CONTROL SYSTEM TO BALANCE A BIPED ROBOT BY THE SENSING OF COG TRAJECTORIES

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Abstract—This work is devoted to create a control system that assure the static and dynamic balance of a biped robot under any disturbing condition such as changes in the floor inclination angle and external forces applied to the body. An improved fuzzy controller was developed which uses the COG (center of gravity) trajectories coming from a sensorial system [6] to measure forces under the robot’s feet soles in order to keep the balance in a faster, cheaper and simpler way in comparison with present control systems [3,17]. The robot used for the application and testing experiments was Robonova from Hi-Tec brand [20].

Keywords: Biped, Dynamic Walking, Fuzzy, Control System, Center Of Gravity.

1. INTRODUCTION

Humanoid robots have become a very popular machine in the industry, entertainment, research, and many other applications due to its flexible and multitasking characteristics. The dynamic model of a humanoid robot can be represented in a very simplified way like an inverted pendulum with 6 degrees of freedom (displacements and turns in the 3 axes of the Cartesian plane), on which act inertial forces and momentums due to the gravity force and to the natural movement of its joints when walking. These are some of the reasons the robot is a very complicated and unstable system, besides the high cost implicated when working with a robot of this type [1,2]. Nowadays many institutions have invested in the investigation and development of these biped robots that resemblance the human being, trying to develop new control algorithms and sensorial systems that allow the robot to move dynamically and independently on irregular surfaces. The interest to capture the dynamics of human walking and to transfer it to a robot perhaps is due to the tendency of the industrial machines and robots, since day after day they demand new design specifications due to the fact that they requirements have changed and continue changing within a perfectly marked evolutionary process.

2. PROBLEM OVERVIEW

There are three great disadvantages in the present control systems [5,17]: The first and most evident one is that the present feet of biped robots are non-anthropomorphic and without tactile sensors, which limits in a great manner the dynamic walking of the robot, reason why it is considered a bottle neck to obtain the maximum performance possible of the control loops and to achieve dynamic walking like a human. The second disadvantage is that in irregular surfaces when the robot steps on the floor, the magnitude and duration of disturbances are unknown, since it can be so great and prolonged that the control system does not compensate the disturbance due to its time response restrictions and in a result the robot falls. The third one, which is related to the first two, is that present control systems are very complex and expensive due to the great amount of data that they must process and the fast time response that is required, most of it is due to the fact that they are not measuring the correct variable. They forgot that all the joints reacting forces, tilt angles and inertial forces of the robot come from a basic relationship of cause-effect which is the contact between feet soles and ground. In this work it is proposed that through COG (Center Of Gravity) trajectories under the soles feet could bring a more efficient and cheaper way to achieve the balance control of a biped robot.

3. STATIC CONTROL STRUCTURE

The structure proposed for the balance control of the humanoid robot in standing state is shown in figure 1; it is possible to observe that 3 controllers exist: one Master (ATMega128) and two Slaves (ATMega8). The master microcontroller is provided by factory in robot’s main board MR-3024 which has internally programmed several PWM generators to control the angular position $\alpha$ of the digital servomotors
that conform the humanoid robot. The reference angle of ankles $\theta_{r}$ (process manipulation) is generated by the fuzzy controllers and sent by the serial port to the master controller to control the trajectories of the COG under the soles feet of the robot as shown in figure 2.

Obtain the error between the actual COG and the desired one. This error is processed by the fuzzy controllers and generates a correction angle $\theta_{r}$ for the ankles that is sent back, by the same serial port, towards the master controller who is in charge of driving the shafts of the actuators to this angle. It is important to mention that the reference angle $\theta_{r}$ generated by the slave controllers is for the ankles motors, and from them, the others reference angles for the rest of the legs motors are generated by simple linear equations.

4. FUZZY CONTROL THROUGH COG

System stabilization
In figure 3 is shown an alternative to considerably reduce the oscillations of the COG. This solution is based on the reduction of the radius $r$, which is the distance of the floor to the center of mass of the robot since by reducing this distance the centrifuge $a_{c}$ and tangential $a_{t}$ accelerations are reduced as shown in equations (1) and (2) and therefore acceleration $a_{r}$ is also reduced that altogether with mass $m$ generates the $F_{x}$ force that acts in the same direction as the tangential acceleration but in opposite sense and is the reason of the oscillations in x-axis due to the sudden braking of the robot when arrives at the reference angle $\theta_{r}$.
\[ a_c = \alpha \times r \]  
\[ a' = \omega^2 \times r \]  
\[ F_x = a_{\text{gs}} \times m \]  

This technique of reducing the distance between the center of mass and the floor is used in a natural way by human beings, when a person feels that he is losing the balance because he is pushed by external forces or due to a sudden change in the floor inclination his response is to lower his center of mass immediately by bending the knees, and that is indeed the way in which the robot was programmed to lower its center of mass 0.5 cm in the vertical axis whenever it is inclined a degree on x-axis. This number was found experimentally by trial and error. In figure 4 is observed the improvement in the COGx (x component of COG) response when a change in the inclination angle \( \theta_r \) of 15\(^\circ\) is applied.

![Fig. 4 comparison between normal COGx and improved COGx time response when robot is inclined 15°](image)

In figure 5 and 6 are shown the membership functions (fussification) of the error (SPx-COGx) and the manipulation (angle \( \theta_r \)) for the left and right foot respectively. The difussificated variables are used to control the robot balance through the fuzzy controller shown in figure 1.

![Fig. 5 Left foot fussification for error and defussification of control variable](image)

![Fig. 6 Right foot fuzzification for error and defuzzification of control variable](image)

In figures 5 and 6 it’s possible to observe that the fuzzification of the error was realized in order to cover all the possible values that error of the COGx could take, in other words, the right foot has a setpoint around -10mm with...
respect to its sole center and the left foot of 10mm with respect to the same sole center when the robot remains standing totally vertical, due to the mechanical configuration of the ankles servomotors. If the COGx moves towards the right, lets say to -4mm then corresponding error for the COGx would be of -6mm, which is at the negative side, reason why any movement towards the right of the humanoid will generate a negative error that goes from 0 to -15mm. The opposite case is if moves towards the left, where only the error can move up to +5. The separation rank between membership functions is shortened while the COGx reaches the balance point (error=0) in order to have a better resolution in that rank that can provide certain stability to the fuzzy controller. The manipulation was fussicficated in the same way taking into account that the rank of mobility of the right foot goes from 120º, when the motor of the ankle is totally inclined towards the left, to 100º when it is totally vertical. It is important to mention that in the stability range (around 100º) the separations between membership functions were shortened to have a better resolution in the control variable in that range and to give certain stability to the controller around that point.

In Table 1 is the inference mechanism of the fuzzy control system for the robot balance. It is evident that the linguistic variables of the error and manipulation have a unique correspondence, in such a way that every sampling cycle a data of numerical error is being generated and fuzzified with the membership functions of figure 5 and 6 and by relationship of Table 1 a corresponding linguistic manipulation is generated. In order to obtain a real numerical value of the manipulation which is the one that finally is sent to the ankle servomotors. The method of defuzzification used is the centroid as it is in equation (4), where \( \theta_r \) is the reference angle for the ankle motors and \( \theta_i \) are the centroid angles for each membership function.

<table>
<thead>
<tr>
<th>Error</th>
<th>Neg h</th>
<th>Neg m</th>
<th>Neg l</th>
<th>Zero</th>
<th>Pos l</th>
<th>Pos m</th>
<th>Pos h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manip</td>
<td>hPos h</td>
<td>hPos m</td>
<td>hPos l</td>
<td>hZ</td>
<td>mPos l</td>
<td>mPos m</td>
<td>mPos h</td>
</tr>
</tbody>
</table>

\[
\theta_r = \frac{\sum_{i=1}^{M} \theta_i w_i}{\sum_{i=1}^{M} w_i}
\]  

5. CONTROLLER PERFORMANCE

In figure 7 is depicted the inertial force which acts on the humanoid chest only on x-axis, in which, the fuzzy controller is trying to take the system to a steady state (vertical position) when are applied changes in the ground inclination where the robot is standing. This chart was obtained through a two-axis accelerometer ADXL203 from Analog Devices. It was necessary to incorporate the accelerometer measurement because the process variable, COGx under left and right foot, is being used by the fuzzy controller, located at slave microcontrollers when real time balance control is running, so there is no way that the HMI on the PC could get this variable via serial port to plot it.

![Fig. 7 Time response of Fuzzy controller after floor inclinations of ±30º (obtained from accelerometer)](image-url)
Three stages can be observed in figure 6:

**Stage 1-2**: Accelerometer senses an inclination caused by changing the floor inclination angle, COGx also moves from its set point.

**Stage 2-3**: Fuzzy controller is trying to take the robot back to its set point, vertical position, with several oscillations.

**Stage 3-4**: A relative stability moment where robot reaches its set point. After this period oscillations come out again.

In order to obtain a total stability of the humanoid whenever the fuzzy controllers of both feet find their COG reference and not falling in constant oscillations caused by the COG sensitivity due to the robot movement or the noise generated by sensors, it was necessary to program a low pass filter of ±0.4mm to clear the sensible effect around the set point that produces the prolonged oscillations of figure 7. The time response of this implementation is shown in figure 8.

![Fig. 8 Time response of Fuzzy controller with COG low pass filter (Obtained from accelerometer)](image)

The stages are the same as in figure 7, the main difference is clearly seen at stage 2-3 where the fuzzy controller, limited by the low pass filter of COGx, is trying to correct the robot’s vertical position. The result is an offset in the process variable because the COG filter is applied to the full range of the process variable. It was necessary to add an activation band of the filter in order to obtain the vertical stability desired. This band is of ±4mm around the set point. Results of the final response and total steady state before floor inclinations are shown in figure 9.

![Graph showing time response of Fuzzy controller with COG low pass filter and activation band](image)

6. **CONCLUSION**

The design and development of a sensorial system to measure forces under the feet soles of a biped robot came out to be very useful to measure the way its center of gravity moves. Thanks to this new sensorial system was possible to realize the balance control based on the COG trajectories, because the contact forces between robot’s feet and the surface on which it steps offers information of extreme importance about the static and dynamic state of the robot’s body. Proportional fuzzy controller by itself didn’t work as expected. It has to be complemented by a low pass filter of the COG displacement. A band of activation of this filter also was necessary because the low pass filter was applied to the full range of the process variable and sensibility was decreased in undesirable ranges. In general this control system could improve the performance of dynamic and static balance of a biped robot, in a
simpler and cheaper way than present control systems [3, 15 16, 17].

References

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