Development of Control System in a Biped Robot with Heterogeneous Legs

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Abstract—This paper discusses how a biped robot with heterogeneous legs imitates a person’s walking from gait design, gait planning and gait control. A biped robot with heterogeneous legs (BRHL) robot consists of an artificial leg and an intelligent bionic leg. The purpose of this robot’s design is to make the intelligent bionic leg follow the artificial leg’s movement, which provides an excellent platform for the research of intelligent prosthetic leg. After the introduction of gait design and gait planning, a semi-active kneel control method is proposed for magneto-rheological (MR) damper in the intelligent bionic leg. And an overall control system scheme is presented. Simulative and practical system experiments prove the validity of the presented plan and proposed algorithm.

Keywords—biped robot, bionic leg, control

I. INTRODUCTION

Intelligent bionic leg is an advanced intelligent prosthesis for an above-knee amputee to stand and walk, which is controlled by a micro processing unit (MPU) to follow human leg’s motion. It is a new application of automatic control theory in amputee rehabilitation (D. Datta, J. Howitt 1998). Owing to MPU control, an amputee with intelligent bionic leg can change gait velocity optionally to finish running, walking on slope or stairs, and even riding bicycle. Its gait is more like healthy person’s than that of a common mechanical prosthesis. At present, intelligent bionic leg is studied in some corporations such as BLATCHFORD, OTTO BOCK, ENDOLITE, and some institutes of robotics. However, at this situation, men’s two legs are heterogeneous. In order to provide a test-bed for developing intelligent prosthetic leg, a novel biped robot type named biped robot with heterogeneous legs (BRHL) is proposed [1], which includes an artificial leg and an intelligent bionic leg, as shown in Fig. 1.

Fig.1 (a) shows the structure of BRHL robot, which consists of two legs, an artificial leg and an intelligent bionic leg. Artificial leg is use to generate target gaits. The gaits of artificial leg is designed in advance and store in the controller. Fig.1 (b) depicts the components of the intelligent bionic leg, which is equipped with necessary sensors, such as 6-D force-torque sensor and encoders, etc. With the real-time sensor information, the intelligent bionic leg identifies the target gait of the artificial leg, generates desired gait to follow the artificial leg’s movement. Therefore the information between two legs is not symmetrical. How to identify the artificial leg’s gaits and control the intelligent bionic leg to follow the artificial leg’s movement has a big significance in the research of prosthetic leg. The BRHL robot not only provides a test-bed for the research of intelligent bionic leg, but also supplies a platform for multi-agent system’s coordination and distribution control theory research under complex conditions. The rest of paper is organized as following: Section II briefly introduces gait design, gait identification and gait generation; Section III proposes a semi-active kneel joint control method for MR damper, and present an overall control system for the BRHL robot; Section IV depicts simulation and practical system experiments to evaluate the proposed method; Conclusion is drawn in Section V.

II. GAIT DESIGN, GAIT IDENTIFICATION AND GAIT GENERATION

The BRHL robot needs to design gait first and then identify the current gait and generate corresponding gait to imitate the
healthy person’s walking.

A. Gait Design

Gaits can be divided into level direction walking pattern, changing direction walking pattern, slope walking pattern, up-down stairs pattern, down squats pattern, etc. Generally speaking, each gait includes three phases: initiation walking phase, steady walking phase and decelerating walking phase, as shown in Fig. 2.

1) Initiation Walking Phase: Initiation walking phase is a transition phase from immobile biped stand phase to steady walking phase. As shown in Fig. 2, in this phase, the leg steps over ground, generating an acceleration to force the robot moving forward. For a healthy person, this phase could be finished in two steps, and then transfers to Steady walking phase.

2) Steady Walking Phase: When a healthy person walks in this phase, the person needn’t plan his gait and can act as an unconsciousness personal behavior [2]. For a BRHL robot, when gait identification module recognizes the current walking phase is becoming to Steady walking phase, the closest gait reference data should be found and modified according to current speed and step frequency. In order to avoid error accumulating, intelligent bionic leg will calibrate its motion in each step cycle.

3) Decelerating Phase: At this phase, BRHL robot slows itself down by backward contact force from ground when the leg generates an forward force to the ground. When gait identification module recognizes current motion is slowing down, the intelligent bionic leg will restore to stand state by extension force of magneto-rheological (MR) damper.

B. Gait Identification

when a person is walking, the vertical support force from ground is the biggest force. It has two extremes in one step cycle and a bimodal curve [3] can be used to describe the vertical force in one step cycle, as shown in Fig. 3.

The first extreme appears when heel contacts to the ground. And as the whole feet touching down on the surface, the area of contact is enlarged, and the force reduces to the minimum. The second extreme appears when the toes step to the ground, driving body moving forward.

When a person walking, the horizon forces are small and symmetrical. Geng [4] concludes that the bimodal character of contact force for different ages is of no distinct differences.

Tang [5] has estimated the ankle force in the single leg support phase, and the conclusion is that the maximum force is about 4.167 times to itself weight. The statistical test results in [6] show that there are few differences between male and female ankle forces. The gait of artificial leg is design in advance, but the gait of intelligent bionic leg have to be generated by control module with regarding to sensor information. For BRHL robot, the intelligent bionic leg identifies the artificial gait by a 6-D force/torque sensor fixed in ankle joint and an encoder fixed in kneel joint. Based on these measurements, a specific gait, such as level direction walking, changing direction walking, slope walking, up-down stairs, down squats etc., is determined. Asymmetric information in BRHL robot is a bottleneck problem in its walking. So, how to identify the practical gait is a key issue in BRHL’s walking.

1) Level Direction Walking Gait: In this gait, the ground reaction force and kneel joint angle change with step speed and step width. As soon as the maximum fore and aft angle of kneel joint and reaction force from ground is received, the gait identification module ascertains that the current gait is Level direction walking gait, which is depicted in Fig. 4.

2) Slope Direction Walking Gait: As shown in Fig. 5, when walking in a slop, if the speed keeps constant, the ankle moment and kneel joint angle will change along with the pitch of slope. Based on those sensor information, the gait identification module estimates the pitch of the slope first, then, identifies the nearest gait data which is determined in advance and modified it according to the pitch of the slope to generate...
3) **Changing Direction Walking Gait:** When walking in Changing direction walking pattern, the centripetal force in the side direction of BRHL robot is obviously different from the above two walking pattern, which is shown in Fig. 6

During standing phase, the gait identification module compares the reference force-moment curves with sample data observed by 6-D force/torque sensor, then ascertains current walking direction and curvature of walking track.

4) **Up-down Stairs Walking Gait:** When walking on stairs, kneel joint angle and floor reaction force have big differences from other walking pattern, as shown in Fig. 7

Gait identification module compares reference curve with sample data from sensors, and decide the current walking pattern.

C. **Gait Generation**

According to different walking pattern, gait generation module generates target gait in different way.

D. **Level Direction Walking Pattern**

In level direction walking pattern, gait generation module compares reference curve with sample data, and plans the current walking gait.

E. **Up-down Stairs Walking Pattern**

In up-down stairs pattern, the pitch and span of stair are calculated first. Then gait generation module considers both reference data and sample data, as well as the pitch and span of stair to calculates target gait.

F. **Changing Direction Walking Pattern**

In this walking pattern, gait generation module adjusts gait curve based on current walking direction and curvature of walking track identified by task layer.

G. **Other Situations**

For some special situations of squat, stumbling or kicking, the intelligent bionic leg control module will come to standing phase or adopts safeguard strategy by adopting some special reference curves adopted for the knee joint angle.

Details of the real-time gait identification and gait generation module are described in Fig. 8

### III. CONTROL SYSTEM DESIGN

The intelligent bionic leg knee is semi-controlled by a magneto-rheological (MR) damper. Magneto-rheological fluid is a material that can change from a linear viscous fluid state to a semisolid state reversibly when exposed to a magnetic field. The resisting force of MR damper filled with magneto-rheological fluid is controlled by the current in the solenoid.
[7]. With MR damper to control knee joint, it is possible to realize more natural gait than that of passive mechanism. Experiments show that the intelligent bionic leg knee semi-controlled by MR damper is energy saving and its control characters are much more similar to muscle and ligament. A modified Sigmoid model is proposed for MR damper and a semi-active control algorithm is presented for the MR damper.

A. Semi-active Control for Kneel Joint of Intelligent Bionic Leg

1) Mathematic Model of MR Damper: The gait and track of the intelligent bionic leg is realized by a MR damper fixed in the knee joint. There are many mechanical models for MR damper at present. An extension of Bingham plasticity model is effective in describing the force-displacement behavior. However, this model does not exhibit observed non-linear force-velocity response, especially when the displacement and velocity have the same sign and the magnitude of the velocity is small. Spencer [8] proposed a mechanical model for MR dampers based on the Bouc-Wen hysteresis model, which could overcome some problems mentioned above. But this model has too many parameters and those non-linear functions are hard to resolved. Choi [9] proposed a polynomial model, which could be easily integrated with a control system. However, in order to ensure precision, the rank of this model should be more than 12. So it brings a huge computation for real-time control. Xu [10] proposed a model based on Sigmoid model to describe the dynamic characters of MR damper as shown in the following equation:

\[
F = \frac{F_M(1 - e^{-\beta_P \dot{x}})}{(1 - e^{-\beta_P \dot{x}})} + C_P \dot{x} + Kx
\]

where \( F \) is damper force, \( F_M, \beta \) and \( C \) are damper parameters, \( \mu \) is hysteresis parameter.

This model is a Sigmoid model, which uses the median of the upper and lower curves of hysteresis curves to approximate the characters of MR damper. The model is simple and easy to solve. But it doesn’t present the hysteresis character of MR damper in low velocity. This paper proposes a modified Sigmoid model to describe the dynamic characters of MR damper, which can overcome the defects of the above Sigmoid model. The relationship of coefficient with control current will be discussed later with the experimental description.

The schematic configuration of proposed modified Sigmoid model is shown in Fig. 9.

We can divide the hysteresis loop into two regions: positive acceleration region and negative acceleration region. Then, the lower loop or upper loop can be fitted by the Sigmoid curves corresponding to the piston velocity. According to the physical characters of MR damper, accumulator stiffness unit is considered as a spring. So the proposed model can be described as follows:

\[
F_P = \frac{F_{MP}(1 - e^{-\beta_P \dot{x}})}{(1 - e^{-\beta_P \dot{x}})} + C_P \dot{x} + Kx
\]

2) Semi-active Control of Kneel Joint for the Intelligent Bionic Leg: The basic behavior of MR damper can be modelled as a circuit with a resistor and an inductor in series connection, which can be described as the following equation:

\[
L \frac{di}{dt} + iR = U
\]

Where \( L \) and \( R \) are coil inductance and resistance, respectively. So, the MR damper is an inertia equipment. In order to decrease the response time of the MR damper’s magnetic circuit, the method of current driver with PD compensation is adopted. For the residual magnetic field remaining inside the damper after the current has been removed, the damper force can not disappear quickly as current does. To solve this problem, the coils are back-driven by the allowable maximum until the damper force reaches no current state. In this way, it can effectively reduce the influence of the residual magnetic field, allowing a fast response time to be achieved on the downside of the damper force.

B. Overall Control System Scheme

Global view of the overall control system is shown in Fig. 10. It includes both the control of the artificial leg and the intelligent bionic leg.

In the walking process, the sensor information are transformed into digital data and sent to control module. The upper computer generates the target gait of next step cycle with gait identification module and gait generation module, sends the target command to executive layer; and the executive layer drives motors to control the artificial leg and coxa joint of
the intelligent bionic leg. For the control of kneel joint of the intelligent bionic leg, control module calculates the desired damp force and control current based on the characters of target gait, such as velocity, acceleration, angle, etc., first. Then the upper computer sends the command of control current to MR damper controller. After that, MR damper push kneel joint to target position.

IV. SIMULATION AND PRACTICAL EXPERIMENTS

Simulation and practical experiments are conducted to evaluate the performance of proposed methods.

A. Semi-active Control for Kneel Joint of the Intelligent Bionic Leg

First, the comparative experiments between proposed modified Sigmoid model and the practical MR damper data are conducted, which is shown in Fig. 11.

The experiments are done under different MR damper control currents, with the dotted curves being the data of proposed model and the solid curves being practical data. The specific values of coefficient used in this model are listed in Table I.

It is noted that the proposed model can imitate the practical MR damper very well, and the coefficients are scaled to the input current. Thus, we can easily realize an close-loop control to achieve a desirable damp force.

To verify the validity of the current feedback control, the simulation is done, and the results are shown in as Fig. 12 where the dotted curve is the desired current, and the solid curve is the actual current.

Note that the response time is fast and the overshoot is very low to meet the requirements of kneel joint control. As a semi-active component, the MR damper can only output restricted force. So, the kneel joint control is a semi-active control. According to the mathematical model of MR damper and the dynamic model of BRHL robot [1], we can get the comparison of ideal damp force and actual damp force as shown in Fig.13 The differences between ideal damper force and actual damper force are determinate by the characters of MR damper, which is explained as follows.

• For the stiffness of MR damper, more stiffness, more extension force, even without current driving. When the ideal damp force is lower than extension force, the actual damp force can not reach the ideal damp force.

• When human walking, the kneel joint can provide a torque to bend the leg. But the MR damper cannot provide that torque because it is not active driving.

B. Swinging Phase Experiment

The swinging phase experiment describes the situation when the robot changes to steady walking phase from initiation
walking phase in the level direction walking pattern. Fig. 14 gives the experimental curves.

It could be found that the intelligent bionic leg can follow the artificial leg’s movement. However, there exist some lag, especially when the speed is small. This is because the control of MR damper is not a complete optimal control in a whole step period.

V. CONCLUSION

This paper discuss some problems in BRHL robot, including gait recognition, gait generation and gait control during walking under the situation of asymmetric information between artificial leg and intelligent bionic leg. Based on the modified Sigmoid model, a semi-active control plan is proposed for the intelligent bionic leg. And a overall control system is presented for the BRHL robot. Simulation and practical experimental prove the validity of the proposed methods.

ACKNOWLEDGMENT

This work is supported by National Natural Science Foundation of China, ID60475036 and Liaoning Natural Science Foundation, ID20042019.

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