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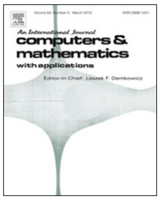

Gait detection based stable locomotion control system for biped robots

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ABSTRACT

It is a challenge to maintain a steady and stable locomotion when a biped robot navigates an uneven surface or a step. Firstly it needs to detect the gait of the robot and related environmental objectives, and then to perform appropriate controls of stable locomotion. In this paper, a new type of sensing module with flexible force is designed to be mounted under the robotic sole to measure the foot pressure map which is essential for the analysis of zero moment point (ZMP) to assist the biped robot to detect the gait conditions. In addition, a neuro-fuzzy control scheme is also proposed to control the ZMP trajectories and relative balancing by integrating the data of a 3-axis gyroscope to adaptive posture. The experimental results show that the designed control system has improved the biped robot adaptive ability to overcome landform changes and the stability of locomotion while standing or walking on uneven terrain.

1. Introduction

As we know, well-designed biped robots could perform superior locomotion to wheel-like robots on uneven terrain. Their legs can make themselves have discrete contacts and pass undesirable footholds to avoid small obstacles. However, the stability and balance problems of biped robots are also of vital importance compared to those of wheeled, three-legged, or multi-legged robots. Most research covering biped robots focused on the investigation of gait detection and control systems for stable locomotion. For dynamic robot locomotion, the driving and balancing controls will be fundamental issues, since biped robots adopt similar multi-DoF (degree of freedom) movements to human beings.

The design of the biped robot locomotion usually takes consideration of the number of DoF and the types of joints. Basically, a joint driven by an actuator such as a motor is regarded as active. On the other hand, the motivation of a joint is passive if it only depends on gravity or the inertia of the links themselves. For most of the biped robots, they have 6 DoF and 6 actuators on each leg: 3 on each hip, 1 on each knee and 2 on each ankle. If the body needs to be involved in the gait control issue, two or three more DoFs are added on the waist [1,2]. It results in a complex frame and one needs to design adaptive control systems for dynamically stable locomotion.

The dynamics of a biped robot consists of two phases in its gait process: the single-support and the double-support phases. Unlike the condition in the double-support phases in which the robot is supported by both legs, the biped robot swings one leg and is only supported by one other in the single-support phase. In most research, the duration of the double-support phase is considered as instant in comparison with the single-support ones. It implies the gait and the motivation of the body are necessarily fast enough for balancing and steady walking. However, if not, the longer duration results in a slower gait. Li et al. integrated PGRL, LPI and fuzzy logic to dominate the walking control of a biped robot [3]. In this approach [4], there are two vision-based fuzzy controllers designed for the support and the swing legs respectively.

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In general, biped walking mode consists of two types: statical and dynamical. While the biped robot acts statically stable when walking, it needs to ensure the robot is without loss of stability even if the legs are frozen and/or the motion is stopped at any time. At the same time, dynamic stability implies the stability can only be achieved through active control of the leg motion. The control issue on dynamical stable walking is still widely discussed in recent years. ZMP and periodic-stability-based control methods are used in most applications for biped dynamic walking control.

The study by Kim et al. [5] indicates the ZMP is varying from the heel to the toe areas during the single-support phase. Huang et al. proposed their observations on ZMP trajectories [6] and concluded that not all ZMP trajectories are able to be estimated. However, by using the static stability compensation range, it is possible to have some safety margin during stability compensation by manipulator motion and make the task plan and vehicle motion plan simple. Sun et al. developed the biped robot with the structure of more DoFs on its waist and trunk which provide compensation for instant torque [7].

The ZMP trajectory, proposed by Vukobratović and Juričić since 1969 [8], has proven effective in estimating robotic stable states [9]. The ZMP is the point where the dynamic reaction force produces no moment; that is, no additional moments are acting at the ZMP. The ZMP can also be regarded as the center-of-gravity position for the walking biped robots. And, since to estimate the ZMP trajectories immediately and continuously costs huge computational effort, most ZMP based approaches proposed adaptive algorithms to overcome such problems. In the study in [10], Harada et al. proposed a simultaneously planning method by using the trajectories of the COG (center of gravity) and the ZMP which demonstrated the fast and smooth change of gait can be realized. Ratliff et al. also developed an optimal gradient algorithm based method to generate a dynamical walking pattern [11]. Juang developed a learning scheme in [12] which combines an adaptive neural network controller with a linearized inverse biped model. It described the concept of measuring ZMP trajectories underlying the dynamics and controls involved in legged locomotion. In the similar study in [13], a designed model of image preprocessing based on nonlinear diffusion and information extraction was proposed. Park et al. in [14] developed a new balance control scheme for a biped robot only based on the visual information of a specific reference object in the workspace, where the ZMPs can be calculated from the visual recognition of the robot's pose.

To estimate the ZMP, the biped robot usually needs to get the force/pressure map between the soles and the ground by using force sensing modules. To detect force, most research adopts force sensing resistors (FSRs) or piezoelectric devices as the sensing components. The main advantage of FSR is that it has simple operation and direct responding properties. Therefore, one can easily disperse them on the robot to estimate the force/pressure map. However, there are some shortcomings of FSR such that it is necessary to calibrate the nonlinear response and it can only be actuated with external power, thus reducing its adaptability. Relatively, the piezoelectric force sensing devices provide the wearable property because of its non-reactive response of mechanical-electro transformation.

PVDF (polyvinylidene fluoride) is a highly non-reactive macromolecular material, which has piezoelectric properties and is mechanically stretched to orient the molecular chains and then poled under tension. The material also has the properties of flexibility, larger range of linearity to piezoelectric response, reliable and repeatable force detection and lower hysteresis effect. From the applications [15–18], it has been proven that the PVDF is a superior piezoelectric material for force/pressure detection of robotic dynamical gaits.

Since the force/pressure map measurement dominates the accuracy of the ZMP determination, its reliability heavily affects the balancing and stable gait controls. In this research, a flexible tactile sensing module in an array of 3 by 5 is firstly developed by the manufacturing process of MEMS (micro electro mechanical systems). The modules are mounted under the soles of the small-size biped robot to determine force/pressure maps, ZMP trajectories and relative gaits during biped robot locomotion. These signals and computations will be adopted as the inputs of the proposed neuro-fuzzy balancing controller for stable gait control.

The proposed neuro-fuzzy scheme integrates neural network and fuzzy system with the capability of adjusting the membership functions and providing the fuzzy inference rules in balancing controls. The neuro-fuzzy system in this paper has the framework of a five-layer network configuration: the input layer, the fuzzification layer, the fuzzy rule layer, the defuzzification layer and the output layer. Since neuro-fuzzy systems can be training by following the spirit of the minimum disturbance principle, their adaptive efficiency and simple structures thus benefit themselves for dealing with real-time control problems. The experimental results shown in similar studies in [3–5] have demonstrated the feasibility of the neuro-fuzzy scheme.

2. Design of tactile sensing array

The tactile sensing module proposed in this research is made according to the manufacturing processes of MEMS. The configuration of the tactile sensing module is illustrated in Fig. 1. In this plan, there are 15 silicone rubbers and 15 microelectrodes in an array of 3 by 5 fixed upon the flexible printed circuit (FPC) thin films which consist of a PVDF film between two FPC films. All components are packaged by polydimethylsiloxane (PDMS) as a sensing device.

In Fig. 2, we introduce the manufacturing process. By these processes of etching electrodes, striping the Ag layer on a PVDF thin film surface, bonding the PVDF into FPC films and silicone rubber structures upon electrodes, and packaging all components with PDMS, the 3 by 5 array sensing module is made with the dimensions of 53 mm × 48 mm × 4 mm. It is worth noting that to disperse micro-structural silicone rubbers upon the electrodes on the FPC film would effectively benefit the sensitivity of tactile sensing. The proposed structural electrodes aim to replace traditional piezoelectric film