# *Responses to reviewer #1*

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

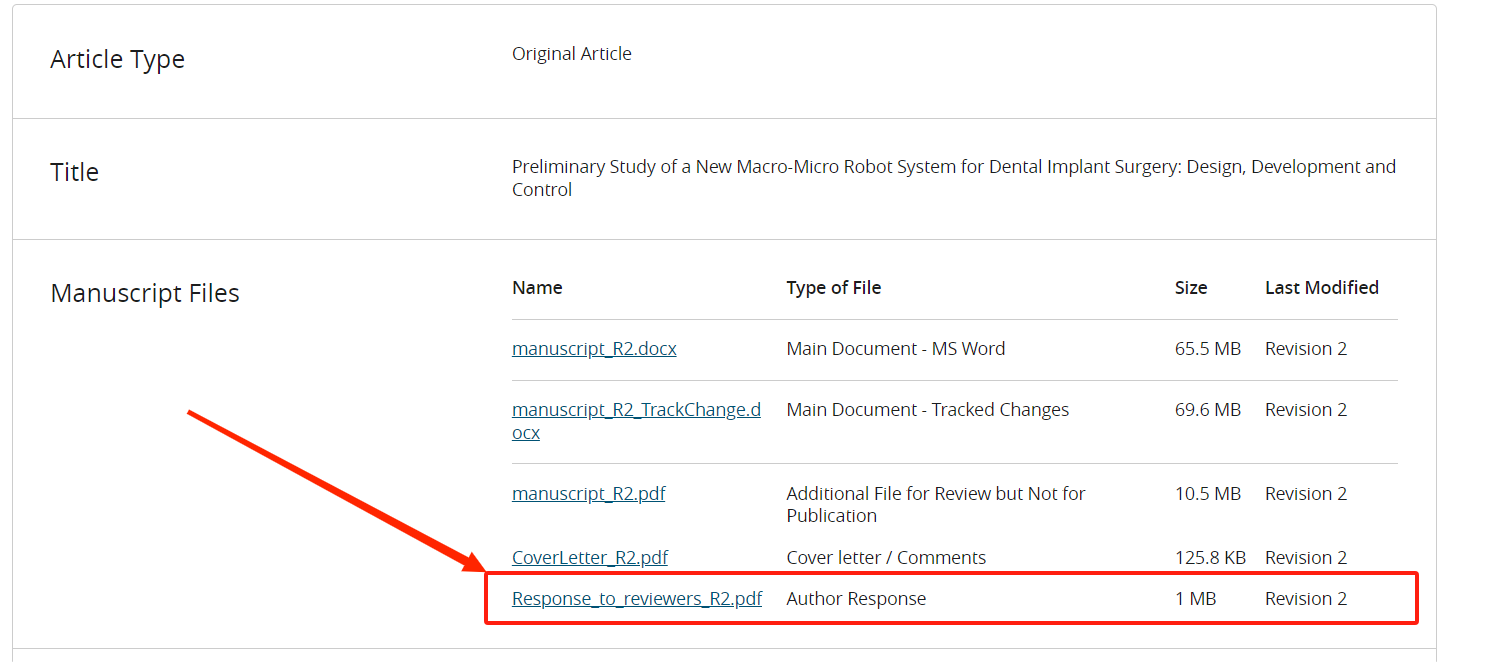
# *Responses to reviewer #2*

Before replying, we would like to express our sincere appreciation and gratitude for your careful review and helpful comments, as well as your valuable time and efforts spent helping us improve our manuscript. The absence of our response letter has made the 2nd round of review work very difficult, and we are very sorry for it. We totally understand the inconvenience and the trouble if a reply document is missed. As a guiding to follow how the suggestions are addressed, the absence of it can make the review extremely long and tough.

In this letter, three parts are included: **Part 1** is about the absence of our reply document. **Part 2** is the overview of our modifications. **Part 3** is our responses to the comments.

**PART 1: About the Absence of Response Letter**

Firstly, we are sorry for the absence of our response letter. However, we have actually prepared a 12-page response letter named “**Response\_to\_reviewers\_R2.pdf**” for the previous review. We have carefully checked the ***Research Exchange*** submitting system, confirming that we have successfully submitted the reply document, as shown in the following picture. It seems that an unexpected technical error has happened, causing the absence of our reply document. Therefore, the previous round of review was inevitably influenced more or less due to this unknown error. Although it is not our mistake, we would still apologize for the inconvenience.



The missed reply document “**Response\_to\_reviewers\_R2.pdf**” is submitted to the ***Research Exchange*** system for the new round of review. If the re-submitted file can not be found, two **download links** are also provided here to ensure our reply document can be found:

**Download link 1**: The GitHub Sharing Website (**Recommended**)

https://codeload.github.com/huohuoqwe000/Responding-Letters/zip/refs/heads/main

**Download link 2:** The KingSoft Cloud File Sharing Function (**Alternative**)

https://www.kdocs.cn/l/cvR6KhxDtkTy (for Response\_to\_reviewers\_R2.pdf)

Also, the download links are attached in the main manuscript file, the location is after the ***Conclusion Section***. Thus, even no reply files can be found from the submitting system, our response letters for both the two rounds of review can still be obtained.

**PART 2: Main Modifications in the Revision**

In the revised paper, the newly added/modified texts are highlighted in **RED**. The modification of the previous version will still keep the blue-highlighting, because the previous round of review is influenced due to the absence of our reply letter, keeping the blue-highlighting will be convenient for possible re-checking or following the previous changes.

The main modifications in this version include three parts:

**1)** The first paragraph of the ***Introduction Section*** is totally rewritten to bring a more solid foundation on the need for a robotic solution. Also, three paragraphs in the ***Introduction Section*** are rewritten/reorganized to bring a more solid foundation for the motivation of our work.

**2)** We added/modified lots of sentences to ***Section 2.1***, bringing more description to the operating of the robot. The newly added descriptions are directly about the concepts of “doctor” and “operation” to strengthen the aspect of practical operation.

**3)** In the ***Discussion Section***, we newly added a paragraph to discuss the issue of the required area to deploy and run the robot. In addition, some more discussions on operating the robot are given here.

**PART 3: Our Reply to Comments**

## Comment 1:

*The introduction does not contain a solid rationale. For example, the need of a robotic solution is motivated only (a bit) in the discussion session?*

## Response to comment 1:

Many thanks for your comment, we agree that the need for a robotic solution is not sufficiently explained, without explaining the need for a robotic solution, the introduction is not solid enough. To address this comment, the first paragraph in the Introduction Section is totally rewritten to bring a more solid foundation for why a robotic solution is needed:

**a)** The narrow workspace of the oral cavity is inconvenient for doctors to perform surgery, with occluded field of view and uncomfortable operation combined, it is easy to get tired and increase the working intensity.

**b)** The subjective experience and skill of doctors will directly decide the quality of dental implantation. And when the operating hand is under fatigue or tremor, or a novice doctor is operating, the reliability and quality can be much lower.

**c)** There is a shortage of qualified dentists, especially in developing regions.

**d)** Robotic solution has the potential to overcome the issue of inconvenient working space, unreliable operation, high work intensity, and shortage of dentists.

With these points combined, why needing a robotic solution can be explained.

**Our revised text are given here:** (***line 38-47, page 1, Section 1***)

Currently, dental implant surgery still mainly relies on the skill of doctors and computed tomography (CT) images [5], with some problems existing. Firstly, due to the narrow workspace, not only the view field is limited [6], but also the operation is not comfortable, and easy to get tired. Secondly, manual operation depends on the experience of doctors, whose subjective feelings will decide how to insert an implant. When the doctor is tired, the hand fatigue or tremors will be adverse to the operation [7], even one mistake can affect the operating quality or damage the tissues [8]. Thirdly, there is a shortage of dentists. Even in developed regions such as Hong Kong, over 7 million people share only around 2000 dentists, let alone the developing regions. With the development of robotics, robot-assisted implant surgery as a new solution, can provide reliable operation in narrow space, reduce work intensity, and help to lower the shortage of dentists. Given these potential advantages, the robotic solution should be exploited and is likely to become the mainstream in the future [9-10].

Furthermore, to improve the structure of the Introduction Section, **we have reorganized the majority of this section**, **rewriting three paragraphs**. After this round of revision, the mainline of the ***Introduction*** is “**Why need robot => Related robots => Current concerns => Force control => Our study**”, and the structure of the Introduction Section can be summarized as:

1) Paragraph 1 introduced the issue of dental implants, and why needs robotics solutions.

2) Paragraph 2 and 3 introduced some related works for dental implant robot, including two aspects: mechanism design and integrated system.

3) Paragraph 4 explained the vision system is imperfect, while the overlooked contact force information is very important. This paragraph carries out the main motivation for our work: providing a important supply for vision system, and enhance the quality of prognosis.

4) Paragraph 5 introduce the concept of force-based control, introduced some related work of force control in dental robot, and discussed current limitations. This paragraph carries out another motivation for our work: the lack of force-controlled application for implant insertion.

5) Paragraph 5 introduce the aim and task of our work, listing the main contributions.

After the revision, the foundation for our work becomes more solid. **The revised three paragraphs are as follows** (***line 65-92, page 2, Section 1***):

“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 systems, which is imperfect due to the error accumulated from its multiple stages (e.g. reconstruction, registration, localization). Meanwhile, the vision marker worn on the mouth for localization is not strictly fixed and may creep due to the deformation of soft tissue, lowering the accuracy of the vision system. Thus, although the current vision system is sophisticated, a small error will still exist, lowering the implanting accuracy. Besides, for implant insertion, the contact force information is an important resource but is overlooked more or less currently. Some biomechanical researches have pointed out that the force or stress is closely related to the prognosis quality [27-29]. When the stress is too small, both the stability of the implant and the rate of bone healing are lower [30]. When the stress is too large, bone resorption may occur, leading to loosening or an increased risk of failure [31]. Thereby, when an implant is inserted with a relatively larger position/posture error caused by the vision system, the contact force will be abnormal, incurring the risk of instability, looseness, or damage that is adverse to postoperative recovery.

To solve the imperfection of the current vision-based robotic system and further enhance the implanting quality, the contact force during implant insertion should be exploited to design a force-based control strategy, for which the relationship between force and motion response is the core [32-33]. In terms of dental robots, force-based control is studied in some works, and the concepts of gravity compensation and impedance/admittance control are involved. For instance, Kan et al. developed a zero-force controller with gravity canceled for hand-guiding tasks [34]. Feng et al. proposed a variable admittance controller based on different distances to assist in safe manual feeding [35]. Kasahara et al. achieved better drilling through the hybrid force/position control strategy in their dental drilling robot [36]. Li et al. proposed an impedance control strategy for their cable-driven dental drilling robot [37]. Further, Impedance control can also be expanded with parameter identification [38], or fuzzy PID method [39]. However, most works on force control mainly focus on the manual dragging or drilling, there is little research work on implant inserting. Therefore a specialized position/posture adjusting mechanism and the corresponding control strategy are needed, which is the main research objective of this work.

In this study, a new dental implant robot system (DIRS) is proposed. Different from other related work whose core is stereo vision, the DIRS system pays special focus on the fine-tuning for implant insertion to enhance the quality of implantation, with a force-controlled robotic actuator developed, including mechanical design and control strategy. The main contributions of this paper can be summarized as:”

## Comment 2:

*The need of a robotic solution for “less-developed regions” is questionable. The lack of skilled doctors is due to a lack of money and without money the robotic solution cannot be bought (as demonstrated with the current available robotic solutions).*

## Response to comment 2:

Many thanks to your insightful comment. To avoid possible ambiguity or misunderstanding, we deleted the concepts of “helping less-developed regions with robotic solutions” from our paper, although the aim to our project includes this reason.

In fact, the core of our work is research and develop new technology and method for dental implantation, it seems to us that analyzing the cost of our robot is the issue of social economics, which is not the task or scope of our work, since the core of our paper are machine and control. Thus, we remove the concept of “less-developed regions” from our paper.

Furthermore, an effective robotic solution can simplify a full skilled medical team, and some local doctors can perform the surgery by using the medical robot if it has the ability to provide a skillful autonomous operation with the help of a control strategy. Adding to this, an effective robotic solution can provide surgery to more patients due to its higher efficiency. Thus, compared with running a full medical team, the deployment of robotic solutions has the potential to save the cost of human resources in the long run. This condition makes robotic solutions potentially beneficial for these regions.

## 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, the information of how to use is important, and we apologize for not providing the information very clearly, which brings some inconvenience for reading and following.

The concept of “**teleoperation**”is deleted from our paper to prevent ambiguity. In fact, it corresponds to the “**feeding sub-system**” in ***Section 2.1***. To drive the sub-system, the doctor grasps and moves the master handle, and the manipulator follows the master command, while the master-salve motion will also be subjected to the **virtual fixture** strategy to avoid collision and guide the actuator to the predefined point. The virtual fixture is the core of the feeding sub-system and is studied in our two previously published works (***Reference [40]:*** *A Guiding and Positioning Motion Strategy Based on a New Conical Virtual Fixture for Robot-Assisted Oral Surgery****, and Reference [41]:*** *Preoperative Planning Framework for Robot-Assisted Dental Implant Surgery: Finite-Parameter Surrogate Model and Optimization of Instrument Placement*). Although the feeding sub-system is not our task for this paper, we have detailedly described it in the revision, such as the texts in the following:

“The feeding sub-system is based on master-slave control, consisting of a master handle, a virtual fixture strategy [40], and an instrument placement strategy [41]. The doctor grasps and moves the master handle and the manipulator can move simultaneously according to the master handle. Because the predefined virtual fixture can avoid collision and guide the manual driving [40-41], 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 111-116, page 3, Section 2.1***)

“Step 1) Master-slave feeding. After therapy is preoperatively planned, the doctor should click the “Feeding” button on the software to switch the system to the master-slave mode and then grasp the master handle to drive the manipulator, carrying the laser drilling actuator into the oral cavity with the help of the feeding sub-system, reaching the planned starting point for cutting” (***line 139-142, page 3, Section 2.1***)

Also, the concept of “**vision-based path planning methods**” is deleted from our paper to prevent ambiguity, and it is actually the “**binocular vision sub-system**” in ***Section 2.1***. In this sub-system, a binocular industrial camera detects the vision marker worn on the patient’s mouth, measuring the position and posture of the oral cavity in real time, and this information should be transmitted to other sub-systems. And the “**path planning methods**” is actually the **virtual fixture** method to guide the manual driving of the manipulator, which belongs to the **feeding sub-system**, and this is our previously published work (***Reference [40]:*** *A Guiding and Positioning Motion Strategy Based on a New Conical Virtual Fixture for Robot-Assisted Oral Surgery*). Because the **virtual fixture** needs the position/posture measured by the **vision sub- system**, the feeding motion can be understood as the “vision-based path planning method”. But, for clarity and to avoid ambiguity, the concept is deleted. Some texts that describes the binocular-vision sub-system can be seen in the following:

“The binocular vision sub-system detects a marker worn on the patient’s mouth, measuring 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. The measured position/posture will be sent to both the mechatronics executing sub-system and the feeding sub-system” (***line 108-111, page 3, Section 2.1***)

“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, so the virtual fixture will adjust in real-time [40], and the doctor should only move the master handle according to his/her feeling and no need to concern missing the feeding target” (***line 142-145, page 3, Section 2.1***)

“Also, the vision sub-system plays the same role as step 1, giving position/posture information to the feeding system to adjust the virtual fixture for collision avoidance” (***line 153-155, page 3, Section 2.1***)

Additionally, to further make our description of “who and how drive the robot” clearer, we newly added or modified an array of sentences directly about “**doctor**” or “**operation**” in ***Section 2.1***, which can give more details about operation, including:

“This sub-system is responsible for directly providing dental implant surgery. Mechanical structure and control strategy are the core of this sub-system” (***line 106-108, page 2-3, Section 2.1***)

“The measured position/posture will be sent to both the mechatronics executing sub-system and the feeding sub-system” (***line 110-111, page 3, Section 2.1***)

“The doctor grasps and moves the master handle and the manipulator can move simultaneously according to the master handle. Because the predefined virtual fixture can avoid collision and guide the manual driving [42-43]” (***line 112-114, page 3, Section 2.1***)

“For the first role of large-scale movement, it is driven by the doctor. For the second role of micro XYZ movement, it is driven by the control strategy, not the doctor” (***line 124-125, page 3***)

“The implant actuator is driven by the control strategy automatically rather than the doctor.” (***line 128-129, page 3, Section 2.1***)

“An operating software (user interface) is running on the PC host computer for doctors to operate.” (***line 131, page 3, Section 2.1***)

“After therapy is preoperatively planned, the doctor should click the ‘Feeding’ button on the software to switch the system to the master-slave mode and then grasp the master handle to drive the manipulator, carrying the laser drilling actuator into the oral cavity with the help of the feeding sub-system, reaching the planned starting point for cutting.” (***line 139-142, page 3, Section 2.1***)

“So the virtual fixture will adjust in real-time [42], and the doctor should only move the master handle according to his/her feeling and no need to concern missing the feeding target.” (***line 143-145, page 3, Section 2.1***)

“The doctor should only monitor the GUI and no need to directly drive the robot during this step. ” (***line 148-149, page 3-4, Section 2.1***)

“This step is performed by the doctor. When the doctor is informed to do this step, the doctor grasps and moves the master handle to retreat the manipulator to the initial position before step 1, then click the “Change Tool” button on the software, switching to the implant actuator.” (***line 150-152, page 4, Section 2.1***)

“Also, the vision sub-system plays the same role as step 1, giving position/posture information to the feeding system to adjust the virtual fixture for collision avoidance.” (***line 153-154, page 4, Section 2.1***)

“The doctor should drive the manipulator, carrying the actuator to the predefined point for insertion. After the alignment error is detected to be lower than a threshold, the feeding is done and the doctor will be informed to release the master handle. Then the manipulator will automatically follow the patent’s head with the help of the vision sub-system [42].” (***line 156-159, page 4, Section 2.1***)

“When the doctor confirms the implant aligns with the implanting hole, the doctor should click the ‘Insert Implant’ button on the software, then the implanting actuator automatically inserts an implant into the hole through vision-based tracking and force-based control strategy.” (***line 160-162, page 4, Section 2.1***)

“When the doctor is informed that the implant insertion is done, the doctor clicks the ‘Retreat Actuator’ button, and the system is switched to the master-slave mode.” (***line 165-166, page 4, Section 2.1***)

Adding to ***Section 2.1***, some related information is also given in the ***Discussion Section***:

“Adding to system experiments, some practical discussion will be further discussed here. On one hand, for doctors, the laser cutting and implant inserting can be automatically executed, during which doctors should only monitor the process without directly driving. Only operating the user software and the carrying of actuators (e.g. feeding, retreating) should be manually performed by doctors, who grasp and move the master handle to drive the manipulator. Moreover, the doctors should be trained to use the operating software and check the system hardware (e.g. electric connection, system communication).” (***line 499-504, page 15, Section 4***)

With these newly added modifications/revision, the information about the entire system and driving the robot can be enriched.

## 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 very much for your reminder. We answered this question in the previous response letter (“**Response\_to\_reviewers\_R2.pdf**”), but did not add them into the paper. We apologize for this oversight of not giving the information in the manuscript.

Now, we have addressed the issue in the red-highlighted paragraph in the ***Discussion Section***, giving the following information:

**a)** This system is 3 meters in length and 2 meters in width, requiring 6-8 square meters to place the system.

**b)** With the doctor(s) involved, the robot needs 10-12 square meters to conduct an operation. It is easy for a hospital or a clinic to spare a room to deploy the robot. Thus, there is enough space for running the robotic system.

**Our revised text are given here: (*line 504-510, page 15, Section 4*)**

“On the other hand, for hospitals or clinics, the required area for the DIRS is not very large. The DIRS is 3 meters in length and 2 meters in width, meaning that the least required area to deploy the system is 6-8 square meters. During the clinical operation, two trained doctors should be involved. While one doctor should operate the software, the other is responsible for checking the robot system (e.g. motor connection and communication) and performing other possible ancillary tasks. Since the robot will execute most of the work, the medical team can be simplified, and a room with 10-12 square meters is adequate for conducting surgery. So it is easy for a hospital or a clinic to spare a room to deploy the system.”

In summary, all the comments or concerns are responded, and corresponding changes or corrections are made and highlighted both in the revised manuscript and in this letter.

Once again, thank you very much for your careful review, valuable suggestions, and thoughtful comments on our manuscript, especially the absence of a reply document have made the review very difficult. All of your insightful suggestions and feedback are the not only the incentives for us to do our work better, but also the directions for our research.

At last, we apologize for not providing some related information very clearly in the previous version, and sincerely look forward to your satisfaction on our revision.

Best Wishes,

Mr. Yan Wang

Prof. Dr. Wei Wang

Prof. Dr. Yueri Cai\*

Mr. Qiming Zhao

Mr. Yuyang Wang

Institute of Robotics,

Department of Mechanical Engineering and Automation, Beihang University.

XueYuan Road No.37, Haidian District, Beijing 100191, China

October 09, 2023