A Technical Report on "A High-Precision Fuzzy Impedance Control Algorithm and Application in Robotics Arm"

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Mrinali Vyas -116189866
Pranali Desai -116182935
ENPM 667 - Project 1
University of Maryland - College Park

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ABSTRACT

In the die and mold industry, it is required that the quality of the surface of the molds be maintained. One challenge in this task is the polishing and molding of the curvatures. This is due to the fact that along with the accurate positioning of the tool, the interaction of the tool and workpiece should also be safe and with precise value of force. This requires precise measurement of impedance from the robotic arm. Impedance control is an essential requirement due to the fact that it is the inverse of mechanical compliance, which plays a critical role in a task which involves contact with the environment. It will thus ensure coupled stability while polishing and molding unknown structures. In this document, it is discussed the method of impedance control and using the admittance is proposed a high precision fuzzy controller with a self-adjustment quantitative factor by attempting to recreate the work done by Yue-Yan Chen, Ji Zhao, Jian-Ming Zhan and Si-Guo Zhu (2018) in the paper - "A high-precision fuzzy impedance control algorithm and application in robotic arm". This method can be implemented in real time, it also helps maintain the stability and dynamic characteristics.

INTRODUCTION

The typical use for the die and mold industry is to produce one or a few tools of the same design. The process includes constant changes in the design and because of the need for design modifications, there is also a corresponding need for measuring and reverse engineering. The main criteria are the quality of the die or mold regarding dimensional, geometrical and surface accuracy. If the quality level after machining is poor and if it can not suffice the requirements there will be a varying necessity of manual finishing work. This work gives a satisfying surface accuracy, but it always has a negating impact on the dimensional and geometrical accuracy. One of the main targets of the die and mold industry is to decrease or eliminate the need for manual polishing and thus improve the quality, cut the production costs and lead times. High-speed machining is an important topic for die/mold machining, as the time needed for milling increases productively to realize both the geometry and required surface finish. In order to have accurate contoured surfaces, it is essential that the impedance control be precise, due to the reason that it takes in the environmental forces and achieves the target impedance for better interaction.

The performance of impedance control of the robot decreases under uncertain environmental stiffness and damping parameters. In order to improve performance, a self-adaptive impedance control for the robot is proposed. This is an integration of offline learning and online adjustment to provide the damping and stiffness of the impedance model control for the uncertain environment. For the offline learning, determining the robot impedance control performance criterion, and ascertaining the geometric representation of the varying stiffness parameter, it is derived the initial values of stiffness for the impedance model. Also, a neural network is designed to estimate the environmental effective stiffness, and combined with critical damping condition of the second-order robot-environment interaction system, it is solved the initial value of damping for the impedance model. During the online adjustment, a rule self-tuned fuzzy controller is dedicated to adjusting the stiffness and damping of the impedance model based on robot's real-time contact force and position feedback.

MODEL

The robotic arm uses the linear driver which produces linear motion for the movement of robotic arm. The linear driver consists of a BLDC Motor i.e. a brush-less DC Motor for actuation. A rotatory linear structure is also present in the driver which converts the rotary actuation to linear actuation. To sense the rotary behaviour a rotor integrated with multiple sensors has been deployed in the linear driver.
The function of the robotic arm can be derived by deriving the function of the BLDC Motor while considering the speed ratio in the driver.
Brushless DC motors provide an efficiency of 85%-90% as compared to 75%-80% of the brushed motors. As brushes eventually wear out and may cause sparking limiting its life span. Brushless DC motors have the advantage of being quiet, light weight and longer life, because computers control the electrical current, brushless DC motors can achieve much more precise motion control, because of all these advantages, brushless DC motors are often used in service robots for accurate force control.

Deriving the equation for position of BLDC motor

- Let the terminal voltage be U_a and the armature resistance be R.
  The armature inductance is L and the armature current be i_a. The back emf be e.
- Thus we derive the mechanical equation of DC motor to be

$$U_a = Ri_a + \frac{di_a}{dt}L + e \tag{1}$$

- The electromagnetic torque be $T_e m$ and the torque constant be K_T.
  Therefore the electromagnetic torque function is

$$T_{em} = K_T i_a \tag{2}$$

- The emf is directly proportional to mechanical variable speed θ_n,
  where the emf constant is K_{em}. Thus the emf function is given as

$$e = K_{em}\frac{d\theta_n}{dt} \tag{3}$$

- Deriving the torque balance equation. We know

$$\frac{T_a}{T_b} = \frac{T_{em}}{T_{output}} = n$$

where the speed ratio is defined as

$$n = \frac{\dot{\theta}}{\dot{\theta}_n} \tag{4}$$

- In a BLDC motor due to its inertia J, damping B, touch torque T_L, gravitational torque T_g, and frictional troque T_f, the output torque is

$$T_{output} = J\frac{d^2\theta_n}{dt^2} + B\frac{d\theta_n}{dt} + T_L + T_g + T_f \tag{5}$$

- Using the equations (4) and (5) the torque balance equation is derived to be

$$\frac{T_{em}}{n} = J\frac{d^2\theta_n}{dt^2} + B\frac{d\theta_n}{dt} + T_L + T_g + T_f \tag{6}$$

- Deriving the transfer function

$$\frac{T_{em}}{n} - T_L - T_g - T_f = J\frac{d^2\theta_n}{dt^2} + B\frac{d\theta_n}{dt}$$

$$T_{em} - nT_L - nT_g - nT_f = nJ\frac{d^2\theta_n}{dt^2} + nB\frac{d\theta_n}{dt}$$

- Writing the equation in frequency domain

$$T_{em}(s) - nT_L(s) - nT_g(s) - nT_f(s) = (nJs^2 + nBs)\theta(s) \tag{7}$$

- Writing equation (1) in frequency domain

$$U_a(s) = (R + Ls)i(s) + k_{em}s\theta_n(s)$$

- Using the equation (5)

$$U_a(s) = (R + Ls)i(s) + \frac{k_{em}s\theta(s)}{n} \tag{8}$$

$$U_a(s) - \frac{k_{em}s\theta(s)}{n} = (R + Ls)i(s) \tag{9}$$

$$\frac{U_a(s) - \frac{k_{em} s\theta(s)}{n}}{(R + Ls)} = i(s) \tag{10}$$

$$\frac{nU_a(s) - k_{em} s\theta(s)}{n(R + Ls))} = i(s) \tag{11}$$

- Substituting value of i(s) of equation (10) in equation (2)

$$T_{em}(s) = K_T \frac{nU_a(s) - k_{em} s\theta(s)}{n(R + Ls)} \tag{12}$$

- Substituting value in equation (6) from equation (11)

$$K_T \frac{nU_a(s) - k_{em} s\theta(s)}{n(R + Ls))} - nT_L(s) - nT_g(s) - nT_f(s) = (nJs^2 + nBs)\theta(s) \tag{13}$$

- Simplifying the equation (12) we get

$$\theta(s) = \frac{nK_T U_a(s) - (n^2 T_L(s) - n^2 T_g(s) - n^2 T_f(s))(R + Ls)}{n^2(Js^2 + Bs)(R + Ls)(K_T k_{em} s)} \tag{14}$$

- Let the PWM constant be C_{PWM}
- The PWM transfer function can be written as

$$G_{PWM}(s) = \frac{U_a}{U_c} \approx C_{PWM} \tag{15}$$

- Substituting in equation (13)

$$\theta(s) = \frac{nK_T(s) U_c C_{PWM} - (n^2 T_L(s) - n^2 T_g(s) - n^2 T_f(s))(R + Ls)}{n^2(Js^2 + Bs)(R + Ls)(K_T k_{em} s)} \tag{16}$$

Impedance Control

To control the dynamic interaction between the manipulator and its surroundings we implement impedance control. It is best suited for the surrounding interactions and object manipulation.
Position control is used in systems where the output position has to be kept constant. This is done by the feedback in the loop, which senses the position and tries to minimize the error.
Drawbacks of Position Control

- No assurance of contact stability.
- No control of error forces.
- Since there is no end effector force, there are problems with quality of the work piece generated after polishing.
- There is a trade-off in stability vs steady state error. i.e. while trying to get least value steady state error we drive the system from stable to marginally stable.

Force control is a closed loop control system that can automatically regulate to diminish force errors.
Drawbacks of Force Control

- Gives very diminished movement of the end-effector.
- Gives no efficacy.

The hybrid force-position control technique describes combined force and torque information with positional data to meet simultaneous position and force to minimize errors.
Drawbacks of Hybrid Force-Position Control

- Even though there is continous force position control, since the environment is changing, we will have to tune the controller multiple times which is tedious.

Impedance control is a control strategy to the control of dynamic interaction between a system and its environment.
Advantages of Impedance Control

- Assures coupled stability for arbitary environment.
- Stability and Performance(SSE) are independent of each other unlike position control.

Basic Concepts of Impedance Control

- Impedance is the relation of effort and flow.

$$Z = \frac{effort}{flow}$$

- Admittance is inverse of impedance.

$$Y = Z^{-1} = \frac{flow}{effort}$$

- For a mechanical system, Effort is defined as the force exerted by the system on the environment.

$$Effort = Force = m\ddot{x} + b\dot{x} + k$$

  Note: Here the reference position is 0.

- For a mechanical system, flow can be either position or speed.

$$Flow = position = x$$

$$Flow = speed = \dot{x}$$

- We derive Impedance as

$$\frac{Force}{position} = \frac{m\ddot{x} + b\dot{x} + k}{x}$$

  Writing in frequency domain

$$Z = ms^2 + bs + k$$

$$Y = \frac{1}{ms^2 + bs + k}$$

Deriving Impedance for rotational system

- It is known effort is T_L and the reference position being θ_r

$$T_L = M_t(\ddot{\theta}_r - \ddot{\theta}) + B_t(\dot{\theta}_r - \dot{\theta}) + K_t(\theta_r - \theta) \tag{17}$$

- Let the difference in position and reference position be

$$\Delta\theta_f = \theta_r - \theta \tag{18}$$

- Writing in frequency domain

$$T_L(s) = (M_t s^2 + B_t s + K_t)(\Delta\theta_f) \tag{19}$$

- Thus we derive Impedance as

$$Z = M_t s^2 + B_t s + K_t = \frac{T_L}{\Delta\theta_f}(s) \tag{20}$$

- A rigid environment is modelled with rigidity as K_e and the position of the environment is θ_e.
- Therefore the modelled T_L due to the environment comes with the concept that it can be treated as a spring with rigidity T_L and desired position being θ.
- Thus we derive the modelled T_L as

$$T_L = K_e(\theta - \theta_e) \tag{21}$$

Position Based Impedance control

- Position based Impedance Control consist of two loop mechanism.
- The main loop which is the external loop consists of Impedance Control.

  It takes in the environmental touch force torque T_L and returns $\Delta\theta_f$ using equation (20)
- Here we will be using Admittance since T_L is being taken in and gives out $\Delta\theta_f$ which is the mechanical compliance or the inverse of Impedance.
- The Inner loop consists of position control, which regulates the position as achieved by the end-effector.
- It does so by the use of feedback from the position it reaches to the reference position. A PID controller is used in this case for the position control.
- Figure (1) shows the two loops of impedance and position.

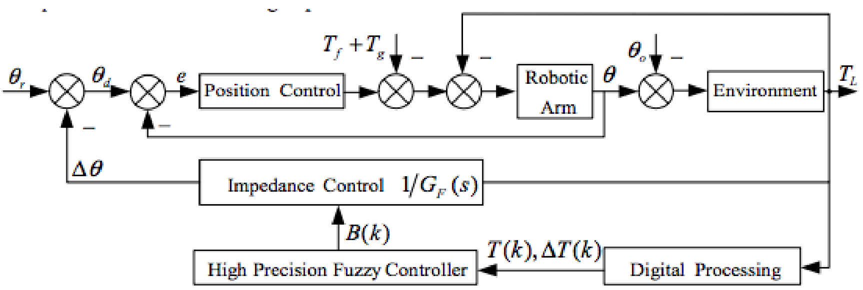

Figure 1: Block Diagram of two loop Impedance Control

- The robotics arm presents the transfer function of the BLDC Motor.
- The third loop is the fuzzy loop which takes the input at T_L and gives out the values of damping - $B(k)$.
- The condition for stability is given in equation(22) from [2].

$$\begin{cases} \xi \geq 0.5(\sqrt{1+2k} - 1 \\ \xi = \frac{B_t}{2\sqrt{(KM_t)}} \\ k = \frac{k_e}{k_t} \gg 1 \end{cases} \tag{22}$$

- We notice that target rigidity has to be extremely small than that of environment for stable transition and target damp should be large enough from equation(22).
- But in real time scenario when we aim to achieve there are slow dynamics response and increased impact and thus use of a Fuzzy controller for self-adjusting damping can play a role for different conditions of target rigidity.
- Thus the self adjusting fuzzy controller for applications in real time interactions is used.

Self Adjusting Fuzzy Controller

Why Do We Use Fuzzy Controller?

Proportional Integral Derivative control is an established method to drive a system toward the target point. It provides almost ideal results in applications where the environment changes whether as a ramp or as a step. In a given application PID variables are made to follow the target value as closely as possible, within the constraints imposed by the process. The major drawback is the time delay i.e. the time to react to input change.

Fuzzy logic is an area of Artificial intelligence based on neither true nor false information. This information is something that is used in the daily life for intuitive decisions. These apply general thumb rules and are similarly applied to those control situations which demand them.

Fuzzy logic controllers have IF -THEN rules which are quite flexible that the solution if applied to the appropriate membership function values will lie in a specific shaded area called true. The advantage is that it can quantify the input signal even in a noisy environment. The interference caused by the noise is dealt with proper interpretation of the information and use of the decision making. There are three parts of a fuzzy controller.

1. Fuzzification
2. Fuzzy Inference Engine (Rule-base)
3. Defuzzification

Fuzzification

In this method crisp quantities into fuzzy quantity are created. This is done by finding some uncertainties in the fuzzy values. This is represented by Membership function.

What is Membership function?

The membership function is a generalized indicator function in classical sets which belong to fuzzy sets. They represent the amount of truth as an extension of valuation. Amount of truth is different from probability as fuzzy truth represents membership in vaguely defined sets and not as an event.

In membership function the value zero means they are not a part of the fuzzy set and the value 1 means its completely a part of the set. The values between 0 and 1 mean that they are partially a part of the fuzzy set. There are various types of membership functions like Triangular, Rectangle, Sigmoidal and Gaussian. In this paper the gaussian membership function is used.

Why Gaussian Membership Function?

Gaussian Membership functions are simpler in design because they are easier to represent and optimize, always continuous, and faster for small rule-bases as compared to trapezoidal membership functions which are simpler in analysis.

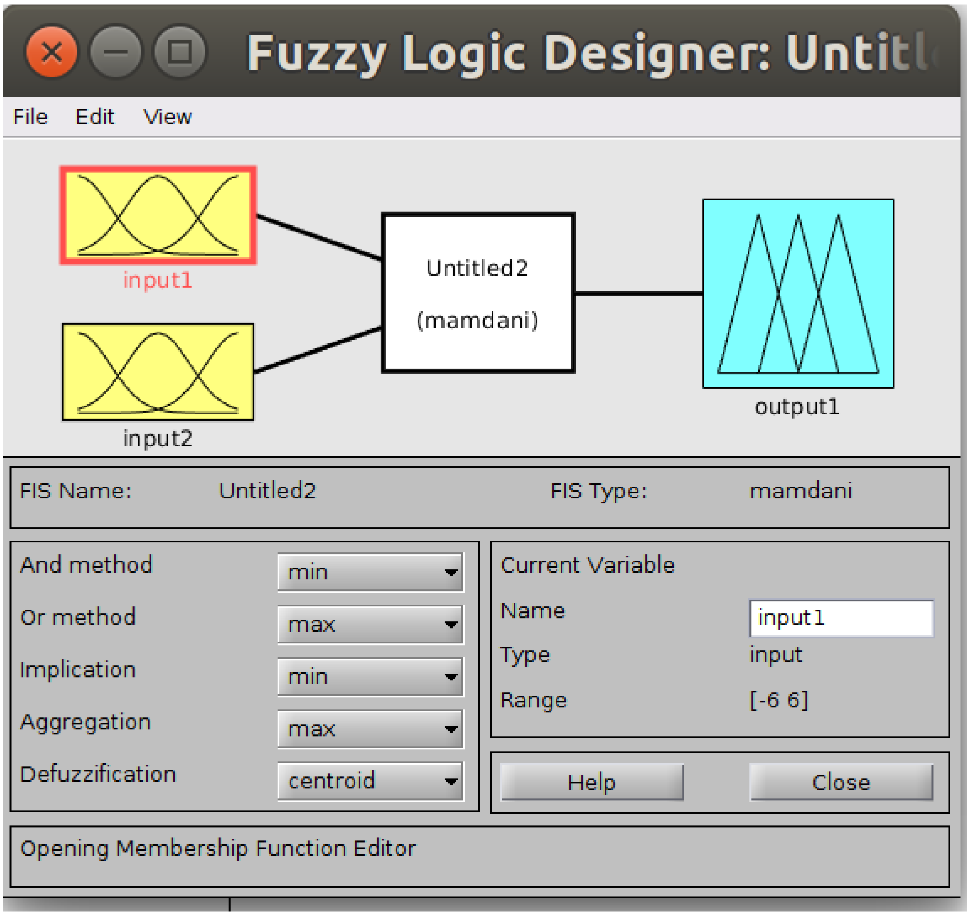

Figure 2: FIS Editor

Figure (2) defines the two Gaussian inputs i.e. Error and Change in Error. In this step we define the type of membership function used and the method for defuzzification.

Fuzzy Inference Engine

This part consists of the formation of the fuzzy rule base.

What Is The Fuzzy Rule Base?

Fuzzy output is based on the rules formed from the fuzzy inputs.The rule-based form uses antecedents and consequents as its linguistic variables. The antecedents express an inference, which should be satisfied. The consequents are the ones which can inferred by us, and is the output when the antecedent inequality is satisfied. The fuzzy rule-based system uses IFâĂŞTHEN rule-based system, given by, IF antecedent, THEN consequent.

There are two methods Mamdani and sugeno. The main difference between Mamdani and Sugeno is that the latter the output membership functions are either linear or constant. Also the difference lies in the consequents of their fuzzy rules, and thus their aggregation and defuzzification procedures differ suitably. The number of the input fuzzy sets and fuzzy rules needed by the Sugeno fuzzy systems depend on the number and locations of the extrema of the function to be approximated. In Sugeno method a large number of fuzzy rules must be employed to approximate periodic or highly oscillatory functions. The mamdani method of formation of rules is used in this paper.

Kt	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NM	NS	ZO	ZO	ZO	ZO
NM	NB	NM	NS	ZO	ZO	ZO	PS
NS	NB	NS	NS	ZO	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	ZO	PS	PS	PB
PM	NS	ZO	ZO	ZO	PS	PM	PB
PB	ZO	ZO	ZO	ZO	PS	PM	PB

Figure 3: Fuzzy Rules

The error signal and the error rate are the selected fuzzy inputs. Fuzzy state variables have to be simple and flexible. We have selected 7 fuzzy states :- Positive Big (PB), Positive Small (PS), Positive Medium (PM), Negative Big (NB), Negative Small (NS), Negative Medium (NM) , Zero (ZO).

In Figure (4) we define the If and Then rules and the weights. These rules are written in the following format.
IF input 1 = x AND input 2 = y then output = z

The image in Figure (5) gives the surface view of the fuzzy rule model. It is an easy way to visualize each rule defining the location of a moving singleton. The singleton output spikes move in a linear fashion in output space depending on what the input is. This makes the system compact and efficient.

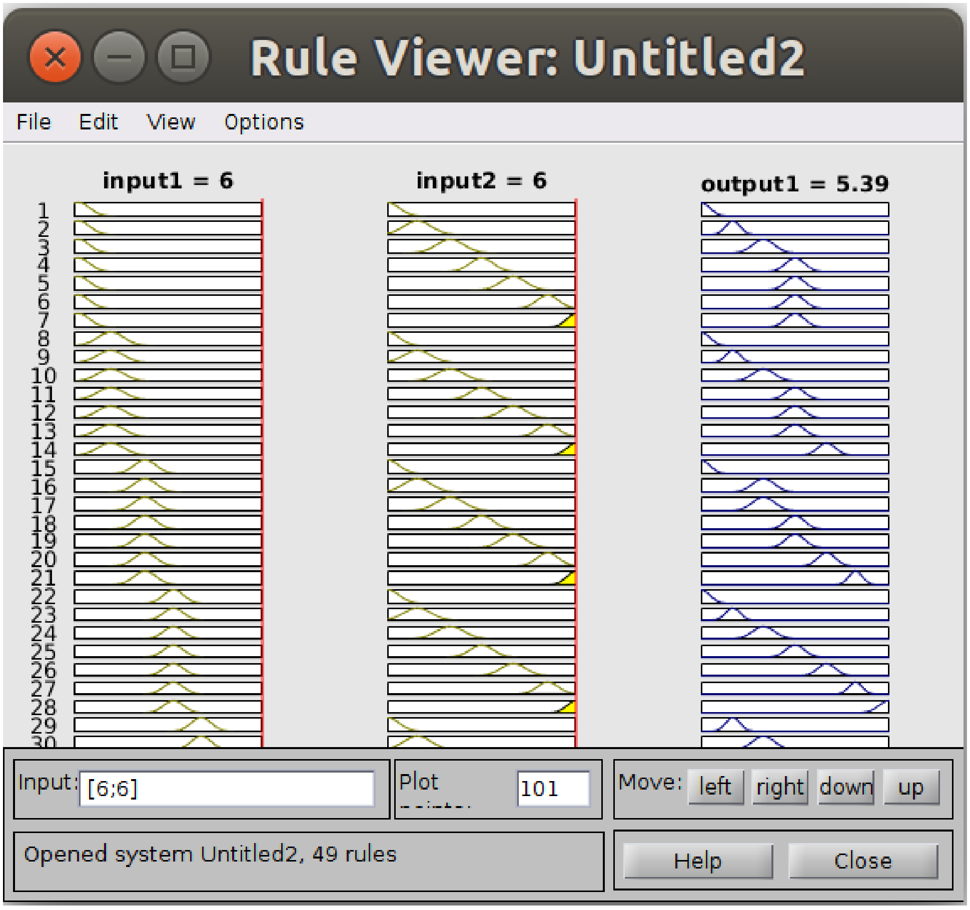

Figure 4: FIS Rule viewer

FUZZY CONTROLLER WITH SELF ADJUSTMENT FACTOR

Linear and non Linear Quantization

The fuzzy inputs error and rate of error are referred to as the universe of discourse of quantized variables. In designing the fuzzy controller we have to determine the entire universe of discourse for input and output. They determine the voltage and current of the D/A or A/D of the controller. They determine the static and dynamic properties of the controller hence should be selected carefully. The quanization factor can be represented as

$$K_T = \frac{n}{T_m} \tag{23}$$

Where T_m is the universe of discourse, and n is universe of discourse of fuzzy set of errors and k is the quantization factor.

There are two methods of quantization Linear and Non linear. In fuzzy controls the widely

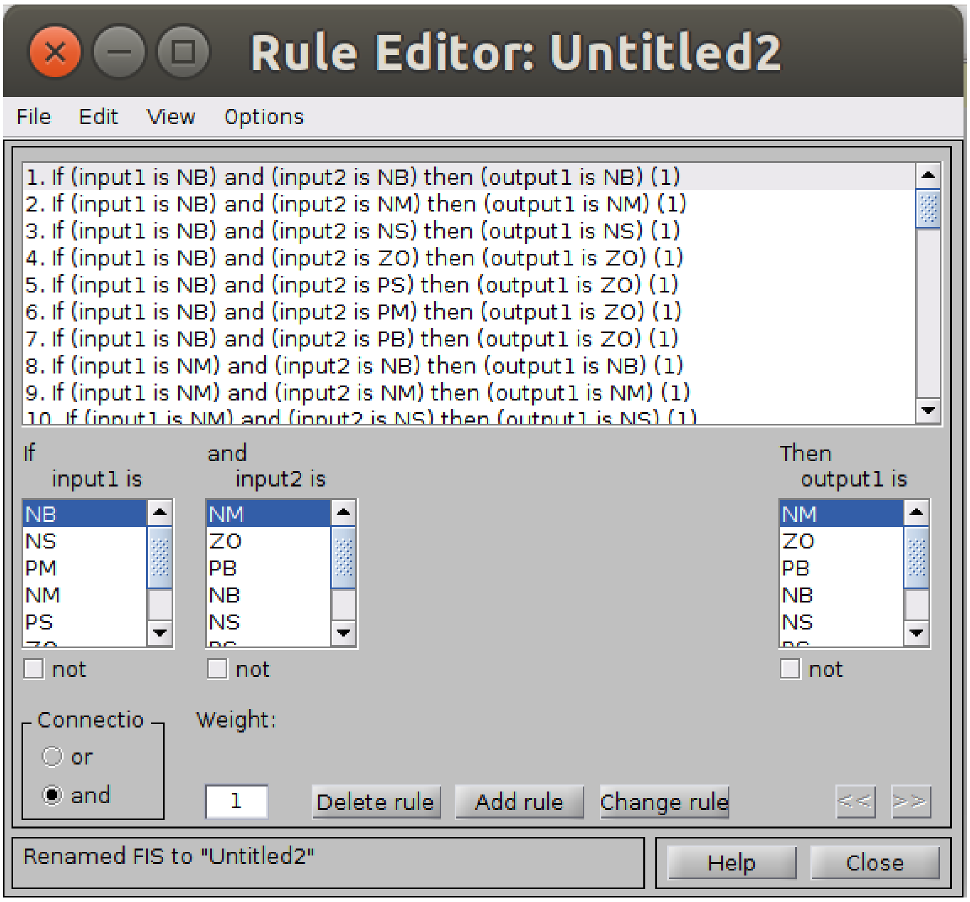

Figure 5: Rule Editor

used method is the linear quantization, but it has a disadvantage that it cannot measure large errors. Non linear quantization however can measure the changes at the boundary and in the universe of discourse. The controller uses similar method where coarse adjustments are done using the large error and fine adjustment is done using the small error in the non linearly quantized fuzzy controller.

From this we infer that fuzzy precision can be obtained by changing the quantization curve. However there is an approximation error that is added which changes the quantization curve if the quantization rank is misused. Let us assume 0.5 to be the additive approximation noise. Which is obtained by the ranking method called centre of maxima.

Hence we get the two input equations for first order control precision as:-

$$T_1^*(k) =< K_{T0(k)} T_k + 0.5 > \tag{24}$$

$$\Delta T_1^*(k) =< K_{\Delta T0(k)} \Delta T_k + 0.5 > \tag{25}$$

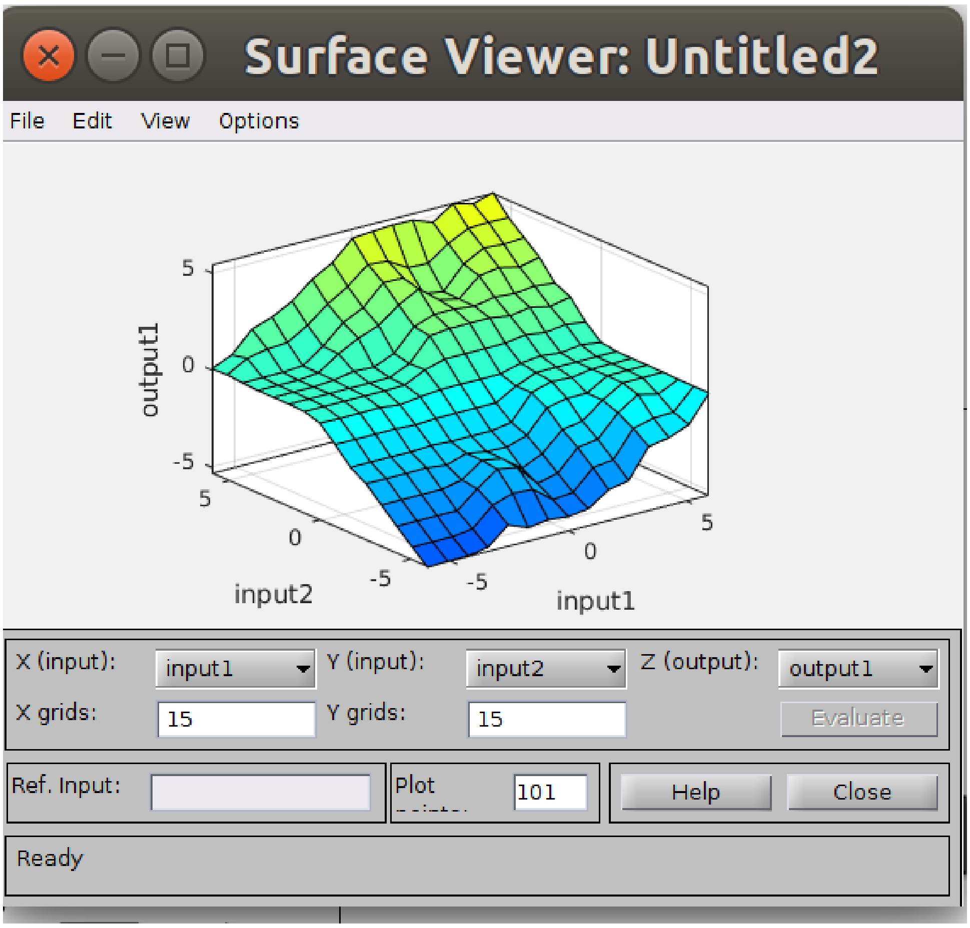

Figure 6: Surface

Where $K_{T0(k)}$, $K_{\Delta T0(k)}$ are the quantization factor of error, change in error which are used for the realignment of the lost data and $K_{BO(k)}$ is the control function quantization error.

$$B_1(k) = K_{B0(k)} B_1^*(k) \tag{26}$$

$B_1^*(k)$ and $B_1(k)$ is calculated from the table fuzzy rule table using the values of $T_1^*(k)$,$\Delta T_1^*(k)$ and $T_1(k)$,$\Delta T_1(k)$.

Considering the improved control precision for a second order fuzzy controller we get-

$$T_2^*(k) = < (K_{T0(k)} T_1(k) - T_1^*(k)) K_{T1(k)} + 0.5 > \tag{27}$$

$$\Delta T_2^*(k) = < (K_{\Delta T0(k)} \Delta T_1(k) - \Delta T_1^*(k)) K_{\Delta T1(k)} + 0.5 > \tag{28}$$

$$\Delta B(k) = K_{B1(k)} B_2^*(k) \tag{29}$$

$$B(k) = B_1(k) + \Delta B(k) = K_{B1(k)} B_1^*(k) + K_{B2(k)} B_2^*(k) \tag{30}$$

Similarly we can derive equations for n^{th} fuzzy controller in this manner.

SIMULATION

- The below figure (7) presents the simulation block of the two loop impedance control in SIMULINK.
- The inner loop consists of position control with the use of a PID controller which regulates the error further.
- The outer loop is the impedance loop which takes input from the T_L and uses admittance and gives out change in speed.
- Note: While we perform simulation the choice of flow is speed that is $\dot{\theta}$
- The input to the system is PWM single.
- The two scopes in the block are used to display the output position - θ and speed - $\dot{\theta}$
- Equation (20) has been used as the transfer function in the block 1/Impedance with values of
  - Mass = 0.01
  - Damping = 0.1
  - Spring = 0.01

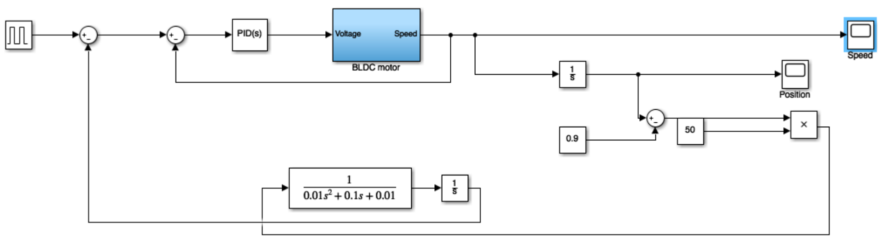

Figure 7: Two Loop Impedance Control

- The values of parameters for the BLDC Motor used are
  - J = 0.01 where J is Inertia.
  - b = 0.1 where B is the damping co-efficient.
  - K = 0.01 where K is the emf constant.

  - R = 1 where R is the armature resistance.
  - L = 0.5 where L is the armature inductance.

- The figure (8) below shows the output of the second scope - $\dot{\theta}$ vs time i.e speed vs time of figure (7).

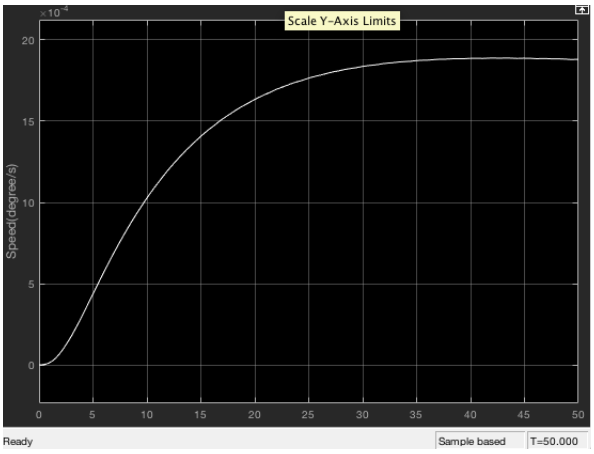

Figure 8: Speed vs Time

- It shows that speed continuously increases till a particular range and then stabilizes since we are controlling that cause our flow in the impedance is speed
- The figure (9) shows the graph of position with respect to time i.e. it θ vs time.

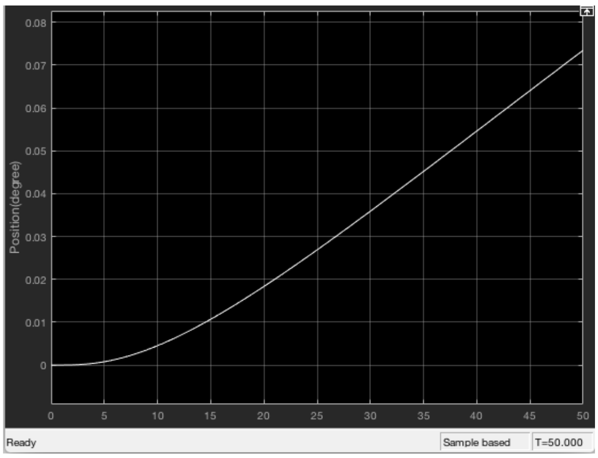

Figure 9: Position vs Time

- It shows that position first increase with variable slope but then increases with constant slop and thus justifying the point of speed being constant after some time.

- The figure (10) shows the simulation block diagram of impedance control along with self adjusting fuzzy controller.
- The values of b, in the equation (20) is given from the output of the fuzzy.
- Parameter adjustment has been used to analyze the data which is outputted from fuzzy.

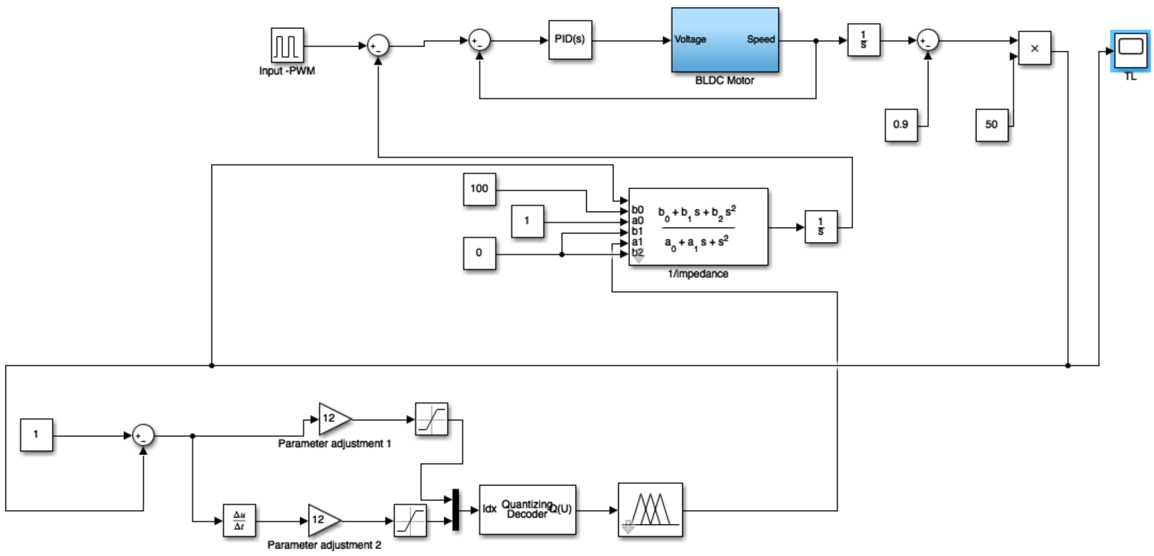

Figure 10: Impedance Control with Fuzzy Controller

- The figure (11) shows the output of the figure (10).

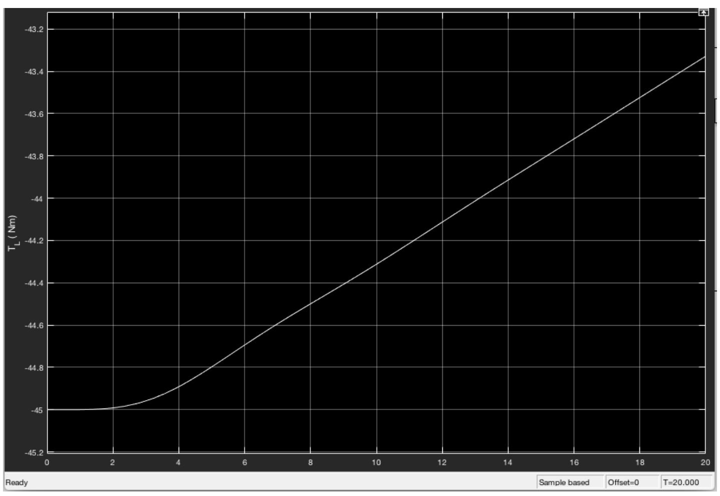

Figure 11: Torque vs time

- This graph depicts the graph of T_L vs time, which is changing due to the fact of self adjusting fuzzy controller.
- The fuzzy controller gives an overshoot and the stabilizes at a constant value of B(k) which when input to the impedance control gives a steady output.
- It is slowly getting stable but the rate is quite slow.

Conclusion and Future Scope

We observe that Impedance Control assures coupled stability and mechanical compliance which position control as a stand-alone is not able to accomplish. Thus having two loops one for impedance control and another for position control assures both positioning and effective interaction with the environment. It also leads in reduced overshoot in the system.

A high-precision fuzzy impedance control method is used to solve the problem to adjust target impedance. This self-adjusting fuzzy controller assures the necessity of varying impedance due to the changing compliance during polishing and molding. Thus the fuzzy controller's output proffers the changed damping, consequently, accounting for the continuous shift in impedance. The self-adjusting fuzzy controller hence gets its name. It also guarantees improving transient stability and dynamic characteristics.

This system with improved learning mechanism like reinforcement learning which is usually used for the interactive environment can be applied too for the precision in tasks other than polishing and molding. This will propose a highly genuine system which can be later on applied to multiple other fields of robotics.

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