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# Human-Robot Collaboration Using Fuzzy Adaptive Virtual Fixture Method for Dental Implant Surgery

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***Abstract*—The purpose of this work is to develop a methodology to improve human-robot collaboration for robot-aided dental implant placement. In this study, a human-robotic implant system (HRIS) is designed according to a hand-guiding control to increase the accuracy and stability of osteotomy drilling based on the surgeon's decision, and robot motion during the implant placement. The proposed method is able to guide the surgeon's hand according to the pose of the desired placement. To guide and modify the pose of the surgeon's hand, the virtual fixture method is used as the main control approach. To verify the performance of the introduced method, the KUKA MED robot is used to perform the dental implant placement using the presented approach on a phantom head with a 3D jaw bone model. Additionally, the results between free-hand drilling and HRIS controlled drilling according to the apical center and head center of the implant placement are compared to evaluate the performance of the introduced method.**

***Index Terms*—Fuzzy Adaptive Virtual Fixture, Dental Implant Surgery, Human-Robot Collaboration**

## I. Introduction

Over the past years, the cooperation of robots and humans is becoming an important field of robotic application. The robotic assistance for Dental Implant Surgery (DIS) can be considered as a known application of human-robot cooperation. In Dental Implant Surgery (DIS), a missing tooth is replaced with dental implants. In this surgery, a dental prosthesis fixed in the jaw bone using an osseointegrated implant is defined as the direct structural connection between the bone and surface of an implant [1], [2]. According to Fig. 1, the dental implant should be placed first into the jawbone, and then a dental prosthesis is attached to the implant. The accuracy of some items such as position, angle, and depth within the jawbone has a direct impact on the quality of the dental implantation [3], [4]. Using the surgical robots in the DIS enables us to have a better view of the operative field and improve efficiently the surgical operation.

According to Fig. 1, this study aimed to propose a method for human-robot collaboration using a hands-on approach to perform dental implant surgery. In addition, the virtual fixture approach is used as the main controller to modify the surgeon's hand. The main idea of the presented approach is that whenever the surgeon deviates from the desired path, the robot will try to revise the motion of the surgeon's hand by changing the stiffness and making a constraint in order to return the surgeon's hand to its desired path. To verify the performance of the introduced method, the KUKA MED robot is used to perform the dental implant placement using the presented approach on a phantom head with a 3D jaw bone model.

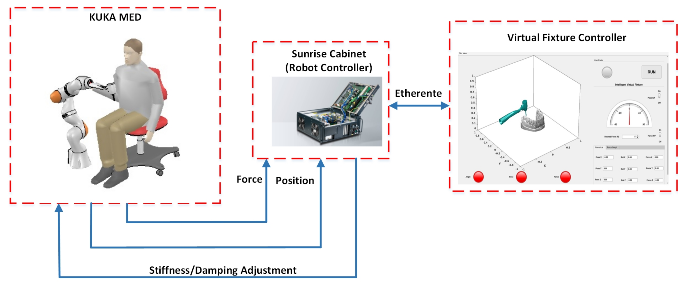


Fig. 1: Proposed high-level controller structure. According to the virtual fixture method, the position and force interaction between the robot and human are received by the developed application software using Ethernet protocol and then the desired stiffness and damping are applied to manipulator.

In this work and according to the proposed controller structure illustrated in Fig. 1., a hands-on synergistic robotic with human-machine collaboration system is developed to perform the dental implant surgery. The proposed approach combines virtual fixture methods and impedance control of the robot to increase efficiently the accuracy of the implant positioning placement. In addition, a fuzzy mechanism is developed to tune the parameter of the virtual fixture. Therefore, the virtual fixture method is adapted according the task execution. In the rest of the paper, the architecture of the proposed hands-on system is introduced in section II. In addition, the model of the robot and impedance profile, and proposed adaptive virtual fixtures is introduced in section III. In the last section V, the performance of the proposed controller is verified using the KUKA Med system and GUI developed for dental implant surgery.

## II. The Architecture of the Proposed System

The proposed structure and experimental setup for the CIS are constructed as shown in Fig. 2, and a jaw model phantom is adopted for the operational test. KUKA Med, a lightweight

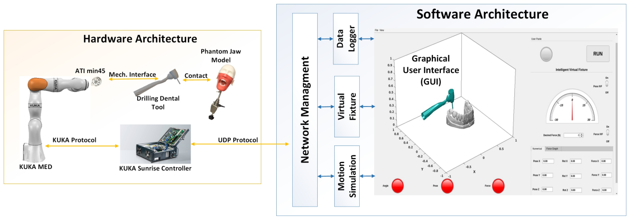


Fig. 2: Proposed CIS structure for dental implant surgery

robot manipulator from KUKA Company, is selected as the surgeon fellow. It has a working range of 850mm and a load capacity of 7 kg, suitable for the requirements of dental implant placement. Because of the cooperation between the robot and surgeon, the robot is able to correct the human position and the user is able to supervise and control the motion of the robot. As result, the proposed CIS method for the dental implant can increase simultaneously both the safety and accuracy of the dental implant surgery. In Fig. 2, the drilling tool can be attached to the robot end-effector using the mechanical interface which is designed to mount and fix the drilling tool at the end of the robot arm. A head phantom is assembled to a fixed place.

## III. Robot Controller Method

Impedance control is a classical control approach that can be used as indirect force control method. Hogan in [5] presented the main concept of the impedance controller method and using impedance parameters such as inertia, stiffness, and damping it can adapt the modulated the end-effector behavior according to desired interaction with the external environment. In order to interact with an unknown environment is required that the impedance parameters can be tuned in order to perform various tasks. In this work, the impedance parameter should be adapted according to the algorithm of the virtual fixture. The desired impedance model of the robot can be considered as

$$\mathbf{M}\ddot{\mathbf{e}} + \mathbf{B}\dot{\mathbf{e}} + \mathbf{K}\mathbf{e} = \mathbf{e_f}\,, \tag{1}$$

where $\mathbf{e} = \mathbf{x_d} - \mathbf{x_c}$ and $\tilde{\mathbf{e}_f} = \mathbf{f_d} - \mathbf{f_h}$ are the pose error and force error, receptively. $\mathbf{x_d} \in \mathbb{R}^{\mathbf{N\times 1}}$ and $\mathbf{x_c} \in \mathbb{R}^{\mathbf{N\times 1}}$, are the desired and command position vector. In addition, $\mathbf{M}$, $\mathbf{B}$, and $\mathbf{K} \in \mathbb{R}^{\mathbf{N\times N}}$ are the inertia, damping and stiffness gains, receptively, and are considered as a positive diagonal matrix.

**Assumption 1.** *It can be assumed that if the robot has a tight position control then* $\mathbf{x} = \mathbf{x_c}$.

Without loss of generality and because of the diagonal matrices of desired impedance profile in (1) , let us take one dimension of impedance model as:

$$m\ddot{e} + b\dot{e} + ke = e_f\,. \tag{2}$$

### A. Impedance Profile for Hands-on Collaboration

The desired trajectory $x_d$ is the human hand position. In fact, the robot should be able to follow human hands' motion in order that the robot keeps in contact with the user's hand. To track the hand, we consider the position of the human as the desired trajectory $x_d = x_h$ and according to assumption 1, we rewrite the (1) as

$$\mathbf{M}(\ddot{\mathbf{x}}_\mathbf{h} - \ddot{\mathbf{x}}) + \mathbf{B}(\dot{\mathbf{x}}_\mathbf{h} - \dot{\mathbf{x}}) + \mathbf{K}(\mathbf{x_h} - \mathbf{x}) = \mathbf{e_f}\,. \tag{3}$$

where $e = x_h - x$. If both the desired and hand force are supposed to be zero $\mathbf{e}_f = 0$, then it can be observed from (3) that $x \to x_h$ for the steady-state. In fact, the robot tracks the human hand.

## IV. Proposed Adaptive Virtual Fixture

To adapt the desired impedance profile according to the desired goal, a virtual fixture method is presented. The proposed method is able to increase efficiently the accurate and stable osteotomy drilling based on the surgeon's decision and robotic manipulators motion during the implant placement. As discussed in the introduction, the virtual fixture can be classified into two main classes: FRVF and GVF. In general, GVF is suitable to guide the robot end-effector towards the desired path, a FRVF is used for the constraining surfaces or delicate region that the robot is forbidden to enter.

### A. Fuzzy Adaptive Virtual Fixture

According to the GVF structure to have an attractive behavior towards the desired path, a constraint enforcement approach including a spring-damper force needs to be considered. In fact, the $\mathbf{f_d}$ should be designed in order that the robot applies the required force on the human hand to modify the motion. Therefore, the constraint force can be presented as

$$\mathbf{f_{vf}}(\mathbf{e}, \dot{\mathbf{e}}) = -\mathbf{K}_{vf}\mathbf{e} - \mathbf{B}_{vf}\dot{\mathbf{e}} \tag{4}$$

where $\mathbf{K}_{vf} \in \mathbb{R}^{N\times N}$ and $\mathbf{D}_{vf} \in \mathbb{R}^{N\times N}$ are positive definite matrices and properly designed diagonal. By considering the GVF defined in (4) such that $\mathbf{f_d} = \mathbf{f_{vf}}$ and impedance profile (1), the closed loop behavior can be obtained as:

$$\mathbf{M_d}\ddot{\mathbf{e}} + \mathbf{B_d}\dot{\mathbf{e}} + \mathbf{K_d}\mathbf{e} = \mathbf{f_h}\,, \tag{5}$$

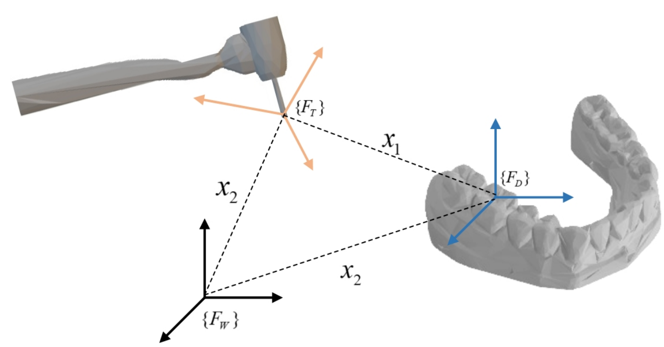


Fig. 3: Guidance Virtual Fixture (GVF) geometry and desired path.

where $\mathbf{B}_d = \mathbf{B}_c + \mathbf{B}_{vf}$ and $\mathbf{K}_d = \mathbf{K}_c + \mathbf{K}_{vf}$. According to the (5), the combination of the GVF and general impedance profile is similar to variable impedance control approach.

To adapt GVF enforcement constraint in (4) for the human-robot collaboration, a nonlinear and varying stiffness profile is considered for the adapting $\mathbf{K}_{vf}$. Accordingly, each diagonal elements of the stiffness matrix to be

$$k_{vf,ii}(e,\dot{e}) = \beta(e,\dot{e})K_{max} \qquad \forall i = 1, ..., N \tag{6}$$

where $k_{vf,ii}$ is the diagonal element of the $\mathbf{K}_{vf}$ matrix, $\beta(e,\dot{e})$ is the impedance shaping function, and finally $e$ is the $i-th$ component of the vector $\mathbf{e}$. In addition, $t$ is the time and $K_{max}$ denotes the maximum value for the adapting the stiffness. Using $\beta(e,\dot{e})$ function, the robot is enable to adapt its impedance parameters to modify and correct human motion. We can propose $\beta(e,\dot{e})$ as

$$\beta(e,\dot{e}) = \begin{cases} 0 & |e| \geq l \\ k_s(e,\dot{e}) & otherwisel \end{cases} \tag{7}$$

where the $k_s(e,\dot{e})$ is adapted using the fuzzy rules in Table I. One of the main properties of the fuzzy logic is that the rules are set in natural language. The fuzzy logic leads to make an inference system in which decisions are flexible, nonlinear, and without discontinuities which closer to human manner than classical logic is [6], [7], [8]. Positive, Zero, and Negative are considered as the linguistic terms of the If part of the fuzzy rules, and Small, Medium, and Large are the linguistic terms of the consequence part. According to the mentioned linguistic term for the fuzzy rules, all membership functions of their corresponding fuzzy sets are Gaussian functions such as:

TABLE I: Proposed Fuzzy Rules To Tune $k_s$

| Rule No. | IF | THEN |
|---|---|---|
| $\mathbf{R_1}$ | $\mathbf{e}$ is Positive and $\dot{\mathbf{e}}$ is Positive | $\mathbf{k_s}$ is Large |
| $\mathbf{R_2}$ | $\mathbf{e}$ is Positive and $\dot{\mathbf{e}}$ is Negative | $\mathbf{k_s}$ is Small |
| $\mathbf{R_3}$ | $\mathbf{e}$ is Zero and $\dot{\mathbf{e}}$ is Negative | $\mathbf{k_s}$ is Large |
| ... | ... | ... |
| $\mathbf{R_n}$ | $\mathbf{e}$ is Negative and $\dot{\mathbf{e}}$ is Positive | $\mathbf{k_s}$ is Small |

$$\mu_m(x) = e^{-\frac{(x-c_m)^2}{2\sigma_m}} \tag{8}$$

where $x$ is the input of the membership function and takes the value $\mathbf{e}$ and $\dot{\mathbf{e}}$ as the position and rate of position error. Additionally, $m$ is used to distinguish the membership function for each of the linguistic terms. The scalar parameters of $c_m$ and $\sigma_m$ in (8) are chosen based on the knowledge about the constrained robot and controlling of the manipulator.

## V. Experimental Results

In this section, the experimental setup is described and the proposed Fuzzy virtual fixture experiments are presented. To verify the performance of the proposed controller, the experimental setup in Fig. 4 is considered. According to Fig. 4, the robot is equipped with the dental drilling tool using the mechanical interface. In addition, a min45 ATI force sensor is used to measure the force.

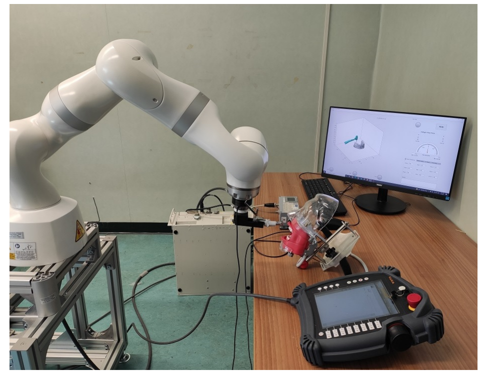

Fig. 4: Experimental setup to verify the proposed approach

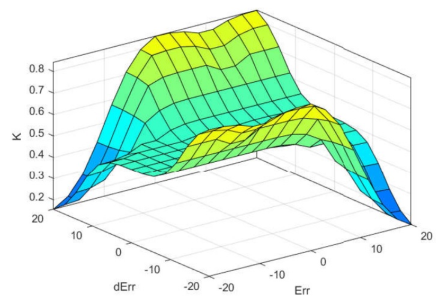


Fig. 5: Fuzzy Surface Rules

### A. Implementation Algorithm

Two scenarios are considered: smooth motion, and tremor motion. In the case of the smooth motion, the user moves the robot according to the monitoring error alarm to the desired point. However, in the tremor motion, the user deliberately moves the robot in a different direction to insert variable stiffness to the end-effector of the robot. In this case, the fuzzy rules are fired and it can be able to evaluate the fuzzy control method and passivity of the system. For the free motion, the stiffness of all directions (X,Y,Z) is considered $500N/m$. For the X modification, the stiffness in the direction X is specified by the fuzzy rules, and for the Y and Z direction, the stiffness is constant value $3000N/m$. For the Y modification phase, the stiffness for Y is specified by the fuzzy rules, and in the directions of X and Z, the stiffness is constant value $3000N/m$. Finally, for the Z motion, the stiffness of the robot in the Z direction is $500N/m$ and for the two others direction is $3000N/m$.

For the Smooth motion, the error position, and stiffness are depicted in Figs. 6, and 7, respectively. By considering Fig. 6, using the proposed adaptive fuzzy VF, error position converges to zero.

For the tremor motion, the error position, and stiffness are presented in Figs. 8, and 9, respectively. According to Fig. It can be observed that by moving the hand's motion in the different direction, the fuzzy rules enable and by changing

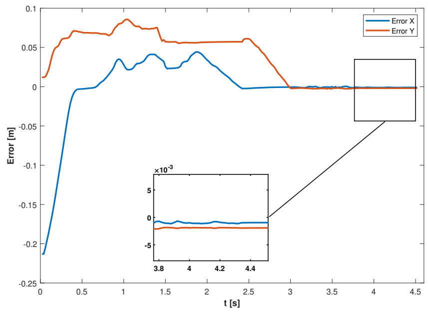


Fig. 6: Error Position for the Case 1

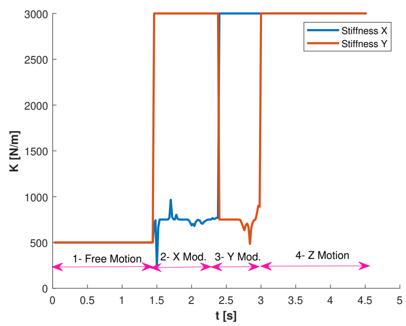


Fig. 7: Stiffness for the Case 1

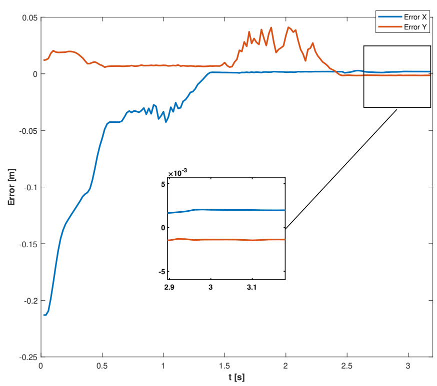


Fig. 8: Error Position for the Case 2

the value of the stiffness and inserting forces try to keep the surgeon hand in the right direction.

## VI. Conclusion

In this article, a hands-on robotic system using fuzzy adaptive virtual fixtures control is introduced for dental implant surgery. The proposed method generates the desired impedance profile to interact with the human hand. The introduced adaptive approach is used to adapt the impedance parameter. Using the proposed adaptive online approach, the stiffness parameters are updated to specify the new impedance profile to enhance the position tracking efficiency. The conditions of the stability of the closed-loop system are evaluated using the tank-energy passivity approach. To verify the performance of the proposed approach, experimental studies are conducted. The introduced approach is not only can be applied for dental implant surgery, but it can also be used for any hands-on robotic surgical operation that required accurate position control. As a result, the proposed adaptive virtual fixtures provide a more effective approach for hands-on robotic collaborative control.

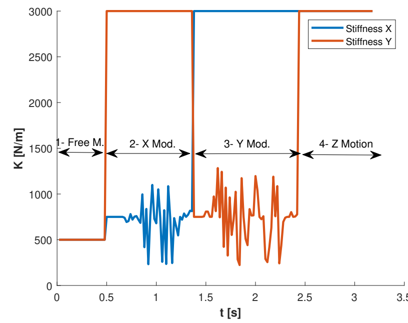


Fig. 9: Stiffness for the Case 2

## VII. Acknowledgment

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