DESIGN AND ANALYSIS OF A FOOT CONTACT SENSOR FOR POSTURE CONTROL OF A BIPED ROBOT

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ABSTRACT
Development of a planar biped robot is currently underway at Yeditepe University. The robot consists of lower extremities with a torso that are designed at anthropomorphic dimensions. This study describes the design and testing of a foot contact sensor for the biped robot.

Dynamic stability of a biped robot is commonly measured by the zero moment point (ZMP) method. Experimentally, ZMP is measured by multi-component force/torque sensors. Due to their low cost and ease of use, force sensitive resistors (FSR) are used to build a foot contact sensor for the biped robot. Four FSRs are mounted at the corners of the robot’s foot to measure the ground reaction force and its moment. Hence, by utilizing the data from the foot contact sensors, a real-time ZMP computation scheme can be implemented.

The performance of the designed foot contact sensor is presented by numerical simulations of a planar biped robot’s postural stability control. Results indicate that reaction force computation by the FSR based force sensors is a viable method to monitor postural stability of biped robots. Force sensors and their electronics are currently being built to be used for the actual tests.

INTRODUCTION
Natural adaptation in human postural balance control involves a number of feedback mechanisms, primarily, the visual, vestibular and proprioceptive systems [1]. Walking robots have borrowed some of the biological adaptation methods from humans. It is possible to derive joint trajectories for a biped robot based on anthropomorphic joint trajectories of human locomotion [2]. Another commonly referred biomimetic approach is to use central pattern generators (CPGs) for the generation of the joint motion [3]. The concept of Zero-Moment Point (ZMP) was introduced by Vukobratovic [4], and has been widely used as a measure of stability and active control of bipedal walking robots [2], [5], [6]. In this study, a ZMP based postural adaptation approach has been utilized.

For a stable walk, most of the bipedal robots require measurement of the contact force between its feet and the ground [6], [7], [8]. Different technologies exist for the measurement of ground contact force such as strain gauge, piezoelectric, optical and force sensitive resistors (FSR). Mechanical design of the foot has a vital importance on robot’s stability. Li et al. [7] proposed a generic mechanical design of a biped robot foot by using six degree of freedom force/torque sensors and an impact absorption mechanism. FSR sensors differ from the others by their low cost, thickness, weight, and ease of mounting. Lebosse et al. [9] investigated the nonlinearities and dynamic behavior of these sensors. They provide an experimental setup by using a strain gauge sensor as a control group and a DC motor, in which an eccentric wheel is mounted on its shaft. This eccentric wheel actuates a cam and follower system, which converts rotational motion to a linear one. By the help of the results of the experimental setup, they identified the nonlinear properties of the sensor and proposed a compensation model. Che et al. [10] used FSR sensors and absolute encoders to build a wearable exoskeleton system for human gait analysis. Braun [8] proposed a planar biped robot foot design and a control approach. They mounted four FSR sensors to four corners of the foot and used them as an on/off switch type sensor to identify the states of the foot motion. Kong et al. [11] proposed a fuzzy stabilization algorithm using ground reaction forces that are measured by FSR sensors in ISHURO-II humanoid robot. Kim et al. [12] introduced a novel foot mechanism, which uses four FSRs in HanSaRam-VI humanoid robot project. They also proposed a new method to compensate for the landing impact force. Yang et al. [13] also...
used four FSR sensors at each corner of the foot to measure AMI2 biped robot’s stability by ZMP method.

In this paper, design of a foot contact sensor for a planar biped robot is presented and viability of this design is demonstrated for the posture control of a planar biped robot. To provide postural stability of a biped robot, a number of sensory feedback based approaches can be utilized. In this study, a ZMP based stability monitoring method has been implemented. A foot design which incorporates force sensitive resistor (FSR) based contact sensors is considered. The designed foot contact sensor can provide measurements of the vertical ground reaction force and its moment about the axis of rotation of the ankle joint. The force and moment values are then used for the ZMP computation. Thus, a ZMP monitoring postural control method for the bipedal robot can be realized by using the proposed foot contact sensor design.

A joint trajectory tracking control scheme has been implemented on the multi-body dynamic model of the 7-link planar biped model. Postural stability performance of the currently developed planar biped robot equipped with the designed foot contact sensors is presented. The simulation results confirm that control of the height posture of the planar biped can be achieved while monitoring its stability in real-time by using the FSR based foot contact sensors.

FSR BASED FOOT CONTACT SENSOR DESIGN

In this study, the ZMP method has been selected as a measure of the dynamic stability of the biped robot. Experimental determination of ZMP can be done by using a set of force/torque sensors positioned at the foot. Multi-component force/torque sensors have been utilized for the measurement of the state of ground contact in some biped robots [6], [14]. However, due to their high cost and larger dimensions, commercially available multi-component force/torque sensors are not preferred. Due to their low price, thin and flexible form, FSR based sensors are used (Tekscan Inc, FlexiForce A201, 0-25 lb range, see Figure 1). The sensors have a reported typical linearity of ±3%, a repeatability of ±2.5% and a hysteresis of ±4.5% of the full scale output [15]. The FSR sensor is a very thin (~0.2 mm) and flexible printed circuit, which can be integrated into a wide variety of force sensing applications. The sensor with a force range of 0-110 N is used in the current study.

For ease of machining, foot is divided into two main pieces. Upper part is designed to mount directly to the robot’s ankle joint. Another consideration in foot design was to transmit the ground reaction forces to FSR sensor properly. To protect the sensor and reduce the effect of the impact, rubber pads are used to absorb the ground contact force. FSR sensors are mounted at the corners of the bottom surface of the upper piece by an adhesive. Retaining rings are used to keep rubbers in place when the foot is in the air.

FSR sensors are mounted at four corners of each foot for measuring the moment and the ground reaction force under the feet. Once the moment and the total ground reaction force is measured, ZMP computation can be done easily (see Eq. 2). To achieve an even distribution of the applied force and accurate force measurements, rubber pads that fit the sensing area of the sensor are used. Rubber material also compensates for the shear forces and protects the FSR sensors.

Figure 2 EXPLODED VIEW OF THE FOOT ASSEMBLY

Force Sensor Characterization

FSR sensors have a nonlinear force-resistance relationship, which has to be linearized by means of a proper conditioning circuit. With a prototype conditioning circuit, the FSR sensor force vs. circuit output characteristics have been obtained. Design of a conditioning circuit was necessary, since the sensor acts as a variable resistor in an electrical circuit. When the sensor is unloaded, its resistance is very high (>5 MΩ). As a force is applied to the sensor, its resistance varies as inversely proportional to the applied force. To convert this resistance value into a 0-5 V analog output, a dual-source inverting amplifier circuit with an MCP6002 op-amp, as recommended by the sensor manufacturer [16], has been built. Equation (1) defines the output of the conditioning circuit [16]. A negative test voltage, \( V_T = 5V \) results in a positive (0-5 V) output signal, \( V_{out} \), which is proportional to the applied load. Choice of the feedback resistance, \( R_{feedback} \) directly affects the relationship between the output voltage and the force applied. A feedback resistance of 10 kΩ is selected to keep the output voltage within the linear range of the op-amp, as the applied
force varies within the 0-110 N range. A ±5 V is supplied to the circuit by using two 9 V batteries and two voltage regulators (7905 and 7805). A 47pF capacitor is used to suppress the measurement noise. The circuit uses one MCP6002 op-amp, which can handle two FSR sensors simultaneously.

\[ V_{\text{out}} = -\frac{R_{\text{feedback}}}{R_{\text{FSR}}} V_T \]  

(1)

In order to get accurate results, a conditioning procedure has been performed prior to testing, as recommended by the manufacturer of FSR sensors [15]. Conditioning procedure is required for new sensors, and for sensors that have not been used for a long time. To condition a sensor, 110% of the rated load (121 N) is placed on the sensor, and held until the sensor output stabilizes, and then the load is removed. This process is repeated 4-5 times.

Experimental setup consists of the FSR circuit, the FSR sensor and a tensile testing machine, as shown in Figure 3. Load is applied by a computer controlled universal testing machine (Instron 3382). While the applied load is measured by the load sensor of the tension tester, voltage output from the FSR circuit is collected by the analog input port of the robot’s motor controller that is interfaced to a PC. The sensor output for a loading range of 0-100 N is measured and the loading procedure is repeated three times. A linear trend line is fitted to the first loading curve. Resulting calibration curve of the sensor is shown in Figure 4.

**SIMULATION OF BIPED ROBOT HEIGHT POSTURE**

In this section, performance of the foot contact sensor on height stabilization of a planar biped robot is presented. Currently, a 7-link planar robot is being developed at Yeditepe University. To build a simulation model, the robot parts designed in 1:1 scale in CAD software are imported to ADAMS multi-body dynamics and motion analysis software as Parasolid files. When the material properties are assigned, ADAMS automatically handled calculation of center of mass and inertia tensors for each part. These are assembled together by using fix and revolute joints at assigned joint coordinates. Parts like bearings, sensors and gussets that are not significant compared to other parts are removed from the assembly to reduce the complexity of the model. Thus a realistic model of the robot is generated. Total mass of the model is 18.32 kg and its location of center of mass in sagittal plane is 430 mm from the bottom of the feet when the robot is in standing configuration. The generated planar biped robot model has 87 moving parts, 6 revolute joints, 80 fixed joints, and 3 degrees of freedom in its sagittal plane. The assembled robot model is shown in Figure 5.
damping coefficients are selected as 10000 N/m and 1000 Ns/m, respectively.

To simulate the operation of force sensors, forces are measured at each contact location. FSR sensor’s output is added with a white noise signal, such that the force measurement will have a same accuracy as the actual sensor (5% of the full scale output). The generated white noise has a normal distribution with a mean of 0 N and a standard deviation of 2.75 N, which corresponds to a measurement uncertainty of ±5.5 N, with a 95% confidence.

Force measurements from the simulated FSR sensors lead to computation of the ZMP criterion, as defined by Eq. (2). In Eq. (2), $F_i$ is the force measurement of the $i^{th}$ sensor, and $x_i$ is the distance of the $i^{th}$ sensor to the ankle joint in the horizontal direction.

$$d_{ZMP} = \frac{\sum_{i=1}^{4} F_i x_i}{\sum_{i=1}^{4} F_i}$$  \hspace{1cm} (2)

A square wave shaped ankle joint reference trajectory is defined by Eq. (3), where $f$ is the frequency and $t$ is the time. The reference trajectory has an amplitude of ±0.05 rad. with respect to a reference origin of -0.35 rad. The ZMP stability boundaries located at the center of the foot along the horizontal direction are shown in Figure 6.

$$\theta_{ref}(t) = -(0.35 + 0.05 \text{ sgn}[\sin(2\pi ft)])$$  \hspace{1cm} (3)

A PD control loop is implemented at the robot joints (ankle and knee), for tracking the reference trajectory and generating the joint torques (see Figure 7). The knee joint controller keeps the robot height at a desired reference (90 cm). Appropriate proportional and derivative gains are found by manual tuning.

The frequency of the square wave reference signal is chosen as 0.5 Hz. The ZMP distance, ankle trajectory and the robot height are shown in Figure 8. Results indicate that the ZMP criterion mostly stays within the safe region. That is, the robot can safely follow the given posture commands without losing its stability. Successful ankle joint trajectory tracking was observed. Robot height was also fairly close to the desired level. RMS errors for the important variables are shown in Table 1.

<table>
<thead>
<tr>
<th>ZMP distance (m)</th>
<th>Ankle joint error (rad)</th>
<th>Height error (m)</th>
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<tr>
<td>0.0695 (rms)</td>
<td>0.0311 (rms)</td>
<td>0.0049 (rms)</td>
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A stable height posture control can be achieved, while monitoring the ZMP criterion in real-time. The ankle joint tracks the desired reference and keeps the height at the desired level, simultaneously. During this process, ZMP criterion is kept within the stability boundaries. Simulation results indicate that the low-cost FSR sensors can be utilized for the real-time stability monitoring of biped robots.

CONCLUSIONS
This study presents a FSR based foot contact sensor design and its application to posture control of a planar biped robot. The proposed foot contact sensor can be utilized for the real-time computation of the ZMP criterion. The measured ZMP can then be used within a trajectory tracking feedback control scheme. Simulations of a 7-link planar biped robot indicate that, using FSR based foot contact sensors can provide real-time postural stability information even though the force measurements contain a certain amount of error.

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REFERENCES