, as a computer simulation technology, combines various technologies such as virtual reality, computer vision, computer network, and human-computer interaction. AR has been widely used in medicine. The introduction of AR can effectively help the doctors to complete preoperative planning, intraoperative guidance, postoperative evaluation, and medical training. Oral medicine is a major branch of modern medicine. AR can enhance the doctor's visual system, making the internal structure of the oral clearer and effectively reducing the difficulty of oral repair/surgery. Real-time tracking, registration, display, and interactive technologies for AR will play an important role in oral medicine. Among them, registration technology has become an important indicator for evaluating the AR system, and it is also the main bottleneck restricting the stability and applicability of the current AR system. Therefore, we reviewed the registration technology of AR in oral medicine. First, we conducted a hot spot analysis of AR keywords based on Citespace. And then, the registration technology is divided into static registration and real-time registration according to the actual clinical application, among which static registration is divided into rigid registration and non-rigid registration. We discussed problems and limitations of static registration and real-time registration in oral applications at this stage. Finally, the future direction of AR registration technology in oral medicine is proposed.

INDEX TERMS Augmented reality, image registration, oral medicine, dentistry, Citespace, review.

I. INTRODUCTION

Augmented reality (AR) technology emerged in the early 1990s as a computer simulation technology [1]–[3], which uses computers to process images. This technology allows users to see real-world images and computer-generated images [4]–[6]. The early development of AR technology was partly due to the need for auxiliary virtual information in medical surgery [7]. The risk of surgery can be greatly reduced by projecting a virtual model of the diseased organ onto the patient's body [8]–[13]. The three-dimensional image can be visualized according to two-dimensional image data such as CT and MRI obtained through medical equipment [14]–[16]. The virtual model is overlaid into the real surgical scene in real time. The doctor wears a pair of ''see-through'' glasses, and can understand the accurate organization information of the operation position without invading the patient's body, which greatly reduces the risk of surgery [17]–[19]. With the improvement of computer computing level, AR technology can be developed at a high speed, making the application of AR in the medical field more extensive and mature [20]–[23].

As a major branch of modern medicine, oral medicine mainly studies the occurrence and development of soft and hard problem in the teeth and its surrounding oral and maxillofacial regions [24]. It is a practical, comprehensive and

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highly intersecting clinical medical science for the etiology, pathogenesis, diagnosis and treatment of its diseases. According to statistics [24] from the World Health Organization, more than 60% of school-age children and nearly 100% of adults worldwide have dental caries, and nearly 20% of adults aged 35-44 have severe dental disease [25], [26]. It can lead to the risk of missing teeth. As for the population aged 65-74, the total tooth loss rate is as high as nearly 30% [27]. The concept of oral health has gradually increased with the increase of the number of elderly people and the aging of society [28], [29]. Oral diseases have become an important public health problem and promoted the continuous development and progress of global oral medicine technology [24], [30].

The introduction of AR can overlay the virtual oral tissue model reconstructed from the oral image onto the corresponding organ position of the patient, thereby enhancing the doctor's visual system and improving the surgical ability [31]. At the same time, the internal structure of the oral medicine is clearer and more intuitive, reducing the blind spot and difficulty of oral repair or oral surgery, and the success rate of surgery and benefiting patients can be increased. During the operation, the AR tracking and positioning technology can be used to track the position of the doctor in the surgical scene and the angle and direction of the head line of sight in real time, so as to guide the repair/surgical operation in real time [32]. The interactive performance of AR systems can greatly improve the accuracy of complex oral prosthetics/surgery, thereby reducing the risk of repair/surgery. At present, AR is mainly used in the field of dental implant, oral and maxillofacial surgery, and orthodontics. In addition, AR has also promoted the development of oral education [33]. The introduction of AR has improved the traditional teaching mode (in vitro teeth, dental models and clinical internships), greatly enhancing the immersion and interactivity of the dental training process [34], [35]. It will provide a more realistic dental virtual surgical environment for trained doctors to achieve better surgical planning, surgical guidance and training feedback, training assessment.

The AR system used in oral medicine generally needs to complete four basic steps [33]–[36]: (1) Collecting real-world surgical scene information, and analyzing and processing it. The real world of collection is the real operating environment that doctors need to observe and perceive, and it is also the surgical environment that AR systems need to enhance. (2) Generate a virtual oral/tooth model [35]. The desired virtual oral/tooth model is generated based on the reference or marker points in the actual surgical environment. A virtual oral/tooth model rendered by a computer is used to enhance the filling of the real surgical environment. (3) Virtual and real registration, scene fusion and interactive processing. Positioning markers or calculations for the real surgical environment to determine the correct position of the virtual oral/dental model overlay, seamlessly blending the two together to show the doctor a new environment. (4) Interaction ability [37]. It is necessary to change the virtual oral/dental model reasonably according to the doctor's request or the movement of the surgical environment [38].

The purpose of the AR is to overlay computer-generated virtual objects, scenes, or system information into real world [39]–[43]. In order to achieve a seamless overlay of virtual oral model and the patient's oral, researchers have conducted extensive research on registration technology [37], [38].

The registration technology is to place virtual objects or scenes accurately in the real world based on sensors, hardware devices, identification points and track registration algorithms [39], [13], [44], [45]. The implementation of registration technology is mainly based on sensors or hardware registration technology and machine vision-based registration technology [46]–[48]. Sensors or hardware-based registration technology uses some sensing devices or position tracking devices to capture the user's current location information, including magnetic field tracking registration technology, mechanical tracking registration technology, acoustic tracking registration technology, optical tracking registration technology, and GPS tracking registration technology [49]–[51]. The machine vision-based registration technology uses image processing technology and computer vision technology to register, and then can be divided into manual identification point method and natural identification point method according to different identification points.

In oral medicine, the AR system need to calculate the posture of the camera according to the feature information of the real world surgery scene, obtain the transformation matrix of the oral virtual model and the visual plane, and locate the superposition position of the oral virtual model in real time [32]–[34]. In order to prevent excessive registration error during the operation, the entire AR system must be able to use the identification tracking algorithm to obtain the exact registration location of the virtual model. However, in practical applications, the AR surgical system technology possesses very high precision and stability for registration [9], [52]–[55]. Doctors will be very sensitive to visual errors, even a small tracking registration error will affect the actual surgical results of the doctor, where the reduction of the efficiency of surgery may occur [56]–[58]. Therefore, registration is the most important technical link in AR technology, which will directly determine the success or failure of AR systems. Improving the accuracy of tracking and registration of AR has always been the focus and difficulty of AR technology research.

In summary, the registration technology plays an extremely important role for AR applications in the oral medicine or other medical field. At present, some researchers have reviewed the application of AR in the oral medicine [32], [34]–[38] and the registration technology [51]–[62] separately. However, registration method of AR in oral medicine has not been systematically and specifically reviewed.

In this paper, registration method of AR in oral medicine is reviewed. We survey and search literature based on ''Methodology of literature search and analysis'' in **section II**; secondly, we divide the registration methods into static registration and real-time registration according to the registration type, which are in **section III** and **section IV** respectively. In **section V** we discussed the registration method and its future direction. Finally, the full text is summarized in **section VI**.

II. METHODOLOGY OF LITERATURE SEARCH AND ANALYSIS

A. LITERATURE SEARCH

The literature search can be created via three steps.

1) STEP 1 PLANNING

The planning phase is the initial step in literature search. We defined the timescale of the reference, the databases, and select the software for managing the references in the planning phase.

The timescale of reference is from 2000 to 2019 and reference is derived from the following database:

- Web of science (www.apps.webofknowledge.com);
- IEEE Xplore (www.ieeexplore.com);
- Google Scholar (www.scholar.google.com.cn);
- ScienceDirect (www.sciencedirect.com/);
- Springer (www.springer.com);
- Elsevier (www.elsevier.com);
- Engineering village (www.engineeringvillage.com)

Citavi (www.softhead-citavi.com) is utilized to manage references. Citavi is perfectly embedded in Microsoft Word. Simply insert your classification system from Citavi and see the references, citations and insights you have collected for each chapter.

2) STEP 2 SEARCHING

In the searching phase, the string: (''augmented reality'') OR (''AR'') OR (''registration'') OR (''oral'') OR (''dental'') are entered into the above databases for searching. At the same time, we searched for the following keywords, which are visualization, tracking technology and human-computer interaction.

3) STEP 3 ASSESSING

The number of references is narrowed in assessing phase. Inclusion and exclusion criteria are opposed in this phase. The inclusion criteria include three points: 1) The application of AR in oral; 2) AR registration state of the art; 3) visualization state of the art; The exclusion criteria include four points: 1) Older than 2000; 2) Not engineering or computer science field; 3) Not related to oral field; 4) Not computer simulation technology.

B. ANALYSIS OF RESEARCH HOTSPOTS BASED ON CITESPACE

1) CITESPACE

Bibliometrics is a quantitative analysis method [63]–[65] that uses mathematical and statistical methods to describe and evaluate various external features of scientific literature, so as to predict the research status and development trend of science and technology in this field [66]–[68]. The main feature of this research method is that its output must be quantified [69]. Many researchers analyzed the oral medicine based on bibliometric [63]–[71].

Citespace (Drexel University, Philadelphia, PA, USA) software is a visual document analysis software developed based on Java language, with keyword analysis, institutional analysis, author analysis and other functions [72], [73]. New trends and new developments in scientific development can be identified and displayed in the scientific literature, suitable for finding research progress in a subject area, hotspots and current research frontiers [74], [75].

According to the literature search in section 2.1, we used the ''Web of Science Core Collection'' to search for the keyword ''augment reality'' to get 11086 articles, and entered ''medical'' in the result set to get 571 results. Save 571 results as citespace readable files via ''save to other file formats''. The bibliometric method is used to quantitatively analyze the data of the augmented reality related literature collected from the ''Web of Science Core Collection'' database in 2004-2019. The citespace visual analysis software is used to qualitatively analyze the content of the augmented reality research, and then the augmented reality research is summarized. At the same time, the importance of registration technology is verified.

2) KEY WORDS CO-OCCURRENCE NETWORK MAP

Keywords co-occurrence network map keywords are a high-level summary of the topic and center content of academic papers. Analysis of keywords can help to understand the hotspots in the research field. The mixed learning related literature data derived from Web of Science Core (WOS) is processed, and the collected mixed learning related literature data is analyzed by using the ''keyword'' co-occurrence analysis function in Citespace software to obtain a keyword co-occurrence map. This map can directly reflect the research hotspots in the field of augmented reality research. In Fig. 1, there are 575 nodes and 2668 keywords are connected. Each node represents a keyword; if the ring of the node is larger, the frequency of keyword co-occurrence is larger; points with a center-degree above 0.1 are key nodes in the map. Table 1 lists the top 20 keywords and their centrality and year. The breadth of research, the higher the frequency, the more likely to become a research hotspot in the keyword co-occurrence network. The higher the value of centrality, the stronger the centrality of the keyword in the entire co-occurrence network. If the frequency of a node is high but the

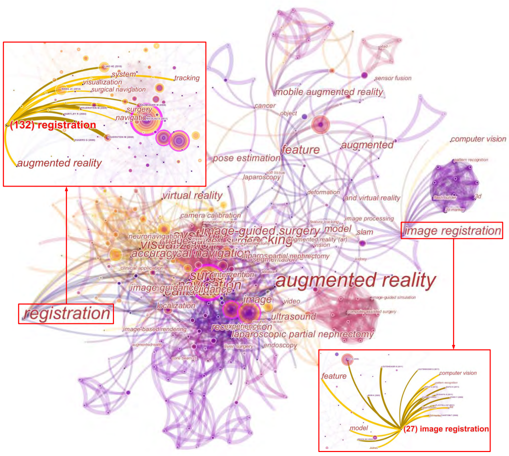


FIGURE 1. Keywords co-occurrence network map of augment reality.

TABLE 1. Keywords co-occurrence count, centrality and year.

Initial year of the literature	Keyword	Count	Centrality
2004	Augmented reality	267	0.45
2004	Virtual reality	87	0.04
2005	Surgery	70	0.09
2004	Registration	67	0.19
2004	System	54	0.07
2004	Visualization	41	0.18
2004	Simulation	38	0.07
2004	Medical education	28	0.04
2013	Navigation	24	0.03

center degree is 0, it means that although the keyword appears frequently, it is an isolated node and cannot be regarded as a key node.

In the Table 1, the order of the first six is augmented reality, virtual reality, surgery, registration, system when we sorted by count; the order of the first six is, augmented reality, registration, visualization, surgery, simulation, system when we sorted by centrality. Excluding search keywords (augmented reality, virtual reality) and keywords with a central value of less than 0.1 (Surgery, System, Simulation, etc.), we found that registration is a hot topic of augmented reality, which verifies the purpose of this review.

III. STATIC REGISTRATION METHOD OF AUGMENTED REALITY IN ORAL MEDICINE

According to the medical image registration method, the static registration method of the AR can be divided into rigid registration and non-rigid registration according to the type of the registration object [57], [62].

Rigid registration method refers to the registration of medical images of rigid body parts that are hardly deformed inside tissue organs at different time intervals, for example, images of teeth, skull areas and bones [60]. This registration method ignores subtle changes in the human body and it can be considered that the distance between any two points in the medical images acquired at different time intervals is fixed. Therefore, the rigid registration method can achieve spatial registration of the images to be mutually registered. However, rigid registration is only suitable for registration without deformation or rigid body, and it is not possible to register a deformed organ image [47]. As deformations between images become more complex, many important clinical applications require non-rigid transformations to describe the spatial relationship between images.

Non-rigid registration method refers to the registration of medical images that will change at different times. This change is due to the spontaneous movement of the organs, which causes the internal tissues and organs to change in size, shape and volume [54]. There are some irregular internal deformations in this type of medical image, such as liver, heart, and image-guided neurosurgery, which are less used in the oral and dental fields [62]. Non-rigid registration method mainly includes spatial transformation-based registration methods and physical model-based registration methods, where non-rigid transformations include affine transformation, projection transformation, nonlinear transformation [56].

At technical level, the essential difference between the two is that the degree of freedom of spatial transformation is different. Rigid registration completes a 6-degree-of-freedom (DOF) transformation that maps points in the source image to corresponding points in the target image, and the distance between any two points in the rigid transformation remains the same [54]–[56]. In contrast, non-rigid registration method can extend these linear transformation models to nonlinear transformation models by adding additional DOF (more than 6-DOF) [58]. The nonlinear transformation model can be used to fit the deformation of the image and compensate for the deformation image to achieve registration. For example, the affine transformation model has 12-DOF, allowing for scale transformation and shear transformation; the non-rigid registration method based on the B-spline function can control the local deformation by controlling individual points [62].

A. RIGID REGISTRATION METHOD

In recent years, dental implant has received extensive attention as a mature and reliable new technology in oral medicine. Dental implants are surgically implanted into the upper and lower jaws of the human edentulous area. The AR system can effectively improve the planting efficiency, and the implant placement makes the rigid registration method more applicable in this field. D. Katić *et al.* proposed a system for context-aware intraoperative AR in dental implant surgery [76]. The researchers developed AR system based on a head-mounted display (HMD), considering the basic idea of image registration. The rigid registration method is used to calculate the transformation between the virtual and real images by taking the real-world object as a reference. However, in the actual use process, the registered virtual and real images appear to have a large deviation. Furthermore, D. Katić *et al.* added a

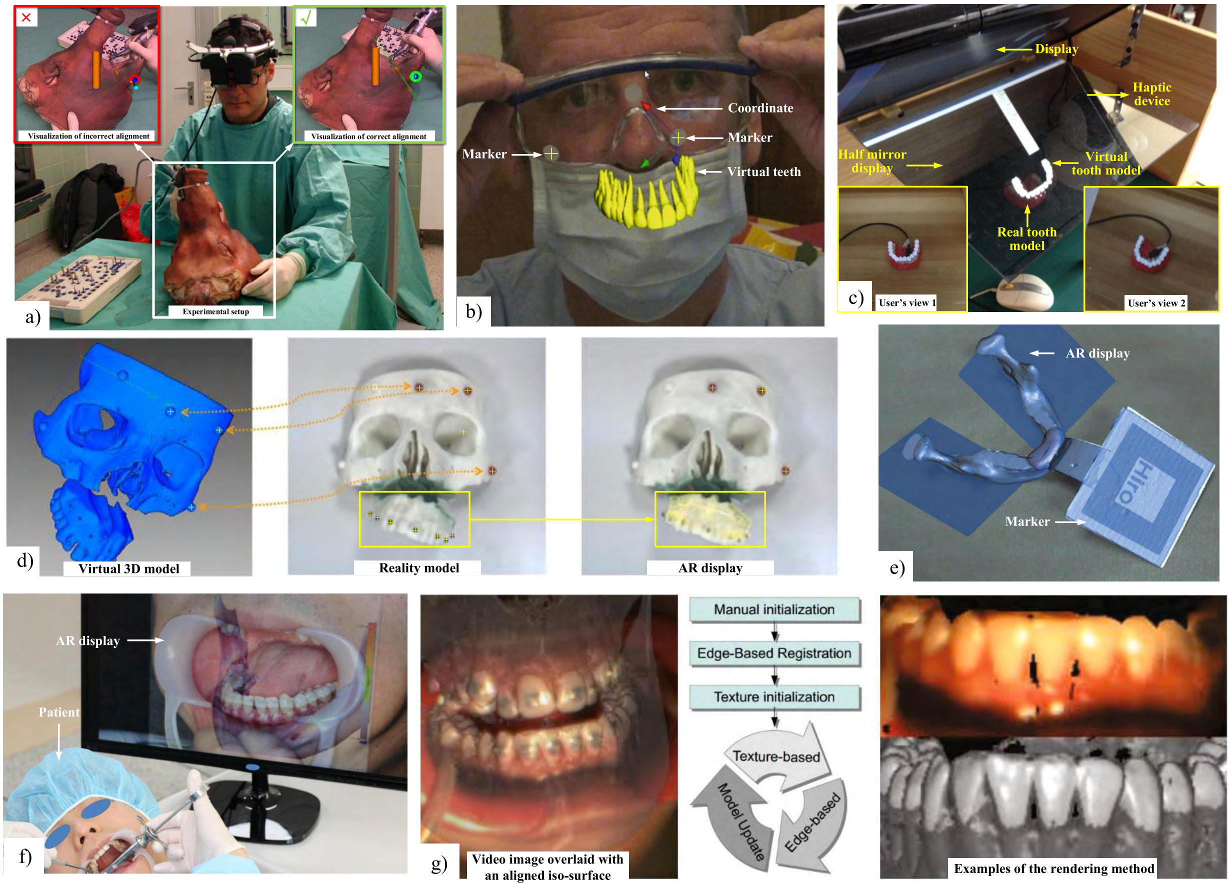


FIGURE 2. Application of rigid registration method. (a) Display of incorrect implant location and correct implant location based on AR [76]. (b) Virtual teeth are displayed in the volunteer's mouth according to the markers and coordinate on the glasses [79]. (c) AR system overview and user's view [80]. (d) Principle of virtual and real registration based on multiple markers [82]. (e) Virtual mandible display based on marker [83]. (f) 3D overlap of patient real image and virtual mandible [85]. (g) Align overlapping video images (left), example of rendering model (center), and AR system principle (right) [86].

follow-up registration scheme (Fig. 2a)), which uses the artificial interaction mode of the virtual chessboard, combined with the registration quality detection to improve the image registration success rate. The registration mean deviation of the new method is 3.01mm. Technical support is provided for subsequent AR visualizations.

Similarly, Y.-K. Lin *et al*. combined surgical templates and AR technology to significantly reduce the deviation of implant placement from planned position, in which stereoscopic visualization concept is combined with HMD. The accuracy of AR image registration [77]. A point-to-point rigid registration method was used to convert from CT image coordinates to marker point coordinates. After real world-to-CT registration, the planning data were matched with the real-world coordinate system. A novel registration method for fabricating a dental implant guiding template also is proposed by Y.-J. Kim *et al*. This novel method is simpler and faster than the previous registration method. It can automatically calculate the machining coordinates, register the processed image and pre-treatment time for about 20 minutes, and the implanting guide plate improves the implant speed [78].

An IGSTK-driven augmented-reality application in dental implant is proposed by Bardosi *et al*. IGSTK is an AR extension provided by SimViewX [79]. Fig. 2b) showed that researchers set up markers on a pair of glasses for image registration and visualized the AR with 3D image overlays. A distortion overlay of the virtual scene in the original camera image and a way to combine with the undistorted camera image in the virtual scene are achieved. From the perspective of the registration algorithm, Bardosi *et al*. decomposed the projection matrix and used the camera matrix of the undistorted image for the input of the registration algorithm, which reduced the rigid matrix transformation between the camera matrix and the tracker eye-glasses, reducing the registration error in the range of 0.5-4.0mm, and visualizing the AR of the patient's teeth before implanting the teeth.

All of the above, rigid registration methods are based on the identification point method in the field of dental implant. However, in the actual operation process, it is necessary to rely on the identification point, which destroys the authenticity of the scene in the AR. As a result, Onishi *et al.* developed a projection AR dental simulator in dental training that got rid of the traditional marking point, which is shown in Fig. 2c). In the simulation system, the AR effect is generated by combining the real tooth and the virtual tooth image, and the cutting and drilling of the tooth can be completed by using the haptic device [80]. In addition to implant and dental training, the most widely used AR in the oral and maxillofacial surgery. The researchers applied AR technology to the restoration of the maxillary and the mandible and proposed a registration method for solving such problems [81].

Representative in 2014, a wearable system for realizing AR technology in maxillofacial surgery was proposed by Badiali *et al*. When registering the maxilla, the researchers used a method based on multiple reference points for registration [82]. First, three red spheres need to be set in the upper part of the human skull to ensure the alignment of the virtual coordinate system and the real coordinate system. Fig. 2d) showed that seven black spheres were then placed at the bottom of the maxilla as a reference point for registration, and a virtual image of the target maxilla was reconstructed in the human skull model. In contrast, the amount of osteotomy involved in mandibular surgery requires more consistency between the operation effect and preoperative planning, and it is also the key to a successful surgery. Therefore, the visualization of AR technology has made it more widely used in mandibular surgery applications. Zhu *et al*. proposed an AR registration strategy for mandibular angle oblique split osteotomy [83]. The dental model is used to simulate the actual mandible of the patient. The registration method is based on the identification point, and the identification point is made on the dental model. Then, the AR toolkit software is used to identify the identification points, and the spatial position and posture of the virtual image are adjusted by 3DMax to overlap with the rapid prototyping model of the mandible to achieve registration.

In 2015, Badiali *et al*. continued to apply AR Toolkits and 3DMax to achieve precise positioning of an intraoral distractor in patients with hemifacial microsomia, which shown in Fig. 2e). On the basis of theory [83], it is applied to clinical patients. During the patient's operation, the dental cast with the marker point is used to identify the marker point during the operation, and the virtual image is projected to the center of the marker point to realize the preoperative planned mandibular image registration [84]. Similarly, the presence of marker points may affect the actual surgical procedure of the doctor. Therefore, Won and Kang proposed to overlap the 3D mandible image with the actual patient's oral image to achieve an AR markless image registration [85], which is shown in Fig. 2f). The inferior alveolar nerve block operation was performed using a simple augmented reality technique. During the local anesthetic injection, the doctor used the overlaid image as a reference to locate the hole of the mandible in the oral medicine. In addition to the above dental applications, Aichert *et al.* makes the application of AR technology in the orthodontic field feasible, and proposes a tracking solution and novel guidance system for orthodontic. Its purpose is to guide bracket placement in orthodontic correction [86]. The method is based on the edge information of the teeth, overlaying the video image and the preset position of the bracket, which is shown in Fig. 2g).

B. NON-RIGID REGISTRATION METHOD

Although non-rigid registration is mainly applied to organs such as the liver, heart, and breast, some researchers have applied non-rigid registration to the dental field. Non-rigid registration method can provide correspondence information for two similar shapes by deforming one to another. Non-rigid registration is usually complex, and it is necessary to establish a reasonable deformation model to adapt to various complex tissue deformations [62], [87]. Therefore, researchers believe that the superposition of three-dimensional virtual objects onto non-rigid objects still has important research prospects in the future. Berkels *et al.* proposed a new multimodal non-rigid registration method to match digital photos and quantitative light-induced fluorescence (QLF) images of tooth decalcification, which is shown in Fig. 3a). Through the binarization and morphological processing, a curve representing the shape of the tooth is extracted from the QLF image to distinguish the tooth region from the non-dental region [88]. An automatic non-rigid registration method under curvature-based registration is proposed by Leung *et al.*This method improves the original manual registration method, and the manual registration method can easily affect the registration quality [89]. This method provides accurate registration images for digital subtraction radiography (DSR). Similarly, in 2007, Nikaido *et al.* proposed an efficient dental radiograph registration algorithm using phase-only correlation (POC) function [90]. Vögtlin *et al.* compared the denture models with a non-rigid registration algorithm (Fig. 3b)). The local deformation of the denture models relative to the steel model was analyzed by three-dimensional non-rigid registration of 15 sets of data sets [87]. Non-rigid registration methods are also used in oral and maxillofacial surgery. Andresen and Nielsen proposed a non-rigid registration algorithm by geometry-constrained diffusion, which is shown in Fig. 3c). The non-rigid registration method solves the three-dimensional surface and is highly popular, involving only Gaussian convolution and surface projection [91]. In this paper, the mandible is used as the experimental object to establish the three-dimensional surface of the mandible. Bijar *et al.* present an automatic atlas-based method that generates subject-specific finite element meshes via a 3D registration guided by magnetic resonance images (Fig. 3d)). In order to ensure the quality of the mesh, a diffusion-type non-rigid registration based on B-spline free deformation is adopted [92]. In the actual experiment, the biomechanical response of the tongue to the activation of important tongue muscles before and after cancer surgery was simulated.

C. SUMMARY OF STATIC REGISTRATION METHOD

Static registration can be divided into rigid registration and non-rigid registration. Because the teeth and jaw are mostly

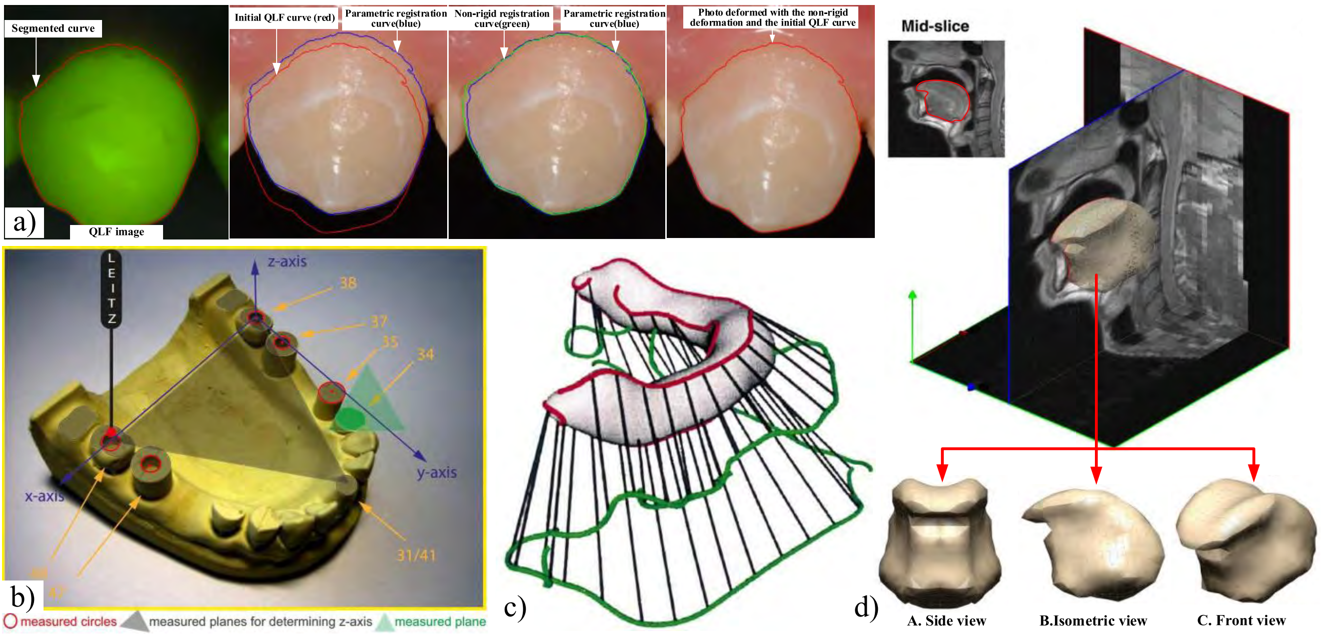


FIGURE 3. Application of non-rigid registration method. (a) Multiple curves non-rigid registration results [88]. (b) Dental model measurement scheme [87]. (c) Iso-surface and crest lines (red and green) of mandible(Gaussian smoothed: 3 mm) [91]. (d) Atlas' MR data overlaid with the 3D atlas' FE tongue mesh (three views) [92].

rigid, researchers have done a lot of research and application, including: dental implant, oral and maxillofacial surgery, dental education, and orthodontics. Rigid registration is simple and easy to operate, and the deformation relationship between the models can be neglected to complete the registration. Non-rigid registration is less used in oral medicine, mainly for registration of soft tissue in the oral or deformation on the surface of the tooth, including: dental image, oral and maxillofacial surgery, and denture manufacturing non-rigid registration. The non-rigid registration is more complicated than the rigid registration matrix. It is necessary to consider the deformation amount of the registration model. We have summarized rigid registration and non-rigid registration, summarized in Table 2.

IV. REAL-TIME REGISTRATION METHOD OF AUGMENTED REALITY IN ORAL MEDICINE

Real-time registration is necessary for the actual application process [40]–[42], [44]. In order to ensure the real-time performance of the AR image registration process, the researchers proposed the following research results, including application of preoperative navigation [46], [93]–[98], oral and maxillofacial surgery [99]–[102], and dental training [103]–[107].

In the field of oral implants, Yamaguchi *et al*. proposed an implant surgery navigation system that combines AR technology, Retinal Imaging Display (RID, Prototype of Retinal Imaging Display, Brother Industries, Ltd., Japan) and image overlay registration technology. First, the researchers set marker1 on the tooth model and marker 2 on the RID device worn by the doctor [93]. ${}^{implant}_{marker1}D$ represents the translation matrixes from marker 1 to the implant, ${}^{eye}_{marker2}A$ represents the translation matrixes of marker 2 to the human eye, and ${}^{marker1}_{tracker}D$ and ${}^{marker2}_{tracker}D$ represents the transformation matrix of the optical tracker in real time. Therefore, the researchers simulate the implant CG image to the translation of dentist's eye matrixes ${}^{eye}_{implant}P = {}^{marker1}_{implant}D^{tracker}_{marker1}D^{marker2}_{tracker}D^{eye}_{marker2}A$ (where, ${}^{marker1}_{implant}D = {}^{implant}_{marker1}D^{-1}$ and ${}^{tracker}_{marker1}D = {}^{marker1}_{tracker}D^{-1}$). Finally, it is proved by experiments that the preoperative navigation system is real-time and reliable. In 2018, Ma *et al*. proposed an AR surgical navigation with no marker points, achieving accurate cone beam computed tomography (CBCT)-patient registration for dental implant placement. The registration method applied in this paper is based on previous research results of the researchers [94]. The researchers designed patient in vitro registration equipment for implant surgery, tracked the registration equipment, calibrated the drill with reference markers, and finally used AR to guide the implant surgery. Fig.4 a) shows that the whole system developed realizes a real-time and real AR navigation scene. At the same time, the experiment proves that the registration result is accurate and shortens the implantation operation time under AR navigation [46].

In the practical application of oral surgery, real-time is great significance [40], [94]. Suenaga *et al*. has done a lot of research on this field [95]–[99]. In 2013, their research team evaluate the feasibility and accuracy of a three-dimensional AR system for imaging oral and maxillofacial regions [95]. The position of the patient/surgical instrument is identified and tracked using a 3D optical tracking system

TABLE 2. Overview of static registration method.

Registration type	Application field	Publication, Year	Mainly Contribution	AR display mode	Image form
Rigid registration [76-86]	Dental implant [76-79]	D. Kati´ *et al.*, **2015**, Fig. 2a) [76]	✓ Calibration method based on SPAAM ✓ Redesigned registration process ✓ Two display formats: static display and contact analog AR ✓ Deviation of the realized implants was <2.5 mm by new calibration method	HMD	2D→3D
		Y.-K. Lin *et al.*, **2013** [77]	✓ Setting a surgical template ✓ Registration method based on artificial identification point method ✓ Introduce virtual auxiliary lines to complete implanting ✓ Evaluated the accuracy between virtual planned implants and actual preoperative implants	Stereoscopic visualization (SV); HMD	2D→2D
		Y.-J. Kim *et al.*, **2012** [78]	✓ Registration method for fabricating a customized dental implant guiding template. ✓ Registration is simple compared to the previous method ✓ Automatic calculation of machining coordinates ✓ Only once CBCT scanning	Direct display	2D→2D
		Z. Bardosi *et al.*, **2012,** Fig. 2b) [79]	✓ IGSTK-driven augmented-reality application ✓ Set markers on the glasses for image registration ✓ 3D image overlay ✓ Reduce registration error by reducing rigid matrix transformation between camera matrix and tracker eye-glasses	HD-video overlay; 3D-tracker	3D→3D
	Oral and maxillofacial surgery [82-85]	Yu-Jin Won *et al.*, **2017,** Fig.2f) [85]	✓ 3D mandible image overlaps with the actual patient's oral image ✓ Markless AR ✓ Easy to use for dental clinics	HD-video overlay	3D→3D
		G. Badiali. *et al.*, **2014**, Fig. 2d) [82]	✓ Set 10 reference points for registration ✓ Registration method based on machine vision algorithm ✓ Developed a wearable AR system ✓ Localizer-free ✓ AR assisted bone repositioning method	HMD	2D→3D
		M. Zhu *et al.*, **2015**, Fig. 2e) [84]	✓ AR toolkits and 3D max applications ✓ Artificial identification point ✓ Preoperative planning image registration of the oral mandible ✓ Mimics model reconstruction ✓ Intraoperative navigation	Optical tracking; image projection	3D→3D
		M. Zhu *et al.*, **2011** [83]	✓ AR toolkit's marking points are installed in the braces and nipples. ✓ Artificial identification point ✓ 3D image overlay	HD-video overlay	3D→3D
	Dental education	K. Onishi. *et al.*, **2014**, Fig. 2c) [80] [81]	✓ Developed AR dental simulator ✓ Provide visual feedback and tactile feedback ✓ Observe the deformation of the virtual dental model through the operation of the actual hand ✓ Project a virtual dental model to a real tooth model	Image projection	N/A
	Orthodontics	A. Aichert. *et al.*, **2012**, Fig. 2g) [86]	✓ Monocular AR system ✓ Digital volume tomography (DVT) ✓ Dental image tracking algorithm ✓ Registration method based on dental edge information ✓ Video image is overlaid on the position of the bracket	HD-video overlay	2D→3D
Non-rigid registration [87-92]	Dental image [88-90]	B. Berkels. *et al.*, **2016**, Fig. 3a) [88]	✓ Multimodal non-rigid registration method ✓ Binarization and morphological processing ✓ Quantitative light-induced fluorescence (QLF) registration of images with real dental images	Direct display	2D→2D
		A. Nikaido. *et al.*, **2007** [90]	✓ Phase-Only Correlation (POC) function registration algorithm ✓ 2D discrete Fourier transforms ✓ Dental x-ray photo registration scheme	Direct display	2D→2D
		C.C. Leung *et al.*, **2005** [89]	✓ Automatic curvature-based registration ✓ Affine linear transformation ✓ Numerical solution of the underlying euler-lagrange equations	Direct display	2D→2D

TABLE 2. ***(Continued.)*** **Overview of static registration method.**

Oral and maxillofacial surgery [91] [92]	A. Bijar *et al.*, **2016**, Fig. 3d) [92]	✓ Automatic atlas-based method ✓ 3D transformation by registering the atlas volume image ✓ Diffeomorphic non-rigid registration based on B-spline freeform deformations	Direct display	2D→2D
	P. R. Andresen *et al.*, **2001**, Fig. 3c) [91]	✓ Geometry-constrained diffusion ✓ Only involves Gaussian convolution and projection of surfaces	Direct display	2D→2D
Denture manufacturing	C. V¨ogtlin. *et al.*, **2012,** Fig. 3b) [87]	✓ Analysis of local variations of denture models relative to steel models ✓ Quantify the local defects of the model relative to the steel standard	Direct display	2D→3D

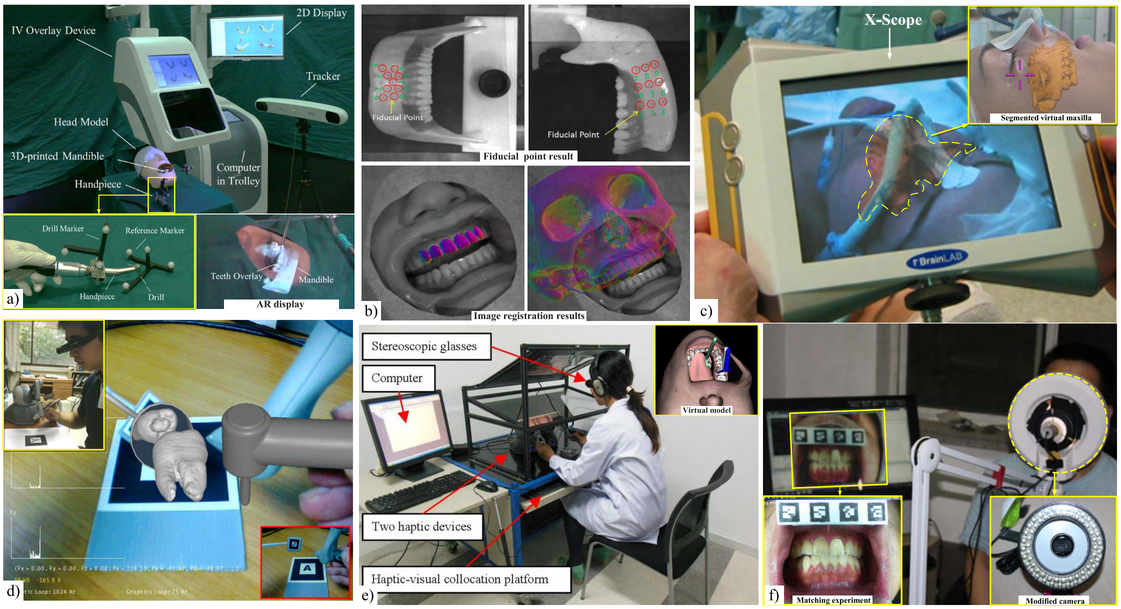


FIGURE 4. Application of real-time registration method. (a) AR navigation system and practical clinical application [94]. (b) Fiducial point result and image registration result [99]. (c) Surgeon's view and X-Scope [100], [101]. (d) AR environment and user operation environment [104], [105]. (e) AR system: two haptic devices, a haptic-visual collocation platform, stereoscopic glasses, audio speakers [107]. (f) teeth shade matching system based on AR [108].

(Northern Digital Inc., Waterloo, Ontario, Canada) to obtain a registration location. A complete image of the jaw, teeth and surgical instruments are overlaid on the patient's mouth. The coordinates of the tooth are registered with the coordinates of the image by measuring the coordinate system of the patient's features. In 2014, this team continued to propose a CGII (Computer Graphics) rendering method for generating medical three-dimensional images, the imaging of which belongs to the integral imaging method. Compared to projector-based or stereo-based AR, this method of 3D image overlay technology can handle image overlays in small surgical sites (compared to projector-based image overlay technology) without the need for bulky visual device (compared to stereoscopic image overlay technology). Correspondingly, a closed-loop automatic and real-time three-dimensional image registration method is proposed, and the registration process does not require any physical calibration device. The contours of the upper or lower jaw are reconstructed in real time through a stereo camera, and the corresponding contour extraction surface model is registered. The registration matrix is obtained using the iterative closest point (ICP) algorithm. The root mean square errors of the anterior teeth area and the molar area were 0.81 mm and 0.74 mm, respectively. In the same year, Wang *et al*. proposed a similar method, proposed an AR navigation system with automatic markerless image registration using 3D image overlay and stereo tracking for dental surgery [96]. Image registration is done by patient tracking and real-time 3D contour registration, without any reference and reference marks. Various aspects of the system were evaluated experimentally, and the image coverage error of the entire system was 0.71 mm. In 2015, the research team continued to explore the registration problem in the oral medicine, and proposed a real-time registration method based on stereo vision for markerless. In this paper, the edge of the tooth (200 feature points) was identified by two stereo cameras, and the dental position information was acquired, and the registration error was less than 1 mm [97]. The automatic markerless method is adopted, which makes the 3D-CT image display with high precision in the real oral medicine through the AR technology, and completes the surgical guidance. In 2016, a real-time markerless image registration method is proposed by integrating a shape matching method into a 2D tracking framework [98]. The method is more advanced in the original research, the target coverage error is about 1mm, the real-time registration update rate is 3-5 frames per second (fps), and the registration camera is a 4K camera [99]. The method of the registration is based on a 3D-2D global matching approach with a 2D tracking framework, and this method can well address the initial alignment problem and perform accurate registration in real time without any manual adjustment, which is shown in Fig.4 b).

In addition to the above teams, the Mischkowski team also explored such problem [100], [101]. In 2006, an AR device (X-Scope) allows for visual tracking of orthognathic surgery. However, in order to ensure the accuracy of the X-Scope registration, it may prolong the operation time or cause a surgical interruption [100]. In order to compare the maxillary translocation with the preoperative plan, the WinCephs software (COMPUDENT, Koblenz, Germany) was used to analyze the preoperative, postoperative lateral position and frontal position. In 2013, this team continued to use the X-scope (Fig.4 c)) device to navigate the surgery in real time and AR. It provided a precise technique of waferless stereotactic maxillary positioning, which may offer an alternative approach to the use of arbitrary splints and 2-dimensional orthognathic planning [101]. Through the video graphics array (VGA) camera, the virtual plan of the upper jaw and its real position can be completely overlaid during the operation. In 2017, a novel rotational matrix and translation vector (RMaTV) algorithm is proposed by Murugesan *et al*. The algorithm belongs to the enhanced iterative closest point (ICP) to eliminate the geometric error of image registration and superposition (from 1mm to 0.3mm-0.4mm) [102]. The accuracy can be calculated based on the overlaid error of the enhanced video in the actual surgical scene [103]. The processing speed of the video is increased from 7-10 fps to 10-13 fps. The individual images are registered for CGII.

The application of AR in dental training requires higher real-time performance. A virtual reality (VR) and an AR dental training simulator utilizing a haptic device are developed by Rhienmora *et al*. The AR environment allows students to practice correct postures, combine 3D dental and tool models with real-world perspectives, and display results through a video perspective HMD [104]. An HMD is used with a camera and ARToolKit library attached to the front. With the help of ARToolKit, real-time head tracking can be achieved by continuously acquiring camera images, detecting AR markers and 3D object registration [105]. Fig.4 d) shows that real-time head tracking can be achieved by continuously acquiring camera images, detecting AR markers, and 3D object registration according to the application of ARToolKit. In order to improve the training method for cleaning calculus, Hashimoto *et al*. developed a simulator for the training by using a PHANToM and a video-see-through HMD. In the AR environment, the patient (teeth, gums, calculus) and the scaler are virtual objects, and the trainee's hand is a real object. Similarly, the researchers used ARToolKit to register the marker points in the environment and placed 20 square markers around the PHANToM [106]. Moreover, the position and the angle of the virtual scaler are synchronized with the stylus motion of force display device to achieve the effect of real-time registration. In addition to washing teeth, the same problem exists in the training of tooth extraction. Wang *et al.* simulated the 6-DOF tactile interaction process during tooth extraction [107], and proposed a multi-stage model to simulate the gradual change of the connection strength between the target tooth and the surrounding gum, which is shown in Fig.4 e). The method is capable of maintaining a tactile presentation of a 1 kHz 6-DoF dental forceps in contact with multiple regions of the oral tissue in a narrow oral medicine. This method is capable of teaching the expected force pattern and correct tool posture. In addition, Qiao *et al*. proposed an AR system-based dental shadow matching system to help dentists verify the correctness of dental shadow matching and assess the acceptance of virtual teeth in cosmetic dentistry, which is shown in Fig.4 f). The entire system consists of a color-calibrated digital camera with a ring-shaped LED light and a bracket in a 500K color temperature environment, a marker point (located above the patient's lips, below the nose), and a computer [108]. The camera uses identification points to register and virtualizes the color matching teeth on the patient's teeth for color matching. The system provides a virtual verification before patient repair is completed, which reduces duplication of visit time and waste of labor and materials.

V. DISCUSSION AND FUTURE DIRECTIONS

A. DISCUSSION

This paper reviews the registration methods and related technologies of AR in oral medicine. We discuss the key technologies and existing limitations of static registration and real-time registration.

1) STATIC REGISTRATION METHOD

Static registration can be classified into rigid registration and non-rigid registration according to the conversion model. Rigid registration is primarily used for registration of dental or jaw images in the mouth [76]–[86]. The development of techniques for calculating rigid registration of simple and easy to manipulate medical images has been relatively mature compared to non-rigid registration techniques, particularly in the field of oral and rigid teeth that are not deformed [84]. However, rigid registration does not meet the current medical requirements, so non-rigid registration studies can be used to compensate for the limitations of rigid registration [87]–[92]. Researchers apply non-rigid registration methods to solve more deformable problems in stomatology [56]–[58], [60].

TABLE 3. Overview of real-time registration method.

Application field	Publication, Year	Mainly Contribution	Real time parameter	AR display mode	Image form	Automatic registration
Oral and maxillofacial surgery [95-102]	Y. P. Murugesan *et al.*, **2017** [102]	✓ Rotational matrix and translation vector algorithm (RMaTV) based on iterative closest point (ICP) ✓ Improve geometric error in image registration and overlay (from 1mm to 0.3mm-0.4mm) ✓ Registration accuracy can be calculated according to the actual application scenario.	❖ Video accuracy 0.30-0.40mm ❖ Registration processing speed 10-13fps ❖ Depth perception increased by 90-100mm	4K (4000 pixels resolution) camera; Bounding-box tracking	2D→3D	Automatic
	H. Suenaga / J. C. Wang *et al.*, **2016, 2015, 2014, 2013** *(The literature is in the table from top to bottom according to the year.)* [95-99]	✓ Markerless registration method ✓ Clinical settings are more convenient and seamlessly linked to the treatment process ✓ Rapid system response time ✓ View-based 3D-2D global matching method combined with 2D tracking framework	❖ Target coverage error is approximately1mm ❖ Registration update frame rate is 3-5fps ❖ Registration time 0.20-0.40s	4K camera; HD-video overlay	3D→3D	Automatic
		✓ Markerless registration method ✓ Setting Two stereo cameras to identify the edges of the teeth (200 feature points) ✓ High-precision display of 3D CT images in real environment ✓ Introduce the regions of interest (ROI) region to improve camera registration rate	❖ Average registration error is less than 1mm ❖ Registration time is less than 3s	HD-video overlay; 3D optical tracking; Stereoscopic visualization	3D→3D	Automatic
		✓ Introduction of Target registration errors (TRE) ✓ CGII (Computer Graphics) integral imaging rendering method for producing medical 3D images ✓ Direct ray-casting algorithm ✓ Closed loop automatic three-dimensional image calibration method	✓ Image rendering speed is 5-8fps ✓ Surface model rendering speed is 50-60fps ✓ The root mean square error of the anterior teeth area is 0.81mm ✓ The root mean square error of the molar area is 0.74mm	HD-video overlay; 3D optical tracking	3D→3D	Automatic
		✓ The iterative closest point (ICP) algorithm is used to obtain the registration matrix ✓ Setting a CG model (consisting of five spatial spheres) ✓ IP-Camera virtual space tag registration method ✓ Real-time markerless registration method	❖ Fiducial registration error: 0.35mm ❖ 3D image overlay average total error 0.71mm	HD-video overlay; 3D optical tracking	3D→3D	Semi-automatic
		✓ Using spectrum optical tracking system ✓ Mounted on volunteer teeth based on artificial identification points ✓ Real-time tracking of infrared reflective ball attached to the surface	❖ Positional error: 0.77mm ❖ Angular error: 0.68°	HD-video overlay; 3D optical tracking	3D→3D	Semi-automatic
	R. A. Mischkowski *et al.*, **2013, 2006,** Fig.4 c) *(The literature is in the table from top to bottom according to the year.)* [100] [101]	✓ Waferless stereotactic maxillary positioning ✓ Application of video graphics array ✓ Meet arbitrary splints ✓ 2-dimensional orthognathic planning	❖ Orthogonal dimension: <0.67mm ❖ Kull base edge: <0.41°	Interactive image-guided visualization display (IGVD); HD-video overlay	2D→3D	Semi-automatic
		✓ Real anatomical structure for visual tracking ✓ AR device application	❖ Maxillary positioning accurately within a range of 1 mm	HD-video overlay; X-Scope®	2D→3D	Semi-automatic
Dental education [104-107]	D. X. Wang *et al.*, **2015**, Fig.4 e) [107]	✓ Dental extraction simulator ✓ Interactive tooth extraction six-degree-of-freedom tactile simulation ✓ Multi-stage model to simulate the contact relationship around the gums ✓ Energy accumulation model calculates the rotation and translation of the	❖ Haptic device 1kHz 6-DOF	Image projection	2D→3D	Semi-automatic

TABLE 3. ***(Continued.)*** **Overview of real-time registration method.**

		forceps				
	P. Rhienmora *et al.*, **2010**, Fig.4 d) [104] [105]	✓ Tactile force feedback device combined with AR developed dental training simulator ✓ Detecting strength and quality of care during dental training ✓ AR Toolkit application ✓ Artificial identification point	N/A	HMD; 6-DOF haptic device	2D→3D	Semi-automatic
	N. Hashimoto *et al.*, **2007** [106]	✓ Clean up the teeth stone trainer ✓ Application of AR Toolkit ✓ Artificial identification point	❖ Decreases 50s or less by ten minutes training ❖ Calculus adhesion within the range of 1.5-5N	PHANToM; HMD	2D→3D	Semi-automatic
Dental implant [93][94]	L. F. Ma *et al.*, **2018**, Fig.4 a) [94]	✓ Markerless registration method ✓ Cone beam computed tomography (CBCT) ✓ Shortened the time of implant surgery under AR navigation	❖ Mean target error: 1.25 mm; ❖ Mean angle error: 4.03° ❖ Mean registration error: 0.38mm	Optical tracker	3D→3D	Automatic
	S.Yamaguchi *et al.*, **2011** [93]	✓ Surgical navigation system ✓ Retinal Imaging Display (RID) ✓ Least Median Square (LMedS) ✓ Marker combined with partially edentulous model	N/A	Optical tracker	2D→2D	Semi-automatic
Dental image	C. Qiao *et al.*, **2011**, Fig.4 f) [108]	✓ Dental shadow matching system ✓ Evaluate the acceptance of virtual teeth in cosmetic dentistry ✓ Synthetic virtual teeth using subsurface scattering effects ✓ Registration based on artificial identification points	❖ Continuous output force of the touch device: 1.75N ❖ Position resolution>1100dpi, 0.023mm	18 % gray camera	2D→2D	Semi-automatic

We will continue our discussion based on the key technologies and basic steps of the two.

a: RIGID REGISTRATION METHOD

According to the above application and the reference on rigid registration, the core idea of rigid registration can be summarized as follows: one of the images to be registered is set as a reference, called a standard image; the other image is based on a standard image [76]–[78]. Perform a spatial transformation called a floating image. The process of rigid registration can be decomposed into a series of rotational translation steps, and the floating image enters a series of transformations to coincide with the spatial position of the corresponding pixel on the standard image. The specific steps of rigid registration are: 1) establishing spatial transformation function; 2) establishing registration function; 3) selecting optimized search algorithm. The transformation function is established by the image deformation model [80], [109]. The real-image and the virtual image are transformed into the same coordinate system by the homogeneous coordinate representation, and the transformation relationship between the real image and the virtual image is represented by a matrix. Common transformation models include rigid body transformation, affine transformation and projection transformation [78]–[80].

The optimized search strategy [32] is a critical step in the medical image registration process. The purpose of optimizing the search algorithm is to find the maximum mutual information value by continuously adjusting the registration parameters, and obtain the corresponding registration parameters when the two images reach the optimal registration [82]. Common optimization search algorithms include Powell optimized search algorithm, genetic algorithm, ant colony algorithm and so on. The ant colony algorithm achieves good experimental results on allocation problems and scheduling problems, and has certain advantages in solving discrete optimization problems [109]. The genetic algorithm is characterized by direct manipulation of structural objects, automatic acquisition and optimization of search space, and adaptive adjustment of search direction. Genetic algorithms have played a huge role in combinatorial optimization problems and machine learning [81]–[83].

b: NON-RIGID REGISTRATION METHOD

The core idea of non-rigid registration is divided into the following three parts: 1) transformation between standard image and floating image; 2) measuring the degree of similarity between the floating image and the reference image; 3) seeking a search strategy for the required transformation parameters in the measurement process [88]- [90]. A number of relatively mature non-rigid registration algorithms have researched, such as spline-based registration methods, physical model-based non-rigid registration methods, and optical flow field model-based registration methods [40]. The basic idea of the registration method according to the spline function is to respectively create a two-dimensional grid on the floating image and the reference image, and regard the grid node as a control point. The deformation of the floating image is controlled by the movement of the control point, and the control point fits the motion displacement of the pixel in the image based on the transformation of the spline, thereby obtaining a registration effect [110]. The freeform transformation of B-spline based on function description transformation is the most popular, but the traditional B-spline function has smoothness and singularity or folding effect in the deformation field [92]. Moreover, the single-layer B-spline has a lot of details of image difference after registration, and it is usually impossible to accurately select the initial mesh density. The non-rigid registration method based on the physical model mainly attributes the difference between the floating image and the standard image to certain specific physical changes. Therefore, the core of the method is to find a physical change model that simulate this difference [91]. The basic principle of the optical flow field model registration method is to treat the reference image and the floating image as a series of sequence images. The success of the registration depends on whether the corresponding motion field can be estimated from the sequence image.

2) REAL-TIME REGISTRATION METHOD

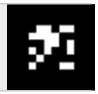
Real-time registration is a research hotspot in recent years [51], which allows doctors not to be limited any more to make preoperative planning. And moreover, AR real-time registration can help doctors to carry out effective intraoperative guidance, and improve the doctor's operating environment during the actual surgery. The doctor can use AR to arbitrarily zoom in, zoom out or rotate the inside of the mouth [8], [13]. The AR real-time registration process based on manual marker points, such as ARtoolkit [105], [106].

a: MANUAL MARKER REGISTRATION

The registration method based on manual marker is to use some natural scenes or artificially placed objects as identification points in real-world [95]–[97]. Then, the camera is used to identify the identification in the image, and at the same time, the tracking and registration of the virtual information is completed in combination with the camera calibration principle. The identification point type is a key step of the registration method, and the types of the marker are classified into an image template matching type and coding features type [111]. The registration mark commonly used in the above reference is ARToolkit, which belongs to the image template matching type, but it has certain limitations [105], [106]. We summarized the various types and characteristics of marker in Table 4.

The image template matching type is readable, and the marker has certain information. Taking the identifier used in ARToolKit as an example, the corrected candidate image needs to be matched one by one with the standard image templates in four directions under three illumination conditions.

TABLE 4. Overview of various types and characteristics of marker.

Marker	Characteristics	Design
ARToolKit	✓ Common registration marker ✓ Vulnerable to light and the environment ✓ Based on graphic template matching	
ARTag	✓ Registration method is the same as ARToolkit ✓ Recognition based on CRC coding features ✓ Robust to illumination and occlusion	
ARToolKit Plus	✓ Develop for mobile devices ✓ Logo pattern border variable ✓ High recognition rate	
AR Studio	✓ Marker pattern: black background and white polygon ✓ Complex graphics and complex recognition algorithms	
Visual Code	✓ Two-dimensional code marker ✓ Increased number of identifiable points ✓ Low registration accuracy	

When there are N candidate identifiers, 12 × N template matching is needed. This method is computationally intensive and affects the real-time performance of the AR system [105]. The coding features type identifies the marker by decoding the inside of the image. The main steps of the common detection of the identification at this stage include: binarization of the input image, finding the connected region, shape fitting the contour of the connected region, and obtaining four corner points [111]. Complex calculation methods such as Hough transform and contour fitting are often used. This type of marker not only improves the recognition speed of the marker, but it also enhances the scalability of the marker.

b: NATURAL FEATURE REGISTRATION

The natural feature-based tracking registration technology uses the natural features in the real world to extract the reference points [100]. Therefore, one of the basic and key technologies of the registration method is the extraction of natural features [111]–[113]. The feature points are some pixels in the real world with special appearance and representative shapes, generally satisfying the following conditions: 1) easy-to-definition spatial position coordinates; 2) vivid image nodes around them to simplify the processing steps of machine vision; 3) ensure certain stability for local and global disturbances in the image range.

The feature point extraction is completed by feature point extraction and matching algorithm. The commonly used algorithms can be divided into three types: spot detection, corner detection and feature point description algorithm [99]–[101]. The algorithmic improvement and processing speed will affect the overall operation time and quality of AR-guided oral surgery. At present, in oral and maxillofacial surgery, the video accuracy can reach 0.3-0.4mm (in terms of coverage error), and the processing efficiency can reach 10-13 fps [102]. We summarized the existing common

TABLE 5. Overview of various types and Characteristics of algorithm.

Algorithm Type	Algorithm	Characteristics
Spot detection	SIFT (Scale-Invariant Feature Transform)	✓ Direction: the gradient direction of the neighborhood pixels of the feature point ✓ Feature point center size: 16*16 ✓ Convolution of the original image with the Gaussian kernel to create a scale space ✓ 128-dimensional descriptor vector ✓ Large amount of calculation and long time
	SURF (Speed-Up Robust Features)	✓ Application of Hessian matrix ✓ Feature point center size: 4*4 ✓ Apply the Haar template to find the response in both directions ✓ 64-dimensional descriptor vector improves computational efficiency relative to SIFT
Corner detection	Harris	✓ First derivative matrix based on image gray scale ✓ Using a Gaussian function as a window ✓ The eigenvalue remains unchanged ✓ Very sensitive to gray scale, extracted pixel-level corners
	FAST (Features from Accelerated Segment Test)	✓ Discretized Bresenham circle with pixel point 3 centered on the pixel ✓ 16 pixels ✓ Machine learning ID3 greedy algorithm to build decision tree to speed up algorithm
Feature point description	BRIEF (Binary Robust Independent Elementary Features)	✓ Select several pixels around the feature point ✓ Binary string is used to describe feature points ✓ Fast calculation ✓ Sensitive to noise, without rotation invariance, without scale invariance
	BRISK (Binary Robust Invariant Scalable Keypoints)	✓ Compare pixel gray values ✓ Neighborhood sampling mode ✓ Construct multiple discrete Bresenham concentric circles of different radii ✓ Better rotation invariance and robustness
	FREAK (Fast Retina Keypoint)	✓ Optimize and improve the BRISK algorithm ✓ Sampling model close to human eye retina receiving image information ✓ 512bit binary descriptor
	ORB (Oriented FAST and Rotated BRIEF)	✓ Combining the detection method of FAST and the feature description method of BRIEF ✓ Randomly take points to compare pixel size for assignment ✓ 256-bit binary descriptor ✓ No scale invariance and rotation invariance

algorithms into Table 5 to discuss their characteristics and limitations.

After extracting the feature points, the feature points are used to establish a world coordinate system. In order to ensure the real-time dynamic update of the registration, it is necessary to map the virtual space coordinates with the image coordinates [104]. It is necessary to complete the transformation of three coordinates: 1) transformation from the world coordinate system to the camera coordinate system; 2) transformation from the camera coordinate system to the image plane coordinate system; 3) transformation from the virtual space coordinate system to the world coordinate system [112]. The transformation of the world coordinate system to the camera coordinate system in the first step is a key step to complete the real-time registration [97]–[99]. Generally, the conversion relationship between key frames is determined according to the camera coordinate system. In order to solve the attitude parameters, a mapping relationship from 2D pixel coordinates to 3D world coordinates is established. Before calculating the pose, you must first calibrate the camera, that is, calculate the internal parameters of the camera [113]. The internal parameters can be used to calculate the homography matrix in the matching process to determine the target, and the two-dimensional pixel points can be converted into corresponding three-dimensional points of the world coordinate system in real time, thereby obtaining the conversion relationship between the two coordinates.

According to the core ideas and specific steps, the key technologies, advantages and limitations of these registration method are listed in Table 6.

B. FUTURE DIRECTIONS

As an important indicator to evaluate the effect of AR, the registration problem has three key technical indicators: real-time (no delay), stability (accurate, jitter-free), robust (not affected by illumination, occlusion, and object motion). The above core problems in the field of oral medicine are particularly important. The following five future directions are derived through the extension of three key technologies:

1) FEATURE EXTRACTION OF ORAL IMAGE REGISTRATION

In feature-based image registration, the automation of registration can be achieved using the internal geometric features of the oral image. The most important part of oral image registration is feature extraction based on geometric features. The acquired features are used to complete the matching between the virtual and real image features. The matching relationship between the virtual and real images can be established through the matching relationship of features. Points, straight segments, edges, contours, closed regions, or a comprehensive feature composed of them, feature selection, extraction, and matching between features are directly related to the accuracy of the registration parameters.

2) RESEARCH ON CAMERA PARAMETERS AND REAL-TIME REGISTRATION ALGORITHMS

The use of traditional camera calibration technology has certain shortcomings. Once the camera moves, the parameters will change greatly. As a result, registration errors will be occurred, affecting the fusion of the virtual model and the real scene, and the realism will be declined. Simultaneous real-time performance requirements for stereo cameras are high, and many challenges are placed on their robust reconstruction. Selecting a more suitable camera, such as a depth camera (Time of Flight, TOF), is not only inexpensive,

TABLE 6. Overview of registration method.

Registration type	Registration method	Key technology	Advantage	Limitation
Static registration	Rigid registration method	✓ Approximate similarity side metric ✓ Spatial transformation function ✓ Registration function ✓ Optimized search algorithm	✓ Simple transformation model ✓ Simple process ✓ Relatively mature	✓ Only suitable for rigid tissues (tooth, jaw, bone) ✓ Higher registration error rate
	Non-rigid registration method	✓ Non-rigid transformation method ✓ Polynomial, odd function and spline function ✓ Search strategy for transform parameters	✓ Compensating for image distortion caused by organ deformation ✓ High-degree of freedom local spline curve control	✓ Physics model method has large calculation ✓ B-spline curve has a long singularity
Real-time registration	Manual marker registration	✓ Manual identification point type ✓ Manual identification detection algorithm ✓ Model transformation matrix and viewpoint transformation matrix ✓ Solution of camera external parameters	✓ No need to rebuild the real world ✓ Tracking registration calculations are less complex ✓ Achieve better real-time performance and accuracy	✓ Placing the marker affects the integrity and naturalness of the real world. ✓ Reduce the doctor's AR experience ✓ There are drift and flag occlusion issues during the tracking registration process
	Natural feature registration	✓ Feature point identification and matching algorithm ✓ Linear imaging model of the camera ✓ Camera internal and external parameters ✓ Transformation matrix of three coordinate systems	✓ High registration accuracy, ✓ Ensure real world integrity ✓ Wide range of applications	✓ High computational complexity ✓ High system delay ✓ Depend on algorithm tracking to register

compact, easy to use, and susceptible to texture illumination, but also captures surface depth and color information in real time. In addition to the limitation of camera hardware parameters, the research of real-time registration algorithm also plays an important role. The real-time nature of the system directly affects the wide application of AR technology in medicine. If the real-time problem is not solved well, the AR will not be well applied in the surgical navigation during surgery.

3) VERIFICATION OF REGISTRATION ACCURACY

Nowadays, AR utilized the registration technology to complete the fusion of virtual and real objects in the oral medicine, thus achieving preoperative guidance and intraoperative navigation. However, this key technology for registration can only rely on the geometry of known organs and model experiments for pre-operative verification, and registration accuracy verification system has not yet been established. Especially for the accuracy problem when the three-dimensional entity is registered with the three-dimensional virtual model, the registration relationship of the three-dimensional object is complex and variable, and there are multiple variable parameters. The establishment of registration accuracy verification can further study the registration error law and propose an error compensation model or algorithm to improve the registration accuracy of AR technology in the oral medicine.

4) ORAL IMAGE ACQUISITION AND VIRTUAL MODEL RECONSTRUCTION

The accuracy of oral image acquisition will affect the accuracy of subsequent virtual oral model reconstruction. Oral image acquisition is generally obtained through CBCT images and dental scanners. The key technologies are scanning accuracy, scanning efficiency, data interface, and software functions. Reducing the size of equipment and improving equipment accuracy are the future development prospects. The reconstruction of virtual oral models is generally done in a pre-established manner. Because the virtual oral model lacks the same illumination, shadow, and occlusion effects as the real oral scene, especially in the narrow oral environment, there will usually be inconsistencies when the virtual oral model is registered to the real oral scene. In the field of medicine, AR usually overlays the reconstructed model onto the corresponding organ position. It is important that the reconstruction of the virtual model is accurate and true, which will affect the accuracy of the entire virtual and real registration and the realism of the display.

5) ESTABLISHMENT OF AN ENVIRONMENTAL ILLUMINATION MODEL FOR ORAL SURGERY

In order to realize the seamless integration of the virtual oral model and the real oral environment registration, it is necessary to consider the illumination information of the real scene and feedback to the virtual object drawing and rendering in real time, so that the oral image displayed by the AR is more realistic. At the same time, due to the influence of experimental equipment and ambient illumination, in the process of video image acquisition, the features or logo extraction methods that have been implemented in the experiment often change according to the environment, and thus further clinical research is not suitable in the later stage. Illumination and occlusion problems have a greater impact on the realization of the fusion between virtuality and reality, which will affect the effect of false and real registration, so that the information enhancement of the entire scene is weakened or even lost.

VI. CONCLUSION

In this paper, we reviewed two types of AR registration methods for oral applications: static registration and real-time registration, where static registration is divided into rigid registration and non-rigid registration. Through an overview of these registration methods, we discuss their respective advantages and limitations. At the same time, we propose five future development directions for registration problems. There is important significance for AR registration methods in the oral medicine.

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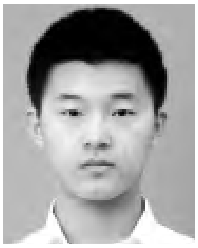

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