

Design Active Robot Controller for Dental Automation

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Abstract

Following the developments in industrial robot technology, robotics has found its way into the medical field and is used in a range of surgical disciplines. The main purpose of the use of robots is to increase the precision, quality and safety of surgical procedures. Robotics is not yet used in dentistry even though all the necessary technologies have already been developed and could easily be adapted. Some of the technologies are already used in dentistry, such as image-based simulation of implant surgery followed by the use of surgical guides, and creating digital impressions of pre parathions using an intra-oral scanner, after which a milling device produces the restoration, but we have not yet seen any robot able to prepare teeth for crowns, inlays or bridges. Such a robot would fundamentally be a dental drilling device coupled with a navigation device to determine the correct position of the device in relation to the patient. The robot would either be operated directly by a dentist or be preprogrammed to perform its functions based on imaging data (CT scan). Finally, an intra-oral scanner would be used to make digital impressions. This data would then be transferred to the lab to produce temporary crowns or bridges in a very short time using a milling machine and to manufacture the final restorations in much shorter time than with conventional procedures. Robotics could offer dentistry improved accuracy, predictability, safety, quality of care and speed of treatment. One might wonder why robots have not yet been introduced to dentistry, as the functions needed are relatively simple. An explanation could be that robotics in dentistry is an example of a disruptive technology, meaning that the current manufacturers of dental equipment might fear a negative effect on their current business and the alienation of dentists, as robots might be seen as a threat to dental professionals. The passive robotic arm will sense the patient's movement, sending feedback in the form of translation and rotation data to the dental robot giving it the capability to adjust. This device will address the age-old problem in dentistry – precision and safety. This research focuses on the intelligent control of dental drilling procedures on a stationary object. This project addresses the ability of the system to detect movement of the object and accordingly adjust the drill before continuing the procedure.

Keywords: *fuzzy sliding mode controller, fuzzy-based tuning, rule base, sliding mode controller, uncertainties*

1. Introduction and Background

One of the best ways to maintenance of comprehensive oral health is Nanodentistry. It is employing nanomaterials, biotechnology, including tissue engineering and ultimately, dental nanorobotics. Nanodentistry can do oral health maintenance using mechanical dentifrobots, like local anesthesia, dentition renaturalization, permanent hypersensitivity cure, complete orthodontic realignments, covalently bonded diamond dised enamel and etc. Any product containing nano particles are Nano products that can be made by combining atomic elements to create mechanical nanoscale objects. Dentin hypersensitive of natural teeth have higher surface density of dentinal tubules and diameter and also larger than nonsensitive teeth. In dental nanorobots, we can use native biological materials, so it could selectively occlude specific tubules in a few minutes and offering patients a quick cure. Even Orthodontic nanorobots could directly effect to the periodontal ligaments, and allowing rapid and painless tooth alignment in correct positioning within minutes to hours. Nanorobotic manufacture of a biologically auto logous whole replacement tooth, that is, 'complete dentition replacement therapy' should become conveniently of a typical office visit with use of a desktop manufacturing facility, which would invent or fabricate the new tooth in the dentist's office not in the laboratory . In Nanorobotic analgesics, don't use needles, so there is a greater ability to control the analgesic effect, fast and reversible with avoid of side effects, to give patient comfort and also reduced nervousness. Nanorobotic dentifrice (dentifrobots) take by mouthwash or toothpaste that could control all supragingival and sub gingival surfaces using once a day or more, metabolizing the organic matter into harmless and odorless vapors and prevent calculus debridement and plaque accumulation . With this kind of daily dental care available from an early age, we can prevent tooth decay and gingival diseases [1-5].

Robots are typically thought to be used for industrial purposes however they are beginning to gain the attention of the medical field. Telem manipulator is collection of links that connect by joints, these joints can be revolute and prismatic that revolute joint has rotary motion around an axis and prismatic joint has linear motion around an axis. Each joint provides one or more degrees of freedom (DOF) [6-7].

Surgery is a medical procedure involving an incision in the human body performed to repair damage or arrest disease. In a fully invasive operation, an open incision is made that is large enough for the surgeon to view the internal organs and perform the operation. For example, in open-heart surgery a long incision is made along the sternum, after which the sternum is split and retracted (median sternotomy). These open incisions increase trauma to a patient beyond what is experienced from the actual repair. After the operation, the patient must heal from trauma associated with the repaired organs and from the open incision. This results in long recovery times and opportunities for infection [3]. Endoscopic Surgery, also called Minimally Invasive Surgery (MIS), is a type of operation that has been developed to reduce trauma associated with making these large open incisions. This type of operation involves viewing the operational field on a television monitor by inserting a special camera, called an endoscope, through a small incision in the skin. To perform the operation, "long, thin, manually operated instruments" are inserted through other small incisions called trocars [3]. This type of surgery reduces the size of the open incisions and therefore results in less pain and scarring after surgery, faster recovery times, and less risk of infection [4].

A dental industry does have benefits over fully invasive surgery but there are also several disadvantages associated with performing this type of operation. The two basic disadvantages involve viewing the internal operational field and the dental tool interface. Using a dental camera, the operational field is viewed on a 2-D television monitor providing only a limited view with no depth perception. Advances in visual technology have provided surgeons with equipment that allow them to view the field in 3-D however this technology is expensive [5]. Another disadvantage is that the dental operation is operated by a dental assistant. This requires the surgeon to communicate motion

instructions which becomes difficult when giving instructions such as how far to move the tools and in which direction. It has also been reported that small tremors from the scope-holding assistant, magnified onto the television monitor, can cause nausea among the dental team [5]. Disadvantages associated with the dental tool interface involve the dental tools and the way that the operation is performed. Often the dental tools are heavy, lacking ergonomic design, and do not have the same DOF/dexterity as a human hand. As mentioned before, these tools are inserted through small incisions in the patient to perform the operation. This creates the fulcrum/lever effect whereas the surgeon is required to transpose each hand motion to get the desired internal motion. For example, if it is desired to move the tool manipulator to the left within the patient the surgeon must transpose this motion in his mind and move the tool handle to the right. Dentists must also deal with the amplification of tremors in their hands due to the fulcrum/lever effect and the length of the tools [3]. Performing an operation through small incisions using dental tools removes the ability for a surgeon to use the sense of touch to gain more information about the internal tissue (haptic feedback). Tools that provide surgeons with this type of information are being developed, however they are not yet in use. Dentists are at risk for musculoskeletal disorders because of lower job control and working long hours. The vascular, neurologic, and osteoarticular disorders in the upper limbs of vibration-exposed workers (like dentists) is called hand-arm vibration syndrome. Also there is a risk for wrist osteoarthritis and for elbow arthritis and osteophytosis in workers exposed to shocks and low-frequency vibration of high magnitude tools that it increased occurrence of digital vasospastic disorders called vibration-induced white finger (VWF) and also hand neuropathy has been reported caused by use of high and low speed tools with high frequency vibration by working with high speed grinding machines that exposed to high frequency vibration up to 40khz. Epidemiologic studies show the increased risk of carpal tunnel syndrome among vibration exposed workers. Low frequency vibration is transmitted from the area of skin that contact with the tool and might produced nerve damaged through swelling of the endoneurium and impaired microcirculation, but with high frequency vibration the mechanical energy is absorbed in the skin so there is no proximal nerve damage accrue. The most important goal among researchers are prevention of hand/wrist complaints. Figure 1 shows the dental robot manipulator.



Figure 1. Dental Robot Manipulator

In the late 1980's, researchers motivated by the limitations of dental surgery turned to robotic technology to make improvements [8-9]. Although the idea of using robotics for telepresence surgery was not a new idea at this time, research and development into this concept rapidly progressed around the success of MIS techniques and became possible with advancements in computing power [10]. By 1998, two major companies had developed surgical systems approved by the FDA for commercial use. Computer Motion in Goletta, California developed the Zeus Surgical System and Intuitive Surgical in Sunnyvale, California developed the daVinci Surgical System. Currently only the daVinci is in production due to the merger of Computer Motion and Intuitive Surgical in 2003. Figure 2 shows DAVINCI Surgical robot System.



Figure 2. Intuitive Surgical DAVINCI Surgical System

One of the fundamental issues in control theory is the ability to design the best controller to propose in robustly stabilizing a system, in the presence of structured uncertainties, such as parameters variations. In the case of finite-dimensional, time variant, linear models, a variety of techniques are available, which range from elementary methods base on the properties of the root locus (which lends itself to a very intuitive characterization of the 'stability margin' inherent to certain design techniques, such as small gain and /or 'high-gain') to more sophisticated methods such as, in the case of parameters uncertainties, those relying upon the analysis of the closed-loop characteristic polynomial (whose uncertain coefficients rang over prescribed intervals) or the design of a feedback controller imposing a fixed (parameter independent) Lyapunov function .In the recent years, similar methods have been gradually developed also for liner and nonlinear systems. In this report, we have chosen to review in some detail one of these methods. Of course, stabilization is just one aspect of feedback design, for linear as well for nonlinear system. It must be stressed, though, that stability is the most important feature a closed-loop system is required to have [11-13].

What it should be supplied by controller are stabilize and robust. The stabilize have to improve the trajectory follows, torque performance, errors and the robust have to improve the system robustness. The above indicated elements are the main element for choice the controller and what are going to be test in controllers is the performance of these elements (trajectory following, torque ,error, robust). The linear and nonlinear controllers' follows the number of technique for control the linear and nonlinear system. These techniques base on the system model divided in two types: model base and model free, the controllers designed base on system dynamic are the model base and the controllers designed independent from system model called model free or artificial intelligent, thus the linear controllers type are model free and nonlinear controllers divided in two model free and model base . Linear controllers are model free that divided in three types: Proportional-Derivative (PD), Proportional-Integral (PI), and Proportional-Integral-Derivative (PID). At present, in some applications robot arms are used in unknown and unstructured environment, therefore strong mathematical tools used in new control

methodologies to design nonlinear robust controller with an acceptable safety performance (*e.g.*, minimum error, good trajectory, disturbance rejection). One of the most important nonlinear safety controllers is linear PID methodology which is used in nonlinear certain systems in limitation variation. Uncertainty in system can causes some problems about dentistry. To solve this problem, neural network, fuzzy logic, and neuro-fuzzy are synergically combined with classical controller and used in nonlinear, time variant, and uncertainty plant (*e.g.*, robot) [14-20].

A fuzzy theory of creating and processing models, similar to those used by a human brain, was sought – Lotfi Zadeh proposed such a theory in 1965 [12]. The development of technology has computerised our life and strengthened the problem of man–machine interaction. Here I mean the man–machine interaction in a wide sense, not just as an interface but as a problem of establishing a harmony in communication between a computer and a human being on the levels of cooperative thinking, logic, language. We have a computer, operating according to Boolean logic with numerical mathematical models constructed by application researchers, and users who operate with another sort of logic and language including a high degree of ambiguity or fuzziness. Fuzzy sets theory aims to bridge this gap [13-18]. It can be extremely useful not just in engineering and technological sciences but in social sciences, eliminating the difference in the approaches between natural and social sciences. In the last two decades, the fuzzy sets theory has established itself as a new methodology for dealing with any sort of ambiguity and uncertainty. An underlying philosophy of the theory is a mathematical framework where imprecise conceptual phenomena in modelling and decision making may be precisely and rigorously studied. It lets mathematical models describe rather ‘unmodelled’ situations and finds solutions of ‘unsolvable’ problems. The theory includes a new mathematical apparatus and computer-realizable models [14-15]. The current number of researchers in this field and research societies mushrooming around the world show the attractiveness of this theory for both theoretical and practical researchers. One of the newest and most challenging technological applications is of the fuzzy logic in the control system of a dental robot, which is fundamentally unstable and with highly nonlinear dynamics [16-20]. In this research the main target is design PID intelligent controller to improve the robust, stability and reliability in dental robot manipulator.

This paper is organized as follows: In section 2, main subject of case study (robot manipulator) dynamic formulation is presented. Detail of PID controller and fuzzy rule base tuning controller is presented in section 3. In section 4, the simulation result is presented and finally in section 5, the conclusion is presented.

2. Theorem: Case Study (Dynamic Formulation of Robot Manipulator)

Case Study (Dynamic of Robot Manipulator): Medical robots are *tools* that are being used by doctors to increase there capabilities and abilities to diagnose and cure diseases. They are not replacing doctors, but they are providing them with ways to perform better. Medical robots use range from autonomously performing a specific task during an operation to providing a human-machine interface that helps perform the entire procedure. There are several commercial companies that offer these systems however they are not being widely used. Some of the reasons for this revolve around questions regarding there effectiveness, safety, and cost [9]. Before talking more specifically about the different types and tasks of medical robots, it will help to give a definition of a robotic system. A robot is a mechanical system that is capable of performing a physical task [10]. It can be broken down into three main components: a control device, actuators and mechanical parts, and sensors. These three components allow a robot to interact with its environment. The controller is the brains of the system processing information and changing the actuators and mechanical parts based on this information. The actuators and mechanical

parts provide the actual motion of the robot system. The sensors of the system allow the robot to get feedback on its position and in smarter systems data from the environment. Benefits of using robotics are that they can perform motions with very high precision repetitively without fatigue. They are capable of performing tasks that are not possible by humans such as lifting heavy objects and can hold a very precise position endlessly. From these benefits it is not hard to see why research is being done to implement robotics into some of the very difficult, fatiguing, and precise procedures that doctors/surgeons are performing. Medical robots can be divided according to their level of autonomy into three categories: active, semiactive, and passive [6-7]. Active medical robots autonomously perform a specific task during an operation that was programmed prior to the procedure. These robots take on an active role of performing a task under the supervision of the operator. Using this type of robot typically involves three steps: preoperative planning, program verification, and performing the operation. Semiactive medical robot takes on some of the features of both the passive and active medical robots. Similar to a passive robot, a surgeon will directly control the robotic system however the system will provide some type of constraint. This type of medical robot has been classified as having constrained cooperative control autonomy [9]. Passive medical robots are systems that perform motions only under the command of a human operator through some interface (joystick, foot pedal, etc.). These robots are also called surgical assistants, surgical extenders, and telemanipulators [9]. These robots are programmed to listen to external interfaces for motion commands and other tasks. As opposed to active medical robots, there is no preoperative motion commands programmed into the controller. Most of these robots are used for dental procedures where they may perform the task of positioning a dental camera or actually manipulate the dental tools under a surgeon's control. The robotic surgical system described in this research is a tool that would assist a surgeon in performing a dental procedure. It does this by holding and physically manipulating an dental tool under the direct control of the surgeon. It should be noted that the robot does not perform the surgery, but only provides assistance by manipulating the tools position and manipulator at the surgeons command. The system is classified as a passive medical robot, more specifically as a master-slave telemanipulator. In this type of system, the master has direct control over all movements of the robotic system. This is an essential feature for a surgical robot because only the surgeon should have the ability to move the robot arm. In between the surgeon and the Robotic System is a human machine interface that provides the surgeon with control of the system.

Robot manipulator is a collection of links that connect to each other by joints, these joints can be revolute and prismatic that revolute joint has rotary motion around an axis and prismatic joint has linear motion around an axis. Each joint provides one or more degrees of freedom (DOF). Dynamic modeling of robot manipulators is used to describe the behavior of robot manipulator such as linear or nonlinear dynamic behavior, design of model based controller such as pure sliding mode which design this controller is based on nonlinear dynamic equations, and for simulation. The dynamic modeling describes the relationship between joint motion, velocity, and accelerations to force/torque or current/voltage and also it can be used to describe the particular dynamic effects (*e.g.*, inertia, coriolios, centrifugal, and the other parameters) to behavior of system [1]. It has a nonlinear and uncertain dynamic parameters serial link 6 degrees of freedom (DOF) robot manipulator. A nonlinear robust controller design is major subject in this work. The equation of a multi degrees of freedom (DOF) robot manipulator is calculated by the following equation [6]:

$$H(q)\ddot{q} + N(q, \dot{q}) = \tau \quad (1)$$

Where τ is $n \times 1$ vector of actuation torque, $H(q)$ is $n \times n$ symmetric and positive define inertia matrix, $N(q, \dot{q})$ is the vector of nonlinearity term, and q is $n \times 1$ position

vector. In equation 2.8 if vector of nonlinearity term derive as Centrifugal, Coriolis and Gravity terms, as a result robot manipulator dynamic equation can also be written as [10]:

$$N(q, \dot{q}) = V(q, \dot{q}) + G(q) \quad (2)$$

$$V(q, \dot{q}) = B(q)[\dot{q} \dot{q}] + C(q)[\dot{q}]^2 \quad (3)$$

$$\tau = H(q)\ddot{q} + B(q)[\dot{q} \dot{q}] + C(q)[\dot{q}]^2 + G(q) \quad (4)$$

Where,

$B(q)$ is matrix of coriolis torques, $C(q)$ is matrix of centrifugal torque, $[\dot{q} \dot{q}]$ is vector of joint velocity that it can give by: $[\dot{q}_1 \cdot \dot{q}_2, \dot{q}_1 \cdot \dot{q}_3, \dots, \dot{q}_1 \cdot \dot{q}_n, \dot{q}_2 \cdot \dot{q}_3, \dots]^T$, and $[\dot{q}]^2$ is vector, that it can given by: $[\dot{q}_1^2, \dot{q}_2^2, \dot{q}_3^2, \dots]^T$.

In robot manipulator dynamic part the inputs are torques and the outputs are actual displacements, as a result in (5) it can be written as [10];

$$\ddot{q} = M^{-1}(q) \cdot \{\tau - N(q, \dot{q})\} \quad (5)$$

To implementation (6) the first step is implement the kinetic energy matrix (H) parameters by used of Lagrange's formulation. The second step is implementing the Coriolis and Centrifugal matrix which they can calculate by partial derivatives of kinetic energy. The last step to implement the dynamic equation of robot manipulator is to find the gravity vector by performing the summation of Lagrange's formulation [19-20].

Dental Robot Platform: The robotic dental system described in this research is a tool that would assist a dentist in performing a drilling procedure. It does this by holding and physically manipulating a dentistry tool under the direct control of the dentist. It should be noted that the robot does not perform the dentistry, but only provides assistance by manipulating the tools position and manipulator at the dentists command. The system is classified as a passive medical robot, more specifically as a master-slave telemanipulator (see Figure 3). In this type of system, the master has direct control over all movements of the robotic system. This is an essential feature for a dental robot because only the dentist should have the ability to move the robot arm. In between the dentist and the Robotic System is a human machine interface that provides the dentist with control of the system.

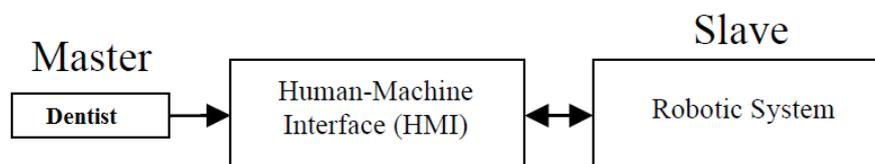


Figure 3. Master-Slave Telemanipulator

The human-machine interface (HMI) is the instruments provided by which the surgeon can control the robotic system to perform an operation. It is composed of a computer (monitor, cpu, keyboard, mouse). The two joysticks provide direct control of the robotic system's movements. The first joystick is used to control the robotic arm while the second joystick controls the dental manipulator. The robotic arm joystick provides XYZ motion control of the drilling end effector in reference to the world frame. Joystick motions along the X and Y axis are converted to X and Y displacements while rotation of the joystick is converted to Z displacements. The manipulator joystick performs five different functions: yaw, pitch, roll, open grip, and close grip. X and Y motions of the joystick are converted

to pitch and yaw motions of the manipulator. Rotating the joystick performs the roll option and pressing button 1 or button 2 performs the close or open grip function. Figure 4 shows Saitek evo Force Feedback Joysticks.



Figure 4. Saitek evo Force Feedback Joysticks

The computer runs the systems software program which performs many functions but most importantly provides the user with the ability to control the robotic system. There are four different states of the program: Initialization, Trocar Placement, Insertion/Retraction, and Operation. The program starts up in the initialization state. The first task is to establish and verify communication with the Robotic Arm, dental Manipulator, and joysticks. Communication does not need to be established with the robot teach pendant since it is part of the robotic system. If communication is not established with any component, the program informs the user and then exits. This is done as a precaution so that all parts of the system are ready for operation before continuing. The second task in this state is to ask the user if the robot arm needs to be initialized. Performing this aligns the arm with the mathematical model of the arm stored in the controller's memory allowing the robot controller to know the position of the arm relative to the world. Initializing the robot can only be executed if the arm is in the homing bracket. This must be done if not previously executed since the robot controllers last power cycle. For safety the user of the system is notified of this action as opposed to automatic execution at the start-up of the program.

3. Methodology

Design of a linear methodology to control of continuum robot manipulator was very straightforward. Since there was an output from the torque model, this means that there would be two inputs into the PID controller. Similarly, the outputs of the controller result from the two control inputs of the torque signal. In a typical PID method, the controller corrects the error between the desired input value and the measured value. Since the actual position is the measured signal. Figure 5 shows linear PID methodology, applied to continuum robot manipulator.

$$e(t) = \theta_a(t) - \theta_d(t) \quad (6)$$

$$U_{PID} = K_{p_a} e + K_{v_a} \dot{e} + K_I \int e \quad (7)$$

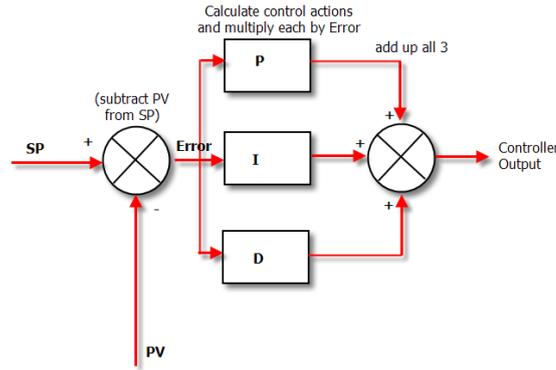


Figure 5. Block Diagram of Linear PID Method

The model-free control strategy is based on the assumption that the joints of the manipulators are all independent and the system can be decoupled into a group of single-axis control systems. Therefore, the kinematic control method always results in a group of individual controllers, each for an active joint of the manipulator. With the independent joint assumption, no a priori knowledge of robot manipulator dynamics is needed in the kinematic controller design, so the complex computation of its dynamics can be avoided and the controller design can be greatly simplified. This is suitable for real-time control applications when powerful processors, which can execute complex algorithms rapidly, are not accessible. However, since joints coupling is neglected, control performance degrades as operating speed increases and a manipulator controlled in this way is only appropriate for relatively slow motion. The fast motion requirement results in even higher dynamic coupling between the various robot joints, which cannot be compensated for by a standard robot controller such as PID, and hence model-based control becomes the alternative.

Based on fuzzy logic methodology

$$f(x) = U_{fuzzy} = \sum_{l=1}^M \theta^T \zeta(x) \quad (8)$$

where θ^T is adjustable parameter (gain updating factor) and $\zeta(x)$ is defined by;

$$\zeta(x) = \frac{\sum_i \mu(x_i) x_i}{\sum_i \mu(x_i)} \quad (9)$$

Where $\mu(x_i)$ is membership function. τ_{fuzzy} is defined as follows;

$$\tau_{fuzzy} = \sum_{l=1}^M \theta^T \zeta(x) = [M^{-1}(B + C + G) + \dot{S}]M \quad (10)$$

To compute dynamic parameters of dental robot;

$$\tau_{fuzzy} = \begin{bmatrix} \tau_{1fuzzy} \\ \tau_{2fuzzy} \\ \tau_{3fuzzy} \end{bmatrix}, M^{-1} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix}^{-1}$$

$$B + C + G = \begin{bmatrix} b_{112}\dot{q}_1\dot{q}_2 + b_{113}\dot{q}_1\dot{q}_3 + 0 + b_{123}\dot{q}_2\dot{q}_3 \\ 0 + b_{223}\dot{q}_2\dot{q}_3 + 0 + 0 \\ 0 \\ b_{412}\dot{q}_1\dot{q}_2 + b_{413}\dot{q}_1\dot{q}_3 + 0 + 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} C_{12}\dot{q}_2^2 + C_{13}\dot{q}_3^2 \\ C_{21}\dot{q}_1^2 + C_{23}\dot{q}_3^2 \\ C_{31}\dot{q}_1^2 + C_{32}\dot{q}_2^2 \\ 0 \\ C_{51}\dot{q}_1^2 + C_{52}\dot{q}_2^2 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ g_2 \\ g_3 \\ 0 \\ g_5 \\ 0 \end{bmatrix}$$

$$M = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix}$$

Therefore, the PID fuzzy controller for dental robot manipulator is calculated by the following equation;

$$\begin{bmatrix} \widehat{\tau}_1 \\ \widehat{\tau}_2 \\ \widehat{\tau}_3 \end{bmatrix} = \begin{bmatrix} \tau_{1fuzzy} \\ \tau_{2fuzzy} \\ \tau_{3fuzzy} \end{bmatrix} + \begin{bmatrix} \tau_{1PID} \\ \tau_{2PID} \\ \tau_{3PID} \end{bmatrix} \tag{11}$$

The main parts to design fuzzy controller are:

Fuzzification: the first step in fuzzification is determine inputs and outputs which, it has two inputs (e, \dot{e}) and one output (τ_{fuzzy}). The inputs are error (e) which measures the difference between desired and actual output position, and the change of error (\dot{e}) which measures the difference between desired and actual velocity and output is fuzzy torque. The second step is chosen an appropriate membership function for inputs and output which, to simplicity in implementation because it is a linear function with regard to acceptable performance triangular membership function is selected in this research. In the membership function choice, one has to solve a few problems: how to choose general parameters, such as the number of classes (membership functions) to describe all the values of the linguistic variable on the universe, the position of different membership functions on the universe of discourse, the width of the membership functions, and concrete parameters, such as the shape of a particular membership function. The third step is chosen the correct labels for each fuzzy set which, in this research namely as linguistic variable. Based on experience knowledge the linguistic variables for error (e), change of error (\dot{e}) and torque are; Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Big (PB).

Fuzzy Rule Base and Rule Evaluation: the first step in rule base and evaluation is to provide a least structured method to derive the fuzzy rule base which, expert experience and control engineering knowledge is used because this method is the least structure of the other one and the researcher derivation the fuzzy rule base from the knowledge of system operate and/or the classical controller. The complete rule base for this controller is shown in Table 1.

Table 1. Rule Base for Fuzzy Controller

		Δe				
e		NB	NS	Z	PS	PB
NB		PB	PB	PB	PS	Z
NS		PB	PB	PS	Z	NS
Z		PB	PS	Z	NS	NB
PS		PS	Z	NS	NB	NB
PB		Z	NS	NB	NB	NB

Rule evaluation focuses on operation in the antecedent of the fuzzy rules in proposed method. In this research *AND* operation is selected.

Aggregation of the Rule Output (Fuzzy Inference): There are several methodologies in aggregation of the rule outputs and used in fuzzy logic controllers, namely,

- Max-Min aggregation
- Sum-Min aggregation
- Max-bounded product
- Max-drastic product
- Max-bounded sum
- Max-algebraic sum
- Min-max.

Two most common methods that used in fuzzy logic controllers are Max-min aggregation and Sum-min aggregation. Max-min aggregation defined as below

$$\mu_U(x_k, y_k, U) = \mu_{\cup_{i=1}^r FR^i}(x_k, y_k, U) = \max \left\{ \min_{i=1}^r \left[\mu_{R_{pq}}(x_k, y_k), \mu_{p_m}(U) \right] \right\} \quad (12)$$

The Sum-min aggregation defined as below

$$\mu_U(x_k, y_k, U) = \mu_{\cup_{i=1}^r FR^i}(x_k, y_k, U) = \sum \min_{i=1}^r \left[\mu_{R_{pq}}(x_k, y_k), \mu_{p_m}(U) \right] \quad (13)$$

where r is the number of fuzzy rules activated by x_k and y_k and also $\mu_{\cup_{i=1}^r FR^i}(x_k, y_k, U)$ is a fuzzy interpretation of $i - th$ rule. Max-Min aggregation is used in this work.

Defuzzification: The last step in the fuzzy inference in any fuzzy set is defuzzification. This part is used to transform fuzzy set to crisp set, therefore the input for defuzzification is the aggregate output and the output is a crisp number. There are several methodologies in defuzzification of the rule outputs that can be used in fuzzy logic controllers but two most common defuzzification methods are: Center of gravity method (*COG*) and Center of area method (*COA*), which *COG* method used the following equation to calculate the defuzzification

$$COG(x_k, y_k) = \frac{\sum_i U_i \sum_{j=1}^r \mu_u(x_k, y_k, U_i)}{\sum_i \sum_{j=1}^r \mu_u(x_k, y_k, U_i)} \quad (14)$$

and *COA* method used the following equation to calculate the defuzzification

$$COA(x_k, y_k) = \frac{\sum_i U_i \cdot \mu_u(x_k, y_k, U_i)}{\sum_i \mu_u(x_k, y_k, U_i)} \quad (15)$$

Where $COG(x_k, y_k)$ and $COA(x_k, y_k)$ illustrates the crisp value of defuzzification output, $U_i \in U$ is discrete element of an output of the fuzzy set, $\mu_u(x_k, y_k, U_i)$ is the fuzzy set membership function, and r is the number of fuzzy rules. Center of gravity method (*COG*) is used in this research.

In most of industrial robot manipulators, controllers are still usually classical linear (PD, PI, or PID controller), but in this research the manipulator dynamics is highly nonlinear, sensitive and have uncertain or variation in parameters (*e.g.*, structure and unstructured), as a result design a classical linear controllers for this system with high impact result is very difficult and sometimes impossible. To solve this challenge PID controller applied to PD fuzzy logic controller to make the robust algorithm in order to reduce the uncertainty problems in a limit variation. In this research, if two fuzzy rules defined by

$$F.R^1: \text{if } e \text{ is } N.B \text{ and } \dot{e} \text{ is } NB \text{ then } T \text{ is } NB$$

$F.R^2$: if e is $N.B$ and \dot{e} is NS then T is NB

To calculate Mamdani fuzzy inference system we must to do four steps:

- Fuzzification is used to determine the membership degrees if all input fuzzy activated by crisp input values $e = -1$ and $\dot{e} = -3.92$, where fuzzy set NB , NS , and NB are defined as below

$$\begin{aligned}
 e_{(N.B)} &= \{(0, -1.5), (0.25, -1.375), (0.5, -1.25), (0.75, -1.125), (1, -1), (0.75, -0.875), \\
 &\quad (0.5, -0.75), (0.25, -0.625), (0, -0.5)\} \\
 \dot{e}_{(NS)} &= \{(0, -5.8), (0.25, -5.17), (0.5, -4.55), (0.75, -3.92), (1, -3.3), (0.75, -2.67), \\
 &\quad (0.5, -2.05), (0.25, -1.42), (0, -0.83)\} \\
 \dot{e}_{(NB)} &= \{(0, -7.5), (0.25, -6.88), (0.5, -6.25), (0.75, -5.57), (1, -5), (0.75, -4.30), \\
 &\quad (0.5, -3.92), (0.25, -3.12), (0, -2.5)\}
 \end{aligned}$$

while

$$\begin{aligned}
 T_{(NB)} &= \{(0, -123), (0.25, -113.5), (0.5, -104), (0.75, -94.5), (1, -85), (0.75, -75.5), \\
 &\quad (0.5, -66), (0.25, -56.5), (0, -47)\}
 \end{aligned}$$

Rule evaluation focuses on operation in the antecedent of the fuzzy rules. This controller used *AND* fuzzy operation, that it can be defined by $T(a, b) = \mu_{A \cap B(u)} = \min\{\mu_{A(u)}, \mu_{B(u)}\}$. The output fuzzy set can be calculated by using individual rule-base inference. So this part focuses on determine the activation degrees of antecedent of $F.R^1$ and $F.R^2$:

$$\begin{aligned}
 \mu_{FR_1} &= \min[\mu_{e_{(N.B)}}(-1), \mu_{\dot{e}_{(NS)}}(-3.92)] = \min[1, 0.75] = 0.75 \\
 \mu_{FR_2} &= \min[\mu_{e_{(N.B)}}(-1), \mu_{\dot{e}_{(NB)}}(-3.92)] = \min[1, 0.5] = 0.5
 \end{aligned}$$

The activation degrees of the consequent parts for $F.R^1$ and $F.R^2$ can be calculated by:

$$\begin{aligned}
 \mu_{FR_1}(-1, -3.92, T) &= \min[\mu_{FR_1}(-1, -3.92), \mu_{T(NB)}] = \min[0.75, \mu_{T(NB)}] \\
 \mu_{FR_2}(-1, -3.92, T) &= \min[\mu_{FR_2}(-1, -3.92), \mu_{T(NB)}] = \min[0.5, \mu_{T(NB)}]
 \end{aligned}$$

Therefore fuzzy set $T_{NB(1)}$ and $T_{NB(2)}$ have nine elements, that can be written by the following form

$$\begin{aligned}
 F.F^1(-1, -3.92, T) &= \{(0, -123), (0.25, -113.5), (0.5, -104), (0.75, -94.5), (0.75, -85), \\
 &\quad (0.75, -75.5), (0.5, -66), (0.25, -56.5), (0, -47)\} \\
 F.F^2(-1, -3.92, T) &= \{(0, -123), (0.25, -113.5), (0.5, -104), (0.5, -94.5), (0.5, -85), \\
 &\quad (0.5, -75.5), (0.5, -66), (0.25, -56.5), (0, -47)\}
 \end{aligned}$$

Aggregation of the rule outputs focuses on the aggregation of two fuzzy set into one output fuzzy set. Therefore by using the Max-min aggregation the output of fuzzy set can be calculated:

$$\begin{aligned}
 \mu_{U_{12}}(-1, -3.92, T) &= \mu_{\bigcup_{i=1}^2 FR^i}(-1, -3.92, T) \\
 &= \max\{\mu_{FR}^1(-1, -3.92, T)_{LL}, \mu_{FR}^2(-1, -3.92, T)_{LL}\}
 \end{aligned}$$

$$U_{12} = \{(0, -123), (0.25, -113.5), (0.5, -104), (0.75, -94.5), (0.75, -85), (0.75, -75.5), (0.5, -66), (0.25, -56.5), (0, -47)\}$$

and by using the Sum aggregation the output of fuzzy set can be calculated by

$$U_{12} = \{(0, -123), (0.5, -113.5), (1, -104), (1, -94.5), (1, -85), (1, -75.5), (1, -66), (0.5, -56.5), (0, -47)\}$$

Fuzzification is the last step to calculate the fuzzy inference system. In this example we use two methods, namely, *COA*, and *COG* defuzzification. For Max-min aggregation the *COA* defuzzification can be calculated by

$$COA = [(0.25 \times -113.5) + (0.5 \times -104) + (0.75 \times -94.5) + (0.75 \times -85) + (0.75 \times -75.5) + (0.5 \times -66) + (0.25 \times -56.5)] [0.25 + 0.5 + 0.75 + 0.75 + 0.75 + 0.5 + 0.25]^{-1} = \frac{-318.75}{3.75} = -85$$

For Sum aggregation the *COA* defuzzification can be calculated by

$$COA = [(0.5 \times -113.5) + (1 \times -104) + (1 \times -94.5) + (1 \times -85) + (1 \times -75.5) + (1 \times -66) + (0.5 \times -56.5)] [0.5 + 1 + 1 + 1 + 1 + 1 + 0.5]^{-1} = \frac{-510}{6} = -85$$

For Max-min aggregation the *COG* defuzzification can be calculated by

$$COG = \frac{[(-113.5 - 56.5)(0.25) + (-104 - 66)(0.5) + (-94.5 - 85 - 75.5)(0.75)]}{0.25 + 0.5 + 0.75 + 0.75 + 0.75 + 0.5 + 0.25} = -85$$

For Sum aggregation the *COG* defuzzification can be calculated by

$$COG = \frac{[(-113.5 - 56.5)(0.5) + (-104 - 94.5 - 85 - 75.5 - 66)(1)]}{0.5 + 1 + 1 + 1 + 1 + 1 + 0.5} = -85$$

To improve the performance of fuzzy logic controller, PID controller is used in this research. PID controller can help fuzzy controller to have more stable result. In this research fuzzy and PID controller have totally six coefficients and to optimize these coefficients; fuzzy logic on-line tuning is selected. In this method, fuzzy logic has two important role: main controller and on-line tuner. In this methodology, the system's performance is improved with respect to the manual tuning controller.

To adjust the coefficients we define $\hat{f}(x|\lambda)$ as the fuzzy based tuning.

$$\hat{f}(x|\lambda) = \lambda^T \zeta(x) \tag{16}$$

If minimum error (λ^*) is defined by;

$$\lambda^* = \arg \min [(\text{Sup}|\hat{f}(x|\lambda) - f(x))] \tag{17}$$

Where λ^T is adjusted by an adaption law and this law is designed to minimize the error's parameters of $\lambda - \lambda^*$. adaption law in fuzzy tuning proposed controller is used to adjust the sliding surface slope coefficient.

4. Results

In this research, proposed method used to control of dental robot. To test this control technique, the arm= 30° , the forearm= 17.8° , wrist= 17.9° and Finger= -7° . Figure 6 shows the robot trajectory control.

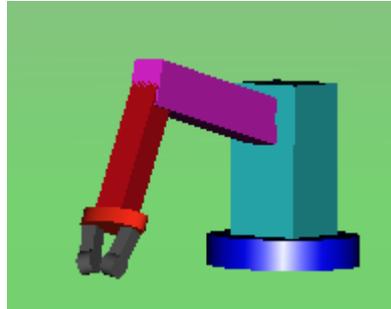


Figure 6. Trajectory Tracking Control

The following Figure (Figure 7) shows the rotation of robot in two position; arm= 30° and arm= 71° .

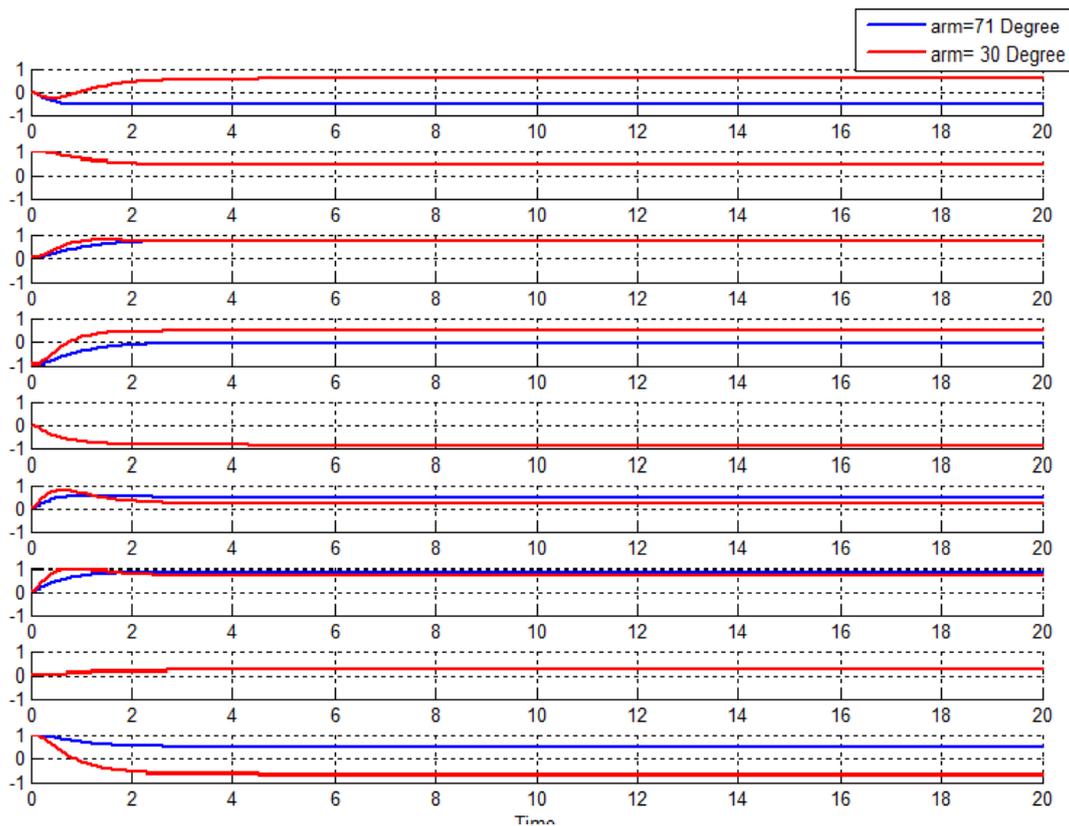


Figure 7. Rotational Tracking Control

Regarding to Figure 8 the translation tracking control shows in two types arm position: arm= 30° and arm= 71° . Based on the following Figure, when the arm position= 71° system will have overshoot.

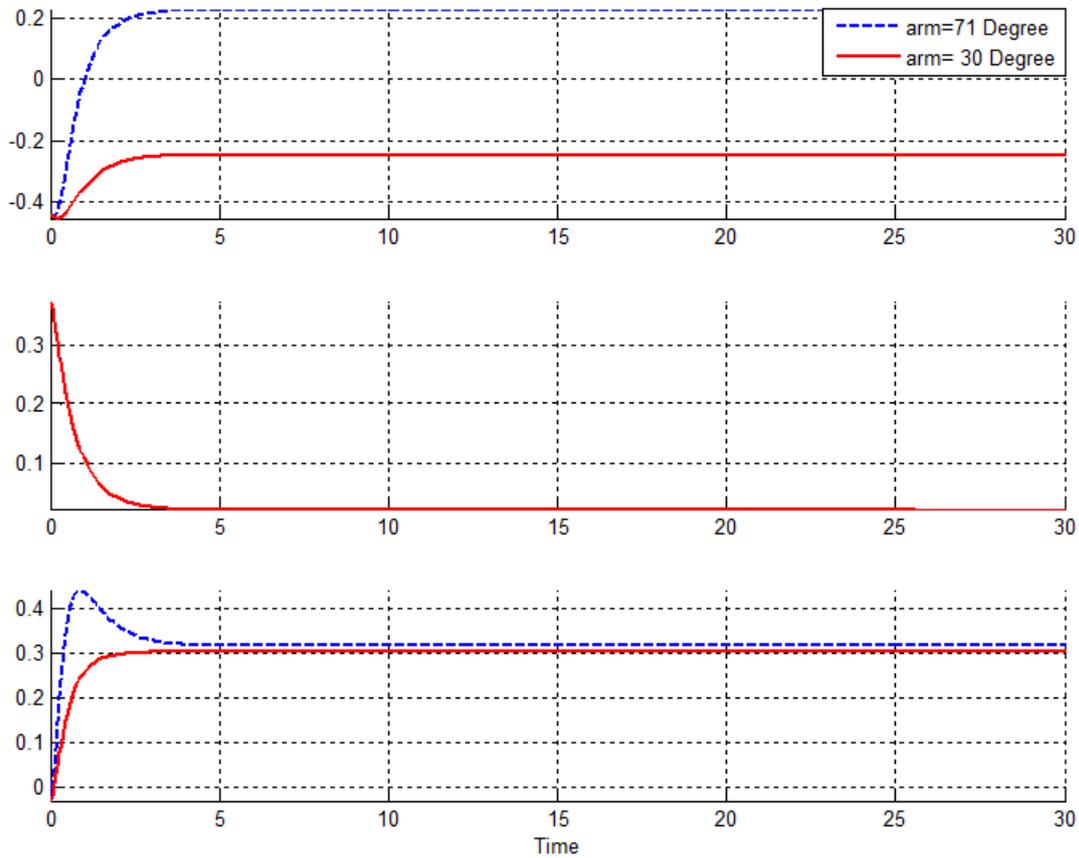


Figure 8. Orientation Tracking Control

5. Conclusion

Refer to the research, effect of fuzzy tuning PID like fuzzy controller is discussion in presence of uncertainty. The main purpose of the use of robots is to increase the precision, quality and safety of surgical procedures. Robotics is not yet used in dentistry even though all the necessary technologies have already been developed and could easily be adapted. Design a reliable controller has played an important role in robo-dentistry. To improve the sensitivity of this robo-dentistry fuzzy logic theory is used. However this type of theory has many advantages but reliability is one of the main challenge in fuzzy logic theory. To solve this challenge PID type controller is add to fuzzy logic theory as a assistant controller. To improve the performance in presence of uncertainty fuzzy logic theory also used to do the second role as on-line tuner. The results criteria is selected for analytical comparison of the controllers are given in tabular form showing the influence of modified rule base on the performance of the process. Obviously robot manipulator is nonlinear and MIMO system so in proposed controller in first step design free model controller based on PID like fuzzy controller and after that disturbance rejection is improved by rule base fuzzy tunable gain. This implementation considerably reduces the output oscillation response in the presence of uncertainties. As a result, this controller will be able to control a wide range of robot manipulator with a high sampling rates because its easy to implement versus high speed markets.

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