Dear Reviewers:

We would like to express our sincere appreciation to all the reviewers for their helpful comments and suggestions on our manuscript entitled "***Preliminary Study of a New Macro-Micro Robot System for Dental Implant Surgery: Design, Development and Control***", as well as their valuable time and efforts spent helping us improve our manuscript. Following the comments, the manuscript has been duly revised, and our responses are listed below.

In this response letter, the **Changed** or **Added** texts in the **revised manuscript** are highlighted in **BLUE**, while the **Original** texts in the **original manuscript** are highlighted in **RED**, which is convenient for checking the revision according to the comments. Moreover, all the revised texts in the manuscript are highlighted in **BLUE** in the ***revised manuscript file***. Among our submitted files, "***manuscript_R2.docx***" and "***manuscript_R2_TrackChange.docx***" are the *MS Word* files of our revised manuscript with and without the *Track Change* function activated. "***Response_to_reviewers_R2.pdf***" is our response letter, in which the contents of our revision, as well as our reply, are listed.

Responses to reviewer #1

Before replying, we sincerely appreciate your careful review, especially the insightful comments which are valuable for improving the quality and readability of our manuscript. In general, to address your concerns and suggestions, three major changes are made:

1) The majority of the ***Introduction Section*** is totally overhauled to bring a more structured and more comprehensive description of our motivation for developing the force-controlled system, including three main changes: **a)** Summarizing the current systems and then introducing the issue of force-based control with some remarkable related works, carrying out the main research objective of our work; **b)** Introducing the reason for using force-based control with the support of biomechanical studies; **c)** Introducing our another motivation of using medical robots to enhance the dental healthcare for less-developed areas where professional dentists are in shortage.

2) We rewrote ***Section 2.1*** to present the overall DIRS system with the related details presented, including: **a)** the sub-system constitution, which consisted of a mechatronics executing sub-system, a binocular vision sub-system, a feeding sub-system, and a laser generating sub-system, is described, with the mechatronics system is detailedly introduced. **b)** The procedure of how to use the system, which module is responsible for each step, and who is responsible for driving during each step are described. **c)** All these details are illustrated in ***Figure 1*** to bring a more intuitive and better understanding of the outline information of our system.

3) In the ***Discussion Section***, we newly added two paragraphs to discuss and summarize the potential of future applications, including: **a)** The rationality for developing our system is summarized. **b)** The potential advantages with respect to manual operation are discussed, showing the prospect of future application.

After our careful revising, some systematic or practical information is greatly enriched and much deeper, improving the readability. Our replying to all the comments are listed as follows.

Comment 1:

The state of the art offers a list of some previous robots for oral surgery without a structured rationale. Why the current robots are not enough to perform dental implant surgery? Given the state of the art, why the authors designed their system with the described architecture, which is huge and integrate a commercial robot?

Response to comment 1:

Many thanks for your comment, we agree that the aim and motivation for designing this system and architecture are not clearly presented, and we apologize for this overlook. Firstly, some systems have already been developed by the academic or industrial communities, of which a few outstanding ones can conduct dental implant for patients, such as the Yomi robot in the USA and the Remebot Robot in China. Thus current robots are gradually stepping into clinical practice, as the sentence "*Both the academic and industrial communities have developed some implantation robot systems and methods, and a small portion of them have already been deployed for clinical practice*" (***line 57-58, page 2, Section 1***) says.

Then, the reason for developing our system with this architecture can be listed as follows:

1) In terms of implant insertion, current systems mainly rely heavily on stereo vision systems or image systems, research on force-based control applications for implant insertion still remains rare. Given that force information is an important resource, it should be exploited and combined with current vision-based navigation to improve the quality of implantation.

2) In terms of the stereo vision system or image system, some possible drawbacks may exists. This part usually contains 3D reconstruction, model registration, vision localization, and hand-eye calibration. During the implementation of these modules, errors can accumulate. Moreover, a vision marker (e.g. a checkerboard, or fluorescence balls) must be worn on the patient's head or mouth to enable vision localization to exert its function. However, the vision marker can not be strictly fixed on the patient's head, it can be changed or disturbed due to the intentional or unintentional deformation of the soft tissue, which can directly lower the positioning accuracy. Therefore, when performing implant insertion, a small misalignment may occur, lowering the accuracy of the implantation.

3) In terms of biomechanical mechanisms, the quality of implant insertion is closely related to the prognosis quality. Some studies (***References [34]-[38]***) have pointed out that the stress between the implant and the alveolar bone is important, both over-loaded and under-loaded stress will do harm to prognosis repair. For example, too small stress will reduce both the stability of the implant and the rate of bone healing due to insufficient stimulation. On the contrary, too large stress can incur bone resorption, damage, or increased risk of failure. Following this, if an implant insertion has a larger misalignment (position/posture error), it can lead to excessively large, small, or both stress. For instance, one side of the implant/bone is over-loaded, while the other side is under-loaded, causing both two sides inappropriate in force/stress distribution. Thus, if the force information during the implanting process can be used to improve the skill, the possibility of harming the postoperative repair can be greatly reduced.

4) In terms of inclusive healthcare for less-developed regions, our research also aims to address the issue of dental implanting for underdeveloped regions. Because the physicians in these

regions often lack sophisticated skills for implanting, combined with the long working hours, fatigue, and the trembling of hands, the quality of implanting can not be well guaranteed. With the help of the proposed DIRS, a skillful implant insertion can be performed without human participation, enhancing the operating quality for less-skilled rural doctors, meanwhile, the operation can be faster. Therefore, as our aim is fulfilled, both the efficiency and effectiveness can be greatly improved.

To sum up, our reason for developing this system includes the above-mentioned four points. Furthermore, as is introduced in ***Section 2.1***, an integrated commercial robot (universal manipulator) is adopted to carry the actuators, play the role of a vehicle for steps including master-slave feeding (steps 1 and 4), tool changing (step 3), and retreating (step 6). Moreover, the universal manipulator also serves as an XYZ linear motion platform for position adjusting during hole preparing (step 2) and implant inserting (step 5). In addition, most of the existing studies also employ a third-party manipulator to execute the motion. Therefore, adopting a commercial manipulator is a widely accepted and reasonable architecture.

The main changes corresponding to this comment are shown below:

【1】 ***Paragraph 4*** of the ***Introduction Section*** (see ***line 57-68, page 2, Section 1***) is rewritten to summarize the current systems and then introduce the issue of force-based control with some remarkable related works, carrying out the main research objective of our work.

The **original text** is

"As an essential part of high-quality surgical operation, control technology is another important issue, in which master-slave control and compliance control are two key aspects. In master-slave control, the surgical instrument follows the master device that is driven by the surgeon [24]. Shi et al. used a dynamic model to establish master-slave mapping [25]. He et al. took model-based gravity compensation and tremor canceling algorithms to improve the operation quality [26]. As for compliance control, the relationship between force and motion response is the core [27-28]. Kasahara et al. achieved better drilling through the hybrid force/position control strategy in their dental drilling robot [29]. Li et al. proposed an impedance control strategy for their cable-driven dental robot [30]. Impedance control can also be expanded with parameter identification [31], or fuzzy PID method [32]. Also, as another form of impedance control, admittance control is more intuitive and is adopted in a prediction-based safety framework [33-34]. In addition, some vision-combined methods have the potential to enhance the control quality [35]. For example, a team from Peking University proposed a markerless position-tracking method for oral surgery [36]. Further, vision information can be combined with other sensors to enhance the information sensing[37], which can be helpful to enhance the control quality. The above works enrich the control technology of surgical robot and are very constructive to the work of this paper."

The **revised text** is

"Both the academic and industrial communities have developed some implantation robot systems and methods, and a small portion of them have already been deployed for clinical practice. However, current systems still rely heavily on stereo vision navigation, without sufficient force-based control, which exploits force information to enhance accuracy. That is to say, the force information during implantation can adjust the motion of robots, having the potential to improve the implanting quality. As for force control in dental robots, the relationship between force and motion response is the core [26-27]. Kasahara et al. achieved better drilling through the hybrid force/position control strategy in their dental drilling robot [28]. Li et al. proposed an impedance control strategy for their cable-driven dental drilling robot [29]. Impedance control can also be expanded with parameter identification [30], or fuzzy PID method [31]. Moreover, admittance control is a more intuitive form of impedance control and is adopted in a prediction-based safety framework for an ophthalmic surgery robot [32-33]. However, there is little research work focused on force-based control for dental implanting (implant inserting). Therefore a specialized position/posture adjusting machine and corresponding control strategy are needed, which is the main research objective of this work."

【2】 Paragraph 5 and 6 of the ***Introduction Section*** (see ***line 69-86, page 2, Section 1***) is totally rewritten to introduce the reason and aim of our research, as well as the rationality and future application value of the force-controlled system with the support of some biomechanics studies, replacing the counterpart of the previous version of the manuscript, whose description is empty and powerless. The reason for introducing force-based control is described in Paragraph 5, and another aim of helping dental healthcare for less-developed areas is introduced in Paragraph 6.

The **original text** is

"A series of problems have been solved in recent years. However, there are still some drawbacks or limitations in most current studies. For example, the implantation process relies heavily on the stereo vision system, with a lack of in-depth research on force-based control methods for implantation. That is to say, the core of most existing systems is usually vision-based navigation, while the application of force control is often limited to manually dragging the manipulator to the target point. As a result, if an error of only 0.5mm is caused by the vision system, the contact force may be very large, posing a risk of damaging the tissue/instrument and lowering the implanting quality. Meanwhile, the marker for vision localization, which is worn on the oral cavity, may creep due to intentional or unintentional deformation of soft tissue, directly lowering the accuracy of vision navigation. Thus, the potential of force sensing and force control is far from being fully exploited, and there are few valuable studies published in the field of force-based implantation strategies, which is a potential direction to make new contributions. Additionally, a mechanism specifically designed for dental implant surgery is still needed, given that traditional structure is universal, without special focus on the oral cavity, causing unnecessarily more work in kinematics constraints, which can be solved unilaterally by mechanical design. Furthermore, most system devices are expensive, imposing more maintenance burdens on users. Therefore, this paper aims to develop a low-cost, modular implant robot system and design an implanting actuator with a simple but effective structure and easy maintenance. Also, preliminary work on force-based control strategies will be introduced."

The **revised text** is

"The reason for introducing force-based control to implant insertion includes two points: Inappropriate force and imperfect vision system. On one hand, implanting accuracy is closely related to the prognosis quality. Some researches have pointed out that the bone's stress is important [34-36]. When the stress is too small, both the stability of the implant and the rate of bone healing are lower [37]. When the stress is too large, bone resorption may occur, leading to loosening or an increased risk of failure [38]. Thereby, when an implant is inserted with a relatively larger misalignment, the implant will be overloaded or under-loaded, or both, incurring instability, looseness, or damage. On the other hand, the vision system may not be perfect due to possible errors from 3D reconstruction, model registration, and vision positioning. Meanwhile, the marker for vision localization, which is worn on the oral cavity, is not strictly fixed and may creep due to the deformation of soft tissue, lowering the accuracy of vision navigation. Additionally, the unintentional disturbing motion of the patient's head may increase such misalignment. Therefore, force-based control should not be overlooked, it is an important resource to further enhance the implanting skill.

Adding to the importance of force-based control, this research also aims to address the issue of dental healthcare in underdeveloped regions, thereby a dental implant robot system (DIRS) is proposed. Because the physicians in these regions often lack sophisticated skills for implanting, combined with fatigue and trembling of hands that can obviously reduce the accuracy due to long working hours, the quality of implanting can not be well guaranteed. With the help of the DIRS, a skillful implant insertion can be performed without human participation, enhancing the operating quality for less-skilled rural doctors, meanwhile, the operation can be faster. Therefore, as the aim is fulfilled, both the efficiency and effectiveness can be greatly improved."

Comment 2:

The end effector robot design and its control strategy seems interesting but there are no ideas about their future clinical application.

Response to comment 2:

Thank you very much for your comment. From your helpful comment, we also think our manuscript mainly focuses on the machine and control, it is a bit bland and lacks details from a systematic and clinical viewpoint.

In terms of ideas for further application, we envisage a scenario in which the doctor of less-developed regions without a good skill can perform a guaranteed dental implant with the help of force-based control. This system has the potential to relieve the imbalance of medical resources for less-developed regions. Therefore, several changes in the revision can address this comment, listed as follows:

【1】 ***Paragraph 6*** of the ***Introduction Section*** (***line 80-86, page 2, Section 1***), which has been shown in ***Response to comment 1***, first introduces the scenario of robot-assisted treatment for less-developed areas, which is an idea of future clinical application.

【2】 In ***line 125-147, page 3, Section 2.1***, a detailed procedure is added, with the primarily responsible modules, and who should operate the robot all described and illustrated in ***Figure 1***, also forming an idea of future application. Because this part is belong to the system information, more details can be seen in ***Response to comment 3***.

【3】 In the ***Discussion Section***, see ***line 476-488, page 15, Section 4***, the issue of future application is discussed and summarized again in a newly added paragraph.

"In summary, this work designed an implanting system with its posture adjustable, also, theoretical and practical research have been made for force-based implant insertion. Although it is currently a proof-of-concept prototype, it has great potential for future application based on its rationality: 1) Force-based compliance control can improve the implanting accuracy, reduce the occurrence of excessively high or low force/stress, and improve the quality of prognosis. 2) For less-developed regions where skilled experts are in shortage, the local physicians whose skill is limited can provide the implanting surgery with better efficiency and effectiveness by using the DIRS system. 3) The vision system is not always perfect due to the accumulated error of its several modules, thus the force-based control can be an important supply for the current vision-based method. With the above-mentioned conditions combined, the force-controlled system can be helpful to better execute the implant insertion, especially aimed at rural areas or underdeveloped regions where the medical resource is far from sufficient. Furthermore, for these regions, the DIRS system also has the potential for remote surgery by inviting experts to participate in the treatment remotely by planning the therapy and providing suggestions without coming into the operating room personally, since the force-controlled system can provide skillful implantation."

Comment 3:

Who and how drive the robot? In the discussion session both teleoperation and vision-based path planning methods are mentioned but without any information about the master robot console and the navigation system.

Response to comment 3:

Thank you very much for your reminder, we are very sorry for not giving information about other modules in our system, which brings some difficulty for reading and understanding.

To bring a more clear information, ***Section 2.1***, including ***Figure1*** are all rewritten, giving necessary information about sub-systems, detailed steps, and who should drive the robot.

The **original text** and ***Figure 1*** are

"Except for the vision system, the proposed robot system mainly consists of four main parts: A 6-DOF manipulator, a laser drilling actuator, a 2-DOF implanting actuator, and a control system. Their functions are listed as follows. 1) The manipulator plays two roles in the system: One is making large-scale movements to carry the actuators into the oral cavity before the surgery, and the other is output linear movement as an XYZ platform during the surgery. 2) The laser drilling actuator is used for preparing a hole in the alveolar bone. 3) The implanting actuator, which is designed in this paper, is used to place an implant into the hole prepared by the laser drilling device. 4) The control system includes a PC host computer, a force sensor, and an electrical cabinet with a programmable controller, which can regulate multi-axis motion and run force-based control algorithms. The overall constitution of the DIRS is shown in Figure 1.

The surgery performed by DIRS includes two stages: drilling and implantation, listed as follows.

1) Prepare hole and change tool. The surgeon drives the manipulator to carry the laser drilling actuator into the oral cavity and then drills the hole on the alveolar bone. After a hole is prepared, the surgeon retreats the laser drilling actuator and carries the implanting actuator into the oral cavity. Except for the laser drilling process, the manipulator always holds responsible during this stage for large-scale adjustment.

2) Implant and retreat. The implanting actuator screws an implant into the prepared hole. Then, the implanting actuator will retreat from the hole to separate the actuator from the used implant. During this stage, the 2-DOF implanting actuator adjusts the orientation of the implant, and the manipulator serves as an XYZ linear platform, forming a 5-DOF small-scale adjustment mechanism. Meanwhile, the 5-DOF small-scale adjustment is determined by a force-based control method.

The method of driving the manipulator during step (1) has already been studied. In this work, design of the implanting actuator and a force-based control method, corresponding to step (2), will be preliminarily studied in the later subsections."

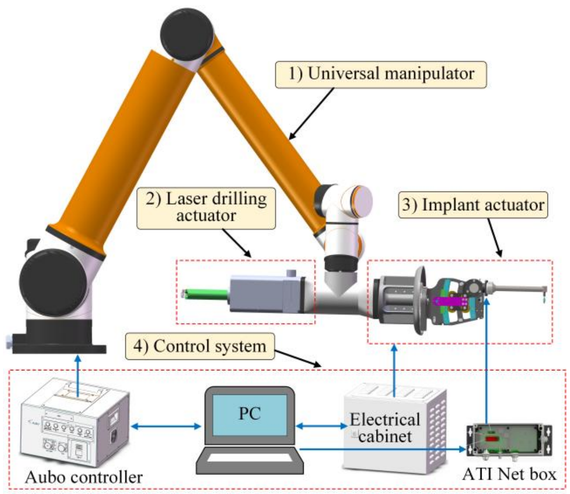

Figure 1. The overall constitution of the DIRS.

The **revised text** and ***Figure 1*** are

"**The DIRS includes four sub-systems**, as shown in Figure 1(a): mechatronics executing sub-system, binocular vision sub-system, feeding sub-system, and laser generating sub-system. 1) The mechatronics executing sub- system is the system for surgical execution, including manipulator, actuators, and controller, shown in Figure 1(b). 2) The binocular vision sub-system detects a marker worn on the patient's mouth, acquiring its position and posture. Because it can track the patient's head, it is not required to immobilize the patient's head during the surgery. 3) The feeding sub-system is based on master-slave control, consisting of a master handle, a virtual fixture strategy [39], and an instrument placement strategy [40]. This sub-system can assist safe and accurate feeding to the planned target. Additionally, parameters for this sub-system will be updated in real-time by the binocular vision sub-system, making it a dynamic guiding rather than a static one. 4) The laser generating sub-system includes a laser generator, light guiding module, and power regulation module [41]. Among these 4 sub-systems, the mechatronics executing sub-system is the most important one and is the work in this paper, while the other 3 sub-systems will not be studied in this work.

The mechatronics executing sub-system, which is the core of DIRS and the objective of this work, mainly consists of 4 main parts, shown in Figure 1(b): a 6-DOF manipulator, a laser drilling actuator, a 2-DOF implanting actuator, and a control system. 1) The 6-DOF manipulator plays two roles: One is making large-scale movements to carry the actuators into the oral cavity before the surgery, and the other is output linear movement as an XYZ platform during the implant insertion. 2) The laser drilling actuator is used for preparing a hole in the alveolar bone by reflecting the laser provided by the laser generating sub-system. This actuator will not be studied in the paper. 3) The implanting actuator, which is designed in this paper, is used to insert an implant into the hole prepared by the laser drilling device. This paper mainly focuses on this part, especially its design and control. 4) The control system includes a PC host computer, a force sensor, and an electrical cabinet. They are the technical hardware for executing the control strategy.

Practically, the operating procedure for the entire DIRS includes 6 steps: master-slave feeding, hole preparing, tool changing, master-slave feeding, implant inserting, and retreating. The procedure is shown in Figure 1(c), and the primary responsible sub-system for each step and who will operate are also shown in Figure 1(c).

Step 1) Master-slave feeding. After therapy is preoperatively planned, the doctor grasps the master handle to drive the manipulator, carrying the laser drilling actuator into the oral cavity with the help of the feeding sub-system. Meanwhile the binocular vision sub-system also partly participates in this step by outputting the real-time position/posture of the patient's oral cavity to the feeding sub-system.

Step 2) Hole preparing. The laser generating sub-system provides high-energy laser to the laser drilling actuator, shining the alveolar bone to prepare a hole. During this step, with the help of the vision sub-system, the robot will track the motion of the patient's head in real-time to compensate for the random disturbing motion.

Step 3) Tool changing. This step makes use of the feeding sub-system to retreat the laser drilling actuator, and the manipulator executes the motion. Also, the vision sub-system plays the same auxiliary role as step 1. Then, select the implanting actuator for implant insertion. This step is performed by the doctor.

Step 4) Master-slave feeding. This step is the same as step 1, carrying the implanting actuator to the target.

Step 5) Implant inserting. The implanting actuator automatically inserts an implant into the hole through force- based control. During this step, the doctor should only monitors the process, without direct participation. Moreover, the manipulator executes the XYZ linear motion for this step, rather than only the implant actuator involved.

Step 6) Retreating. This step is the same as tool changing for which the feeding sub-system is mainly responsible. When the actuator is retreated, the procedure is done.

In the procedure, steps 2 and 5 are two key steps. Step 1, 3, 4, and 6 are auxiliary steps of driving the manipulator, which has already been studied in our previous work [40,41]. In this study, the design of the implanting actuator and a force-based control method, corresponding to step 5, will be carried out in later sections. Moreover, in Figure 1, all the items (sub-systems, modules, and steps) which is studied in this paper are all highlighted."

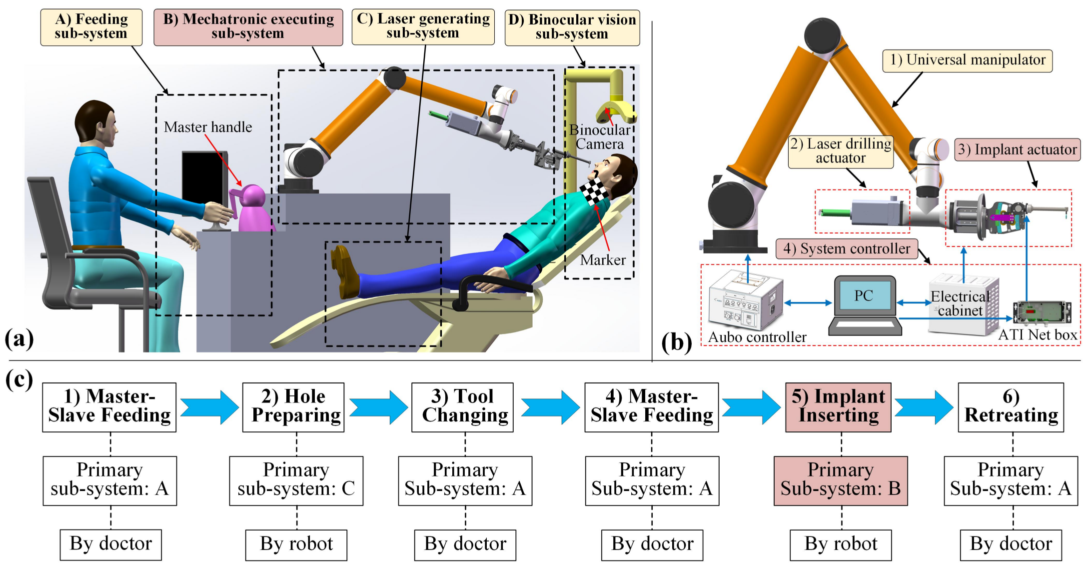

Figure 1. Overview of DIRS. (a) All the sub-systems. (b) Mechatronics executing sub-system is the core of DIRS, and is the research objective. (c) Operating steps, their primary responsible sub-systems, and who should operate.

Following the revision, the DIRS can be categorized to be four systems: mechatronics executing sub-system, binocular vision sub-system, feeding sub-system, and laser generating sub-system. Among them, the mechatronics executing sub-system is the core.

Firstly, the vision system includes a binocular camera and a vision marker worn on the patient's head. The vision marker is designed like a checkerboard to be detected by vision algorithms, and its position/posture can then be calculated by the vision system, as the revised text says "*The binocular vision sub-system detects a marker worn on the patient's mouth, acquiring its position and posture. Because it can track the patient's head, it is not required to immobilize the patient's head during the surgery*" (***line 104-105, page 2, Section 2.1***). Also, the role of providing real-time position information of the patient's head is described in the procedures, giving more information about the vision system, such as the revised text "*Meanwhile the binocular vision sub-system also partly participates in this step by outputting the real-time position/posture of the patient's oral cavity to the feeding sub-system*" (***line 130-131, page 3, Section 2.1***), and the sentence " *During this step, with the help of the vision sub-system, the robot will track the motion of the patient's head in real-time to compensate for the random disturbing motion*" (***line 130-131, page 3, Section 2.1***), which concretize what role the vision system plays during the whole process.

Secondly, the feeding sub-system, which is mainly a software framework that runs on the master console, can assist in an accurate and safe master-slave operation. The hardware of the feeding sub-system is a master handle (Phantom Omni Product). During the operation, the surgeon grasps the master handle, and the manipulator repeats the motion of the surgeon's hand. To guarantee safety and guide the actuator to the planned position/posture, a virtual fixture framework runs in the feeding sub-system, which can prevent undesired motion received from the master handle. This framework includes two parts: one is the design of the virtual fixture algorithm which is our previously published work "*A Guiding and Positioning Motion Strategy Based on a New Conical Virtual Fixture for Robot-Assisted Oral Surgery* ", and the other is how to plan or place the virtual fixture, which is another published work of our research team "*Preoperative Planning Framework for Robot-Assisted Dental Implant Surgery: Finite-Parameter Surrogate Model and Optimization of Instrument Placement* ".

The feeding sub-system is described in sentence "*The feeding sub-system is based on master-slave control, consisting of a master handle, a virtual fixture strategy [39], and an instrument placement strategy [40]. This sub-system can assist safe and accurate feeding to the planned target. Additionally, parameters for this sub-system will be updated in real-time by the binocular vision sub-system, making it a dynamic guiding rather than a static one*" (***line 105-109, page 2-3, Section 2.1***). Moreover, the using of this sub-system is described in the procedure, including step 1 "*After therapy is preoperatively planned, the doctor grasps the master handle to drive the manipulator, carrying the laser drilling actuator into the oral cavity with the help of the feeding sub-system*" (***line 128-129, page 3, Section 2.1***), and step 3 "*Tool changing. This step makes use of the feeding sub-system to retreat the laser drilling actuator, and the manipulator executes the motion*" (***line 135-136, page 3, Section 2.1***).

In terms of who and how to drive the robot, it can be summarized as "The doctor drives the manipulator by master-slave operation, and the actuator performs the implant insertion". The steps (***line 128-143, page 3, Section 2.1***) and ***Figure 1*** describe the procedure, who is responsible, and how to use it for each step.

Therefore, with all the sub-systems are procedures presented, described, and illustrated, the whole system and its practical information can be better clarified.

Comment 4:

Is there enough space for the entire (huge) robotic system and for the clinical team around the patient?

Response to comment 4:

Thank you for your question. There is enough space for deployment. For developing, debugging, and testing the system, the space is enough. For clinical practice, while the system requires no more than 6-8 square meters (length: 3 meters, width: 2 meters), we think it is easy for a clinic to spare a room.

Comment 5:

Is it required to immobilize the patient's head?

Response to comment 5:

Thank you for your question. It is not required to immobilize the patient's head. In our ***response to comment 3***, the vision system is introduced. With the patient's head tracked by the vision system in real-time, robots can perform its motion with the disturbing movement of the patient's head considered. As the sentence "*The binocular vision sub-system detects a marker worn on the patient's mouth, acquiring its position and posture. Because it can track the patient's head, it is not required to immobilize the patient's head during the surgery*" (***line 104-105, page 2, Section 2.1***) says, liberating the patient's head is another feature of the vision system. In addition, because the force-based control has the ability to suit the environment, during the inserting process, the robot can actively adapt to the random disturbing movement of the patient's head, which is another reason for not necessary to fix the patient's head.

Comment 6:

What are the potential advantages in respect to a manual procedure assisted by a navigation system or using patient specific surgical template?

Response to comment 6:

Thank you for your question. Now the revision addresses the issue in the ***Discussion Section***.

On one hand, the two main potential advantages are relieving the working intensity, and the potential to enhance the implanting quality of less-skilled doctors in underdeveloped areas. The last paragraph is newly added in the ***Discussion Section***, with the advantages drawn (***line 489-496, page 15, Section 4***):

"Therefore, based on the two points of rationality, the main potential advantages of the DIRS with respect to a manual procedure assisted by a navigation system or using the patient-specific surgical template are: 1) DIRS can relieve the painstaking manual procedure by automatic but skilled operation, reducing the working intensity especially when dentists are in shortage. 2) DIRS can relieve the shortage of professional dental surgery for underdeveloped regions by force-controlled implantation, improving both the quantity and the quality of dental implanting, given that both the skill and the amount of local surgeons are often lower. With these potential advantages, the DIRS system will further learn technologies and standardization from current commercial surgical robot systems, in order to push it into clinical practice earlier."

On the other hand, because currently, the system is still in its preliminary stage, although its effectiveness is tested and validated, no more clinical data on the force-controlled dental implanting can be acquired at present. Therefore, as our system steps further, some clinical data of "force-vision-based implanting", "vision-based implanting", and "template-based implanting" is planned to be obtained and compared, in order to give comprehensive information on different strategies. For our research team, there is still a long way to go, and hence we can only qualitatively discuss the prospect, without a quantitative and direct comparison. Therefore, we apologize for not giving a more comprehensive clinical comparison and look forward to your understanding.

All in all, all your constructive comments and questions are addressed and replied to. Once again, thank you very much for your valuable time and effort spent improving our manuscript, and thank you for all your help and suggestions. Your valuable comments are the direction of our future efforts. We sincerely look forward to your satisfaction.

Responses to reviewer #2

We sincerely appreciate your careful review, as well as your recognition of our paper. Your kind recommendation is the incentive for us to do our work better. Our response to your comment can be seen as follows:

Comment 1:

I have a small problem, in last paragraph of section 2.1 (above figure 2), "the method of driving the manipulator during step(1) has already been studied.", who studied this? no any information was given, at least, references should be given?

Response to comment 1:

Thank you for your question, we are sorry for not providing further details, which brings some confusion. "The method of driving the manipulator" is a master-slave guiding framework based on the virtual fixture, which is the previous work of our research team.

This framework includes two parts: one is the design of the virtual fixture algorithm which is our previously published work "*A Guiding and Positioning Motion Strategy Based on a New Conical Virtual Fixture for Robot-Assisted Oral Surgery* ", and the other is how to plan or place the virtual fixture, which is another published work of our team "*Preoperative Planning Framework for Robot-Assisted Dental Implant Surgery: Finite-Parameter Surrogate Model and Optimization of Instrument Placement* ". The two works are respectively listed as ***Reference[39]*** and ***Reference [40]***.

Now, to bring a clearer and more informative overview of our entire system, ***Section 2.1*** is rewritten, "The method of driving the manipulator" corresponds to the "feeding sub-system" in the revised ***Section 2.1***. Some information is given in the sentence "*The feeding sub-system is based on master-slave control, consisting of a master handle, a virtual fixture strategy [39], and an instrument placement strategy [40]. This sub-system can assist safe and accurate feeding to the planned target. Additionally, parameters for this sub-system will be updated in real-time by the binocular vision sub-system, making it a dynamic guiding rather than a static one.*" (***line 105-109, page 2-3, Section 2.1***).

Responses to reviewer #3

Many thanks for your review and your kind recognition of our manuscript. Your recommendation is the incentive for us to do our work better.

In summary, all of the comments or concerns of the reviewers are replied to, and corresponding changes or corrections are made and highlighted in the revised manuscript.

Once again, thank you very much for your careful review, valuable suggestions, and thoughtful comments on our manuscript. All of your insightful suggestions and feedback are the incentives for us to do our work better.

Sincerely yours,

Mr. Yan Wang
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Prof. Dr. Yueri Cai*
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