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Humanoid Robots Staircase Stepping Stabilization using Novel Previewed Fuzzy Granular Controller

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Abstract: Humanoid robot staircase stepping requires a zero moment point at each step during climbing. A novel fuzzy controller based on preview evaluates the system by taking a double inverted pendulum movement about the cart as a prototype for the leg motion of the humanoid under the impact of time delay using lookup tables. The fuzzy controller with granular computing brings the pendulum to the upright equilibrium position and then a LQR controller smoothens the final position about the unstable equilibrium position. The advantage of this method when compared with other existing methods is the computation of the system performance under the influence of time delays which is induced into the system state space matrix model. The performance measure is considered in terms of settling time, peak overshoot and offset which predominantly indicate that developing a controller based on fuzzy logic with granular computing and with preview will yield better control which is energy efficient.

Keywords: Double inverted pendulum, Humanoid, stabilization, preview based fuzzy controller, delay;

1. INTRODUCTION

The development of humanoid robots can be treated by an exploded image of various sections which include major modules like the gripper, hands, legs and the heart. In the exploded image of the humanoid, some modules can be treated under the fixed base manipulators and other under the variable base manipulators. The exploded model developed of locomotion might be analyzed by a Double Inverted Pendulum (DIP) which has been a typical prototype for under-actuated non-linear system. The analysis of these systems under the influence of time delay is predominantly important in the context that delay can destabilize systems. The effect of delay is to destabilize the system for most of the under-actuated systems however, the studies on the system would help to better understand the influence of delay on complex dynamic systems.

Zhang et al [1] has elaborated on various fuzzy modeling techniques applied to control and Rajasekharan et al [2] have elaborated on fuzzy and genetic algorithms in a generic sense to various control problems. Min et al [3] have indicated about two classes of conditions on systems with time delay, in which one class in delay independent and another class of systems which is delay dependent condition which define an upper bound for the delays for delay-dependent conditions. The exisiting methods for delay dependent systems have been classified as lyapunov-krasovskii functional method, fixed model transformation method and parameterized model transformations where it is used for understanding stability, which was indicated as an expensive method and the drawback being the case that it cannot efficiently deal with the time-varying delay. Lai et al [4] have developed a constrained based granular computing for a simplified rotary cement klin with nonlinear and time variant characteristics where the constraints have been written based on human experiences. Srikanth [6] has discussed the significance and drawbacks of delays in the pendulum systems and how the system consumes more energy in case of delays. Sigeru [4] et al elaborated

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on a PID based controller for a single pendulum. The simulation results showed the effectiveness of the proposed approach. Xu [5] et al focused on experimental studies of real-time online learning control for nonlinear systems using kernel-based ADP methods. Feifei [7] et al verified the validity of control for an inverted pendulum model taking into consideration the aspects of linearization about an operating point. Liu et al [8] discuss the working the trajectory control of a humanoid fine tuned by taking the generalized lagrangian equation with the help of neural networks. The performance was evaluated using radial basis function network. The studies were based on simulation modeling performed using MATLAB which proves that based on lyapunov stability the control is effective. Similar work on hopping was developed by hong [9] where an evolutionary technique was developed for hopping in humanoid models where experimentally it was verified taking the dynamic system has a constrained optimization model. Best et al [10] have elaborated on soft robots for the validity of a new method for joint-angle estimation for robots with compliant links and joints where a torque model for inflatable joints with pneumatic actuation and have validated the model with model predictive control for improving performance. Zhang et al [11] have discussed about the design of a humanoid robot torso which is very much essential for any further analysis in motion of gaits and humanoid robots. Yao et al [12] have made studies linking the spinal cord structure of humans to the model development in humanoids where the zero moment point (ZMP) gets shifted when the humanoid is in motion and the authors have linked the position and orientation using a three dimensional dynamic laser. Tharun etl al [14] have discussed about the granular computing technique applied to a single inverted pendulum model and Nidhjika [15] has discussed about the model of the system using preview control linked to the particle swarm optimization. Although authors [6-12] have elaborated on various humanoid related issues, there is not much literature found on staircase stepping of humanoids.

Granular computing involves defining entities which classify certain characteristics of the system. In a hierarchy control there are different levels of weights that define each of these characteristics which supersede or precede the given set of characteristics. When hierarchy based granular computing is combined with fuzzy logic, fuzzy rules are defined based on the basic parameters like settling time, overshoot and the voltage levels and current levels and maximum velocity and maximum acceleration allowed which become the constraints of the system. The rule explosion happens based on the number of rules that define the system.

In this work a model transformation technique is proposed where in the dynamics are altered in order to accommodate a time varying delay. This paper integrates the time delay into the system and only considers the case of a time invariant delay added into the system matrix which of the double inverted pendulum which is novel. A preview based control of a double inverted pendulum is considered as the prototype from which humanoid is developed. Earlier work on preview based control was applied only to the single inverted pendulum and there is no literature indicating the application of preview based fuzzy controller to humanoid which is being proposed here.

2. MATHEMATICAL MODELING

The plant model of the double inverted pendulum dynamics is adopted from srikanth et al[16] derived from the basic governing Euler-Lagrangian equations defined in [17] and developed by considering the time delay parameter as an additional state is shown below in equation 1 and 2. The model proposed is a model with minimum set of state variables with an integrated time delay variable into the system matrix. When the system matrix includes the time delay parameter into the variable it by itself uses the least set of variables which makes the design efficient.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \\ \dot{x}_7 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & \alpha_{42} & \alpha_{43} & \alpha_{44} & 0 & 0 & 0 \\ 0 & \alpha_{52} & \alpha_{53} & \alpha_{54} & 0 & 0 & 0 \\ 0 & \alpha_{62} & \alpha_{63} & \alpha_{64} & 0 & 0 & 0 \\ \frac{-4}{\Gamma} & 0 & 0 & 0 & 0 & 0 & \frac{2}{\Gamma} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ B_{41} \\ B_{51} \\ B_{61} \\ 0 \end{bmatrix} u \tag{1}$$

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \\ y_7 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} u \tag{2}$$

Where αij represents generic dynamic system constants defined as in [16] and Γ refers to the time delay embedded into the system matrix. The values for system constants are given based on the following assumptions made as per the nomenclature given, where

$p_1 = (m_1+2*m_2)*L_1;$

$p_2 = m_2*L_2$

$p_3 = 2*m_2*L_1*L_2$

$p_4 = (m_1+4*m_2)*L_1*L_2$

$p_5 = m_2*L_1*L_1$

$Den = M*p_4*p_5+2*p_1*p_2*p_3-p_2*p_2*p_4-M*p_3*p_3-p_1*p_1*p_5$

Where the matrix parameters are parameters are

$$\alpha_{42} = \frac{((p_2*p_3-p_1*p_5)*p_1*g);}{Den}$$

$$\alpha_{43} = \frac{((p_1*p_3+p_2*p_4)*p_2*g);}{Den}$$

$$\alpha_{44} = \frac{-((p_4*p_5-p_3*p_3)*f);}{Den}$$

$$\alpha_{52} = \frac{((M*p_5-p_2*p_2)*p_1*g)}{Den}$$

$$\alpha_{53} = \frac{-((M*p_3-p_1*p_2)*p_2*g);}{Den}$$

$$\alpha_{62} = \frac{((M*p_3 - p_1*p_2)*p_1*g)}{Den}$$

$$\alpha_{63} = \frac{((M*p_4 - p_1*p_1)*p_2*g)}{Den}$$

$$\alpha_{64} = \frac{-((-p_1*p_3 + p_2*p_4)*f);}{Den}$$

$$B_{41} = \frac{(p_4*p_5 - p_3*p_3)}{Den}$$

$$B_{51} = \frac{(p_1*p_5 - p_2*p_3)}{Den}$$

$$B_{61} = \frac{(p_1*p_3 + p_2*p_4)}{Den}$$

3. PREVIEW BASED FUZZY CONTROLLER

Preview based logic compared to classical logical theory is the study using abstract manner with the knowledge of future, where logical reasoning means defining new propositions from existing propositions that are predefined[5]. The systematic framework for uncertainty modeling using fuzzy logic and rules is based on three types of models mostly which could be the mamdani model or Takagi Sugeno model and fuzzy hyberbolic model. The mamdani model constructs a bridge between the operator's knowledge and conditions statements that are framed. The preview based fuzzy controller is designed for the humanoid taking into consideration the zero moment point during staircase stepping as shown in figure 1. The redline indicates the staircase representation in figure1. The instance of stepping requires a preview based control for balance about the equilibrium. This is achieved with the help of a preview based fuzzy controller with granular computing.

Table 1.
Fuzzy Analysis with Variations

CaseID	*Error(E)*	*Rate of Error(Edot)*	*K*	*Step Feasibility*
1	20	0.002	1	Possible
2	20	0.002	100	Difficult
3	20	0.002	10	Difficult
4	2	0.002	1	Possible

Nomenclature:

Symbol	*Description*
m1	Mass of lower pendulum
m2	Mass of upper pendulum
M	Total mass of lower pendulum, upper pendulum and cart
L1	Full Length of lower pendulum
L2	Full Length of upper pendulum
g	Gravitational constant
f	Force acting on the cart

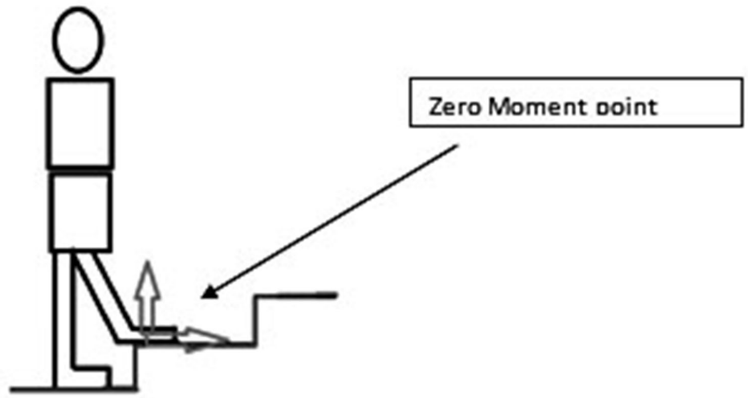

Figure 1: Staircase stepping problem with preview control

The rule base is designed taking into consideration the states defined as X = $(x_1, x_2, x_3, x_4, x_5, x_6)$ which represents the controller input variables. The consequent output contains a single control output U based on [5]. The process states variables X can take n_1 and n_2 linguistic values respectively where the maximum number of rule base is $n_1 * n_2$. The space for the design and study of the preview based fuzzy controller in the universe of possibility is normally bounded by some finite values(min,max) for Xi=1 to 7

A crisp element of X = $(x_1, x_2, x_3, x_4, x_5, x_6)$ of the state space belong to the subspace of the partition associated with rule j, if it holds that

$\forall j \neq k \forall (x_1, x_2, x_3, x_4, x_5, x_6, x_7)$: $\mu_{Rj} (x_1, x_2, x_3, x_4, x_5, x_6, x_7) \geq \mu Rk (x_1, x_2, x_3, x_4, x_5, x_6, x_7)$

Where μ_{Rj} ($x1$ $x2$ $x3$ $x4$ $x5$ $x6$ $x7$) and μRk ($x1$ $x2$ $x3$ $x4$ $x5$ $x6$ $x7$) are fuzzy relations where,

Rule j: if x_1 is $LX_1^{(j)}$ and x_2 is $LX_2^{(j)}$ then U is $LU^{(j)}$

Rule k: if x_1 is $LX_1^{(k)}$ and x_2 is $LX_2^{(k)}$ then U is $LU^{(k)}$

Then and are the membership functions defined for the mamdani type implication are defined as follows:

$\forall x_1, x_2, x_3, x_4, x_5, x_6: \mu_{Rj} (x_1, x_2, x_3, x_4, x_5, x_6, x_7) = \min(\mu_{LX1} (j), \mu_{LX2} (j))$

$\forall x_1, x_2, x_3, x_4, x_5, x_6: \mu_{Rk} (x_1, x_2, x_3, x_4, x_5, x_6, x_7) = \min(\mu_{LX1}(k), \mu_{LX2}(k))$

A Type-1 Fuzzy Logic Controller is considered here with two inputs which include the error and rate of error, and 1 output – F. The objective is to reduce the error and rate of error with the controller which improvizes the system response. The controller has traditional lookup tables which are defined based on fuzzy members for the fuzzy memebership values defined based on possible inputs. The rate of error is additionally differentiated for further granular computing. The analysis is to be done by taking the time derivative of error and error itself and passing on to the fuzzy lookup table where the lookup table has data which is a set of possible fuzzy numbers defined for each of the adjectives of distortion of the pendulum from the unstable equilibrium position which decides the deviation. The output of the fuzzy lookup table-1 is given as the input to the plant model as shown in figure 2 and then a feedback gain matrix defined is used for controlling the plant for a given reference cart position. The model that is developed can be considered for the preview of stepping that happens during a staircase stepping case of the humanoid robot. The preview data is looked up using the fuzzy controller and is passed on to the plant model and is analyzed.

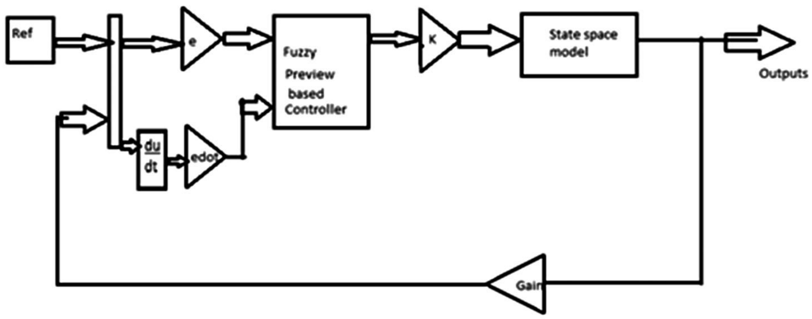

Figure 2: System model with fuzzy control

4. RESULTS

The system model with the preview based fuzzy controller is given in figure 2. The double inverted pendulum model requires stabilization about the unstable equilibrium position. This can be compared to the zero moment point required during the humanoid stepping. So, the evaluation of the performance of the output states is given in figure3 to 5 where the state space data model was analyzed using a linear quadratic regulator which yielded the results as shown is attributed to the humanoid stepping case. Table I indicates the variation of the pendulum positions and the output performance with the fuzzy controller for different error scenarios. The output states are given in figure 3 and figure 4 for cases 1 and 4 where the control is feasible but requires tuning further. Although the results do indicate an oscillation, it is imperative that the control can be achieved with previewing which indicates the step can be taken in the case of the humanoid. The obtained result can be considered as a preview of the controller (lookup value) before the actual control happens and the feasibility for the variations in error gain and error rate gain is seen in figures 3 and 4 which indicate the feasibility of control and case 2 and 3 indicate the case where the preview control is difficult. The feedback gain matrix tuned by LQR is taken as

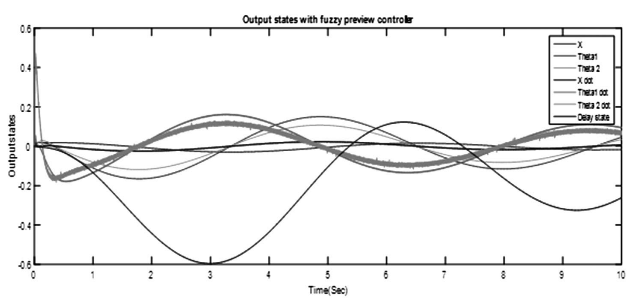

Figure 3: Case ID #1 for lower error bounds

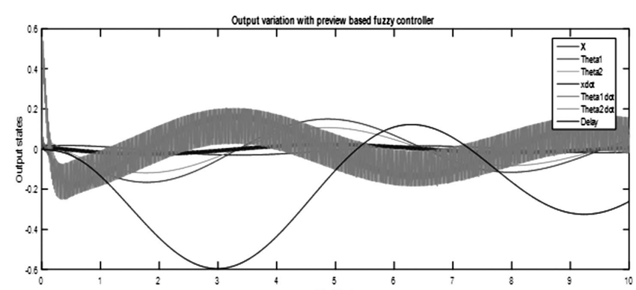

Figure 4: Case ID #4 for higher error bounds

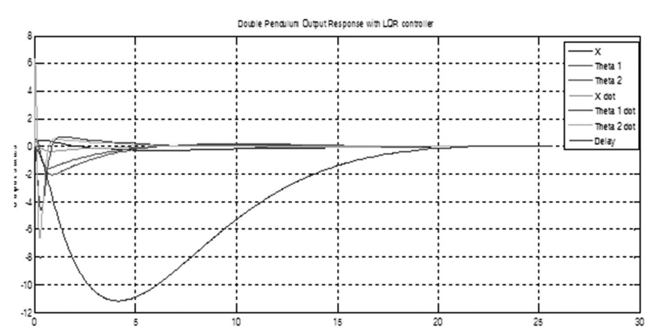

Figure 5: System Response for Standard LQR

Gain = [–51.8604 –35.5576 44.2448 16.7295 –7.4139 2.8860 1.3030]

LQR typically involves larger number of computations and also involves complex equation solving which is not the case with the fuzzy granular computing with preview which considers the case of lookup and then proceed which shows satisfactory results as the number of oscillations here can be attributed to rapid changes in the input signal which indicates that the system is highly unstable and the control effort required is higher however it does indicate that even though the control effort required is higher, taking into fact that perturbed system would oscillate it does show that step feasibility can be better analyzed using granular computing.

5. CONCLUSIONS

The analysis was done based on previewing using a fuzzy lookup table and which indicates the case where the robot stepping can be previewed and analyzed if it can be controlled. The humanoid robot stepping requires proper preview for each step during staircase and the fuzzy controller previewed values will yield values as input to the plant that will achieve stability only for certain values of error and error rate. The analysis paves way to new preview based control for humanoid stepping which would be energy efficient as instead of the control action directly playing a role a preview would enhance the stability chances getter analyzed better.

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