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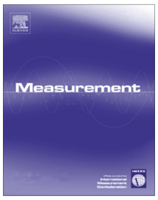

Perception of effective contact area distribution for humanoid robot foot

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ABSTRACT

Maintaining dynamical stability for humanoid robots to walk or run in even environments has so far been achieved. However, it will become a challenge work to keep balance under rough terrains, because the effective contact area (ECA) between the feet and the uneven environments is less than that on even ground. Thus some control schemes are additionally needed for robot to keep dynamical balance, which increases the complexity of control. In view of that, flexible force sensor array (FFSA) system is adopted under robot feet to detect the ECA in the case of stepping on rough terrains. Structure optimum, data acquisition, processing methods, etc., of the FFSA system are all elaborately provided in this paper. And the feasibility and validity of the FFSA system mounted in the robot foot system are experimentally tested on the humanoid robot platform BHR-2.

1. Introduction

The realization for humanoid robots to walk or run dynamically and stably on various kinds of rough terrains has long been considered as the research emphases. Unlike multi-legged robots that can benefit from a stable base of three or more contact regions, the humanoid robot is forced to maintain stability with only one or two contact regions [1–3]. The foot system constitutes the element which ensures the interaction between the humanoid robot and the environment. Apart from supporting the whole weight of robot and sensing external forces, perception of effective contact area (ECA) of foot on rough terrains is indispensably important information supports for various control schemes. A dynamic equilibrium criterion – Zero Moment Point (ZMP) has so far been extensively employed in humanoid robot control [4–7]. Most stable motion control algorithm bases on the assumption that the actual ZMP is always in the support polygon area formed by the contour of the robot feet during walking [8–9]. However, it is not suitable for balance control especially in the case of stepping on rough terrains. And it is difficult to keep ZMP in the small support polygon even though the robot is controlled by a moment compensatory method.

The humanoid robots ASIMO [10], HRP-2 [11], HUBO [12], etc. had also rubber layer set under soles plate for impact absorption mechanisms. Though these foot mechanisms can ensure robot stability on some occasions, it is difficult to be totally applied to the real-time acquisition of the ECA distribution especially for keeping balance on rough terrains. WS-1 (WASEDA Shoes-No. 1) foot system [13] with cam-type locking mechanisms can contact on the ground as four points while could not maintain the large-scare four-point contact on the uneven ground while its foot meets obstacles. Yang et al. [14] proposed a new flexible foot system with 12 degrees of freedom that can automatically adapt to the three dimensional terrain. However, it has a low real-time performance due to revolute joints.

This paper describes our research efforts aimed at the perception of the ECA distribution under the robot feet [15]. The FFSA system was designed by the conception

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derived from the biomechanical information of human foot while in walking motion. Firstly, the Structure configuration, data acquisition and ECA processing methods of the FFSA system elaborately described in Sections 2–4, respectively. Secondly, in Section 5, the feasibility and validity of FFSA system are experimentally tested in the integrated perceptual foot (IPF) system of humanoid robot platform BHR-2. Finally, the conclusions and future works are provided in Section 6.

2. The structure configuration of FFSA system

Wherever a human foot is generally divided into forefoot, mid-foot, and hind-foot, which represent the toes and frontal part, foot arch, and the heel, respectively. The foot–sole contact areas are affected by the structure of the foot as well as the placement of portions of the foot during walking or running. Fig. 1 shows the contact area mainly distribute on the rear foot and forefoot sole from heel-strike to toe-off during single support phase in human walking motion [16]. Most of the present day humanoid robot feet are non-anthropomorphic with solid plate as feet. So during static or flat foot walking, the robot feet would not necessarily show unique contact area distributions, but in the case of dynamic walking or stepping on rough terrains.

To real-timely obtain the ECA distribution in robot walking motion, the simplest measurement type of resistive force sensor arrays have been adopted in the FFSA system with the consideration for light foot weight, small mounting space and being build in-sole sensory system. The FFSA are piezoresistive elements made by screen-printing of piezoresistive ink on thin polymer film substrate. Fig. 2 shows two such layers on which the ink is printed in rows and columns are joined together by an adhesive. The intersection of the rows of one layer with the columns of another layer becomes a pressure sensing element. Its characteristic is that its conductance value increases together with the intensity of a force applied on an active area. Every sensing element behaves a resistor and the resistance is affected by the contact on these surfaces. As shown in Fig. 3, the resistance is inversely proportional to the applied force. The hysteretic characteristics indicate low measurement accuracy.

If R is the resistance and conductance is given by

$$g = 1/R \tag{1}$$

then the gauge factor g_f is given by

$$g_f = g/F \tag{2}$$

where F is the applied force.

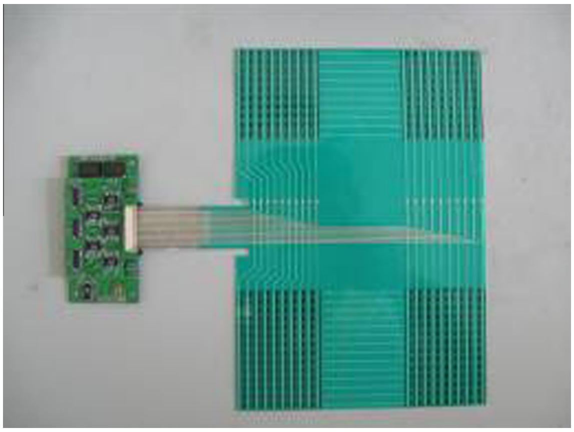

Fig. 2. The FFSA with spatial resolution 5 mm × 5 mm.

The FFSA have a geometry suited for contact area distribution measurement of foot sole contact on ground. Each sensor array element can be addressed by its corresponding row and column. The connections are populated arbitrarily according to requirements of foot contour, and hence the periphery of the sensor film can be trimmed into two parts for the fist-generation prototype shown in Fig. 4, the frontal part is 150 mm × 60 mm in dimension corresponding to the fore sole of human foot. The heel part is 150 mm × 40 mm to the rear sole, since it is flexible and very thin (0.22 mm) and well suited for in-sole measurements; the spatial resolution is 5 mm × 8 mm, and there are about 448 sensing elements.

The FFSA are attached between the lower surface of flat plate sole which is designed curvedly at two ends and the lower layer also called shock absorption layer which contact directly with ground. FFSA behave some switches, however conductance value changes rapidly after pressure reaches a threshold set in advance. It is not fit for accurate measurement because measurement value has an error rating of about F5–F25%. Nonetheless, we do not measure a force precisely, but we use it for measuring force distribution area by calculating the threshold of the loads applied to each FFSA. The FFSA system has only a bandwidth of about 100 Hz, which is lower than the response time for robot control system. So here we merely concern about the contact area rather than applied forces and get bandwidths up to about 200 Hz (*nearly* 5 ms).

Furthermore, the parts of FFSA adhere to the front arc surface and rear arc surface (shown in Fig. 5) can also serve as the switch at heel-strike and toe-off stance respectively for bionic gait planning generation.

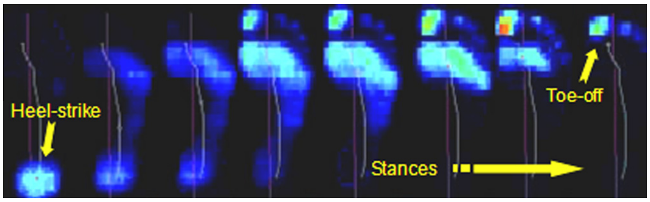

Fig. 1. The evolution of contact area distribution from heel-strike to toe-off stances in human walking.