Development of a humanoid robot foot with distributive force sensors

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***Abstract*—This paper presents a distributive force sensing technology on a robotic foot, whose movement is controlled by pneumatic artificial muscles, during the contact process of a single step. The flexible force sensors on the robot foot and calibrated by characterizing the magnitude and location of the ground ration force on two different platforms. A control strategy for swinging motion of a single-leg robot is also designed. The contact force and the contact point within a gait cycle can be determined by using the developed sensing technology.**

Keywords-force sensor; contact point; robotic leg; pneumatic artificial muscles

I. INTRODUCTION

Human life has evolved with the use of intelligent machines that are capable of operating under different environment dynamically [1]. In order to improve control systems, researchers are working towards a better understanding of machines that are adaptive according to sensor signals that contain information of their working environments [2], [3].

For intelligent humanoid robot, examining the contact process during foot-ground impact is a way to collect information needed. Previous study has shown how strongly the impact force can affect a biped's stability and energy efficiency [4]. Others have also introduced single-point-sensing pressure sensors signal into the control system [5].

Pneumatic artificial muscles (PAMs) [6] are implemented in this work. PAMs are used to provide actuating torque to the robot's hip. We use PAMs because a humanoid robot with PAMs is possible to withstand impact force [7] upon heel strike. From mechanical point of view, the operation of PAMs can be modeled by using a system of springs with variable stiffness [8]. On the other hand, PAMs are also suitable for a robot to perform violent locomotion because of their immediate response provided by sufficient and instant force.

In order to focus on the impact during foot-ground contact, we build a single testing leg to generate the trajectory-replaying [9] single-step movement. Multi-point force sensors are used to detect the contact position on the foot and the ground reaction force (GRF) [10] at every instance during the contact process. To develop the control strategy utilizing the contact signals, we develop a walking model to extract the contact characteristics of the foot on the ground. The contact force and the contact point can be determined with our developed technology. The slope of the contact surface can also be de determined in future studies with the purposed method.

II. MODELLING AND TEST SETTINGS

A. Force Sensor

To measure the position of contact and its GRF on the robot foot, we use force-sensing linear potentiometer (FSLP), 34-00003 from Interlink Electronics. An FSLP consists of two membranes with conductive polymer in the middle, as shown in Fig. 1(a). When an external force is applied, the conductive polymer is compressed and its conductance increases. The conductance increases linearly as the applied force increases.

Inside the sensor, there is a fixed resistor. When the external force is applied, the conductive polymer will act as another resistor, shown as R_p in Fig. 1 (b). The value of R_1 and R_2 are proportional to the distance between A and B. Therefore, we can obtain the ground contact position on the foot by measuring the resistance.

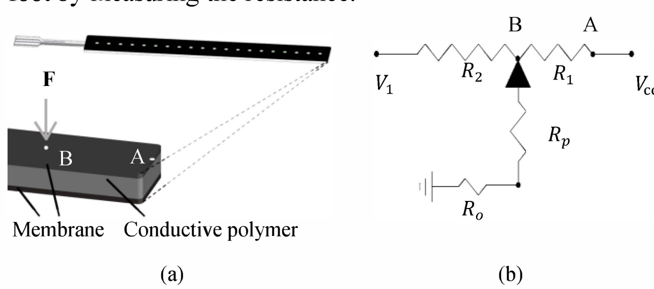


Figure 1. (a) Illustration of the FSLP. (b) Equivalent circuit of the force sensor.

Figure 2. Photograph of installed force sensors.

B. Contact Force Characterization

We established a testing platform that utilized lever principle to amplify and exert force on the foot. The biped foot profile [11] used is a round foot with a radius of 160 mm. Two sensors are attached on the right and left side of the foot in reverse direction, respectively (Fig. 2). The heel is attached to the rear part of the lever, and the contact point will exert force on the platform scale when load is added on the other side of the lever.

The GRF shown on the platform scale as well as the voltage readings V_1 and V_2 of each sensor are recorded. By equation (1), we are able to compute the forces, F_1 and F_2, on each force sensor, thereby, obtain the sensitivity c. And the total force can be calculated as below:

$$GRF = F_1 + F_2 = \frac{c\,V_2}{R_O(V_1 - V_2)} + \frac{c\,V_2'}{R_O(V_1' - V_2')} \quad (1)$$

where F_1 and F_2 are the GRFs, c is the force sensitivity of the sensor, and V_1, V_2 are the measured voltages shown in Fig. 1(b). R_o is chosen to be 3 kΩ in our circuit design.

The contact point on the foot is selected by observing the results from numerical simulation. We choose the first contact point on the foot in each cycle in our simulation as the testing point.

C. Contact Position Calibration

Another testing platform (Fig. 3) is designed to find the relation between contact point and foot angle. The center of the foot curve is pinned on a slider controlled by a servo motor. Friction force makes the foot to roll when the slider is sliding along the horizontal rod, simulating the contact process in a gait cycle.

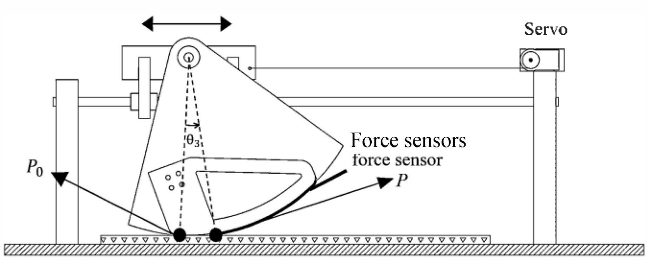


Figure 3. Testing platform for contact position characterization

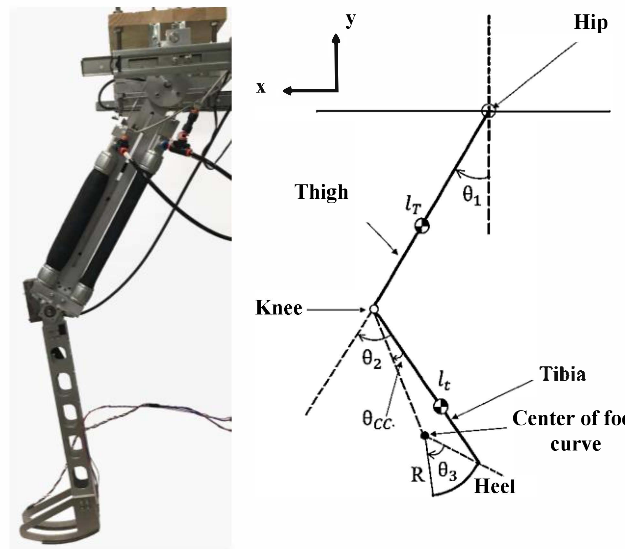
The relation between sensor signal and foot angle can be expressed as

$$\theta_3 = AP + P_0 \quad (2)$$

where foot angle, θ_3, is the angle at the curve center, counted from the heel to the contact point. A is the position sensitivity of the sensor, P is the position signal, and P_0 is the starting point.

D. Single-leg Robot

A single-leg robot（Fig. 4）is built to verify our sensing strategy. Two PAMs are installed at the thigh to generate antagonistic force and provide torque to the hip. The knee joint can swing backwards freely. Conversely, its forward swing is prevented by a stop plate.



(a) (b)

Figure 4. (a) Photograph of the robotic leg (b) Single-leg robot model

TABLE I. SINGLE-LEG ROBOT PARAMETERS

l_T (m)	0.40
l_t (m)	0.39
l_c (m)	0.25
R (m)	0.16
θ_{cc} (deg)	11.77

To calculate the contact point on the foot, let the position of the hip be (0, 0). The position of the knee will be

$$\boldsymbol{x_{knee}} = l_T(sin\theta_1,\ -cos\theta_1) \quad (3)$$

where l_T is the length of the thigh, and θ_1 is the angle between the leg and y-axis (positive for counterclockwise rotation). The position of the heel relative to the knee can be written as

$$\boldsymbol{x_{heel/knee}} = l_t(\sin(\theta_1 + \theta_2),\ -cos(\theta_1 + \theta_2)) \quad (4)$$

where l_t is the length of the tibia, and θ_2 is the angle between thigh and the line that passes through knee and heel. The center of curvature is

$$x_{cc/knee} = l_c(\sin\theta_2', \ -cos\theta_2') \quad (5)$$

$$\theta_2' = \theta_1 + \theta_2 + \theta_{cc} \quad (6)$$

where θ_{cc}, is the angle between tibia and the line passing through knee and the center of curvature.

The contact point relative to the curve center can also be derived as

$$\boldsymbol{x_{contact/cc}} = [R_{\theta_3}]\boldsymbol{x_{heel/cc}} \quad (7)$$

where R is the radius of curvature of the foot, θ_3 is the foot angle, and $[R_{\theta_3}]$ is the rotation transformation matrix.
Using (4) – (8), $\boldsymbol{x_{contact}}$ can be written as

$$\boldsymbol{x_{contact}} = [R_{\theta_3}](\boldsymbol{x_{heel/knee}} - \boldsymbol{x_{cc/knee}}) + \boldsymbol{x_{cc/knee}} + \boldsymbol{x_{knee}} \quad (8)$$

E. Ground slope detection

The slope is tangent to the round-curve-foot at the contact point. Thus, we can determine the slope of the contact surface, ψ, as

$$\psi = tan^{-1}\left(\frac{x_{contact/cc,y}}{x_{contact/cc,x}}\right) \quad (9)$$

III. Control Design

A. Controller, Sensor, and Actuator

Control programs written by LabVIEW are implemented on a develop board, NI myRIO. A proportional directional control valve, MPYE-5-1/8LF-010-B, from FESTO, is used as the controller of the two PAM-actuators, which is controlled by signals from myRIO. Two encoders, RM22Vb from RLS, are installed at the hip and knee to record the hip and knee angles at every moment and provide feedback signals. Force sensors are installed on foot to detect signals from the environment.

B. Control Architecture

To generate a series of step-movement commands, we utilized the data from previous human walking trajectory study [12]. By fitting the angle-versus-time data of hip angle, we obtain a periodic function of the step motion. The hip angle is linear with the air pressure inside the PAM. The pressure inside PAMs are controlled by a proportional electrical valve, whose valve opening area can be controlled by analog signals from 0~10V. Therefore, we can translate angle commands to pressure commands. In order to control the hip angle, a PID controller [13] is used to improve the pressure response, as shown in Fig. 5.

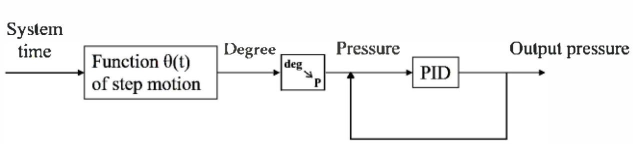


Figure 5. Pressure control of PAMs.

In our test, the single-leg robot starts from the initial position and then replays the stepping trajectory. The foot will contact with the ground surface during its swing-back motion. When contact occurs, sensors attached on the foot will detect the contact force and the contact point; thus, we can record the impact of the contact motion. The leg will then lift up and swing back to its reset position until next step-starring command is given.

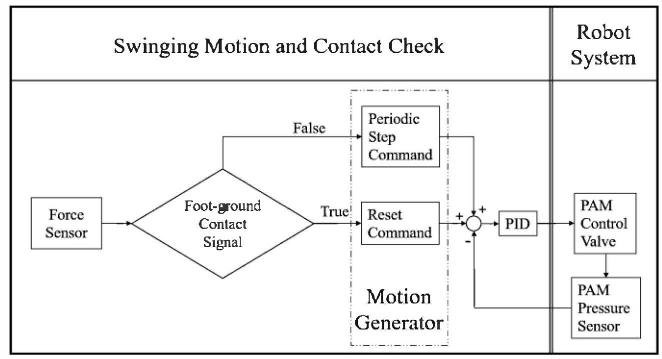


Figure 6. Force sensing step movement control.

IV. Results

A. Force Calibration

The relation of voltage output and GRF is determined using the force calibration testing platform. Given the weight of the robotic leg, the applied force is chosen to range from 0 to 54.0 N, which is adequate for GRF measurement during the contact phase. From the experimental results shown in Fig. 7, the sensor produces reasonably accurate force signals within the whole range of measurement. The sensitivity c was found to be 21949.1 N·Ω.

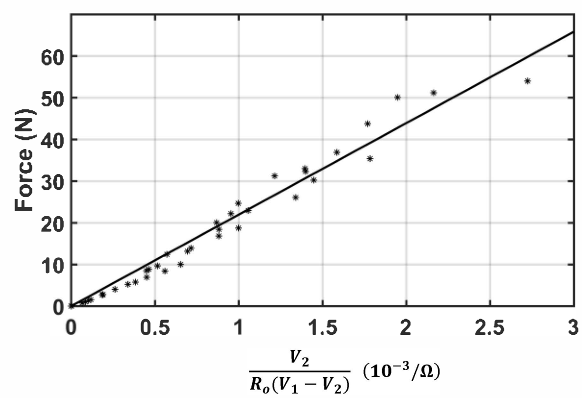


Figure 7. Force calibration result

B. Position Calibration

The contact process between foot and ground is generated by the testing platform shown in Fig. 3. Because the distance between the curve center and ground remains constant during the entire motion, the GRFs should remain constant. Initially, the sensor on the right side does not contact the ground. Once both sensors touch the ground, the sum of GRFs of both sensors remain approximately constant.

From Fig. 8, during the contact period (5000~7000ms) when both sensors contact with the ground, the total GRF remains at range within 10% of the average. Therefore, the force sensor showed decent reliability.

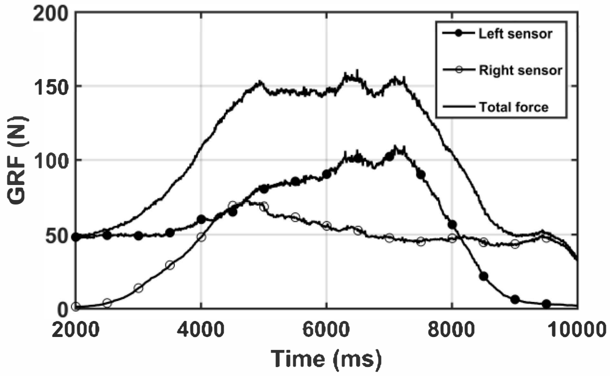


Figure 8. Force sensing result

The angle of the foot is linear to the contact point on the foot, which increases as the slider moves forward. Thus, we can derive parameters that describe the relation between foot angle, θ_3, and the contact point. (Table II).

TABLE II. POSITION CALIBRATION PARAMETERS

	Left	Right
$A\,(deg)$	0.36	-0.36
$P_0(deg)$	0.19	50.81

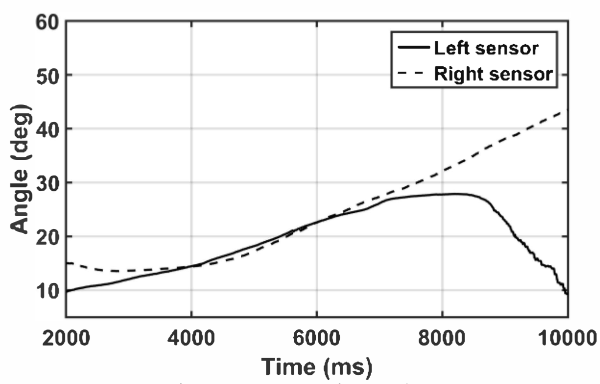


Figure 9. Force sensing result

V. CONCLUSIONS

This paper provides a new method to characterize the ground contact of walking robots by using force sensor installed on foot. It implies the robot foot's ability to recognize its own movement as well as the features of different environments. Therefore, this technology can be implemented into the feedback control of a walking robot to improve stability in varying environment. GRF-detections can also be utilized to determine the smoothness of gait cycles of the robots and optimize the walking trajectory of the robot. We believe that the installation of force sensor on foot and the utilization of detected signals can improve the feedback system and bring the walking stability control to the next stage. In the future, the contact signals can be used to detect the environment and also serve as a reference to determine the efficiency of robot walk.

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