Robust Position Tracking Control and Ground Contact Detection of a Cheetaroid-I Leg by a Disturbance Observer

Jungsu Choi, Byeonghun Na, Sehoon Oh, and Kyoungchul Kong *

* Department of Mechanical Engineering, Sogang University, Seoul, Korea (Tel: +82-2-705-4766; e-mail: kckong@sogang.ac.kr).

Abstract: Quadruped robot systems are being intensively investigated as a new means of transportation systems with multi-purposes. As the operation conditions of such systems, such as a payload and gait speed, are demanding, the control of the robotic legs is challenging. Moreover, the dynamics of a robotic leg is highly uncertain and time-varying due to the ground contact and the ground condition, as well as the unknown payload. Therefore, a control algorithm that can achieve both great control performance and stability robustness is essential for the effective control of a quadruped robot.

In this paper, a robust control algorithm based on a disturbance observer (DOB) is proposed for the control of legs of a quadruped robot, Cheetaroid-I. The DOB enables rejecting disturbances caused by the ground contact, payload, etc., and detecting the ground contact without force sensors. The proposed method is verified by experimental results.

1. INTRODUCTION

Importance of robotic systems has risen in the modern society. Their applications have been extended to not only industrial automation, but also the daily life of humans (K. Kong et al. [2012]). Various robots have been developed for helping humans in recent years. With a great amount of government support, many researchers are making their best efforts to develop robot systems that can replace the role of humans in hazardous and dangerous environments, in particular the disastrous areas by a nuclear accident (J. Savall et al. [1999], K. Nagatani et al. [2011], and K. Kaneko. [2012]). Considering the required dexterity and robustness of robot systems, legged locomotion systems are being intensively investigated. In particular, quadruped robots are receiving great attention as a new means of transportation for various purposes, such as military, welfare, and rehabilitation systems. The use of four legs enables a robustly stable gait; compared to the humanoid robots, the quadruped robots are particularly advantageous in improving the locomotion speed, the maximum payload, and the robustness toward disturbances, e.g., refer to M. Raibert et al. [2008], M. A. Lewis et al. [2011], and B. Na et al. [2013].

The more demanding conditions robots are exposed to, however, the more challenging the control of robotic legs becomes. As the gait speed increases, the frequency bandwidth of reference signals (i.e., desired motions) is also significantly enlarged. Thus the significant enlargement of closed-loop bandwidth of a control system is necessary. Consequently, high gain control with a high-speed data acquisition system is unavoidable, which also necessitates the accurate measurement of physical states without noise.

* This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (NRF-2012R1A1A1008271).
of dynamics variation is required, which is challenging in practice.

In this paper, the dynamic model of a Cheetaroid-I leg system is analyzed, and the nominal plant model and the range of model variations are obtained through extensive experiments. The implementation of the DOB, however, requires extra care due to the unstable zero of the plant dynamics. Therefore, the parameters of the nominal plant model are further optimized considering the closed-loop stability of the DOB, as well as the closed-loop performance. The proposed model optimization process enables the effective control of the robotic leg without performance degradation even in the presence of an unstable zero in the nominal plant model, which is the case of Cheetaroid-I.

In addition to robust stabilization and disturbance rejection, the DOB is also utilized to detect the ground contact, which is necessary information for a higher level motion control algorithm. While the majority of the disturbances estimated by the DOB is due to the ground contact, observation of the magnitude of the estimated disturbance. Consequently, the proposed control system enables both effective control of a Cheetaroid-I leg system and removal of force sensors for detecting the ground contact.

2. CHEETAROID-I ROBOT SYSTEM

2.1 System Configuration

Cheetaroid-I is a quadruped robot that has fourteen degrees of freedom (DoFs), which include three DoFs in each leg system and two DoFs at the waist, as shown in Fig. 1. It is capable of generating various locomotion types, such as different gait phases, gyrations, and so on. The hip and shoulder joints are equipped with customized linear actuators that exhibit high power output with low mechanical impedance. For the details on the design of Cheetaroid-I (B. Na et al. [2013]).
motor, where a control input takes place, and the joint, where the output is measured. The compliance increases the order of the plant model (i.e., the number of poles in the plant transfer functions) and also imposes zeros occasionally. Notice that the equations of motion of the motor and the foot system are respectively

\[ I_m \ddot{\theta}_m + k(\theta_m - \theta_{dis}) = u \]  

and

\[ I_s(\ddot{\theta}_{dis} + \ddot{\theta}_{prox}) + c_p \dot{\theta}_{dis} + m_s g l_s \sin(\theta_{dis} + \theta_{prox}) = \tau + d \]  

where \( \tau = k(\theta_m - \theta_{dis}) \) is the torque transmitted by the timing belt, and \( d = d_{GND} l_s \sin(\theta_{dis} + \theta_{prox}) + f(\theta_{prox}, \theta_{prox}) \) is the disturbances due to the ground contact and the motion of the upper leg part. Although the equations of motion in (1) and (2) are subjected to large disturbances and model discrepancies due to the inherent complexity of a robot system, transfer functions can be obtained rearranging and linearizing the equations above, i.e.,

\[ \theta_{dis}(s) = G_{u \rightarrow \theta_{dis}}u(s) + G_{\theta_{prox} \rightarrow \theta_{dis}}\theta_{prox}(s) + G_{d_{prox} \rightarrow \theta_{dis}}d(s) \]  

where \( \theta_{dis}(s), u(s), \theta_{prox}(s), d(s) \) are the Laplace transforms of \( \theta_{dis}(t), u(t), \theta_{prox}(t), d(t) \), respectively. Notice that the angular position of the distal joint, i.e., \( \theta_{dis} \), is influenced by the motion of the upper part and the disturbances, as well as the control input, \( u \). Assuming that the second and third terms on the right-hand-side of (3) are disturbances to be rejected, the structure of a nominal plant dynamics (i.e., \( G_{u \rightarrow \theta_{dis}} \)) can be obtained. Rearranging (1) and (2), one can easily find that \( G_{u \rightarrow \theta_{dis}} \) is a fourth-order transfer function with no zero. Among the three active DoFs in each leg of the Cheetaroid-I, the control method for distal joint (i.e., the elbow/stifle joint) is introduced in this paper.

2.3 System Identification of a Nominal Plant Dynamics

In order to identify the parameters of \( G_{u \rightarrow \theta_{dis}} \), system identification experiments were carried out. In the experiments, the control input, \( u(t) \), was the pulse width in the range of \([-20000, 20000]\), and the output was the stifle/elbow joint angle in the unit of radians. Eight sets of experiments were conducted with different input magnitudes. Each set of experiments consisted of sinusoidal waves with different frequencies. Once a set of experimental data was obtained, both the input and output signals were Fourier-transformed, and frequency responses were obtained by comparing the input and output signals in the frequency domain.

Figure 3 shows the experimental results. It should be noted that the magnitudes and phases did not exactly match as the input magnitude changed. This implies that the system has nonlinearities or time-varying components. In particular, the model variation was significant at low and high frequencies, where the low frequency uncertainty was mainly due to the friction of the joint, and that of the high frequency was due to the inaccuracy of sensor measurement, noise, and so on. Consequently, a band is formed [see the circles in the figure] and the parameters of \( G_{u \rightarrow \theta_{dis}} \) was obtained considering the magnitude and phase bands as

\[ W(s) = \frac{0.011s^2 + 1.011s + 22.933}{s + 30.000} \]  

The magnitude of \( W(jw) \) is also shown in Fig. 4 [see the continuous line].

2.4 Identification of Dynamics Uncertainties

Since both the nominal plant model and experimental data are available, multiplicative uncertainties can be obtained by

\[ \Delta(jw) = G_{exp}(jw) - G_{u \rightarrow \theta_{dis}}(jw) \]  

The calculated \( \Delta(jw) \) for every experiment in Fig. 3 is shown in Fig. 4. It should be noted that the magnitudes of the model mismatch are large at high frequencies. For the simplicity of the uncertainty modeling, it is assumed that \( \Delta \in \{ W\Delta; W \in \mathbb{S}, ||\Delta||_\infty < 1 \} \), where \( W(s) \) is a minimum-phase transfer function that represents the upper bound of multiplicative uncertainties at each frequency. Then, the upper bound of the multiplicative uncertainties can be modeled based on the experimental data shown in Fig. 4, i.e.,

\[ W(s) = \frac{0.011s^2 + 1.011s + 22.933}{s + 30.000} \]  

The magnitude of \( W(jw) \) is also shown in Fig. 4 [see the continuous line].
3. DISTURBANCE OBSERVER DESIGN FOR LEG CONTROL

3.1 Overall Controller Structure

The overall control algorithm includes a feedforward filter, the feedback controller, and the DOB, as shown in Fig. 5. Since the DOB is not a tracking controller, the feedback (PD) controller is applied as an outer loop of the DOB. If the plant has unstable poles, careful consideration should take place in the design of the controller. In the leg of the Cheetaroid-I, the plant dynamics does not possess any poles outside of the unit circle on the $z$-plane. On the other hand, the reference trajectory of the Cheetaroid-I is generated by inverse kinematics. Since the reference trajectory is generated by considering only the possibility of locomotion, the drastically changing moments exist in the reference trajectory. Therefore, the derivative controller calculates the control input by using only the output of the plant. Assuming that the DOB loop behaves as its nominal model, the feedforward controller is designed based on the closed-loop characteristics formed by the PD controller and the nominal model. A moving average filter is used to reduce the sensor noise.

3.2 Design of a $Q$-filter

In the design of $Q$-filter, the following conditions should be fulfilled to guarantee robust stability:

1. $Q$-filter must be stable, and
2. the magnitude of $Q(jw)$ should be less than that of $W^{-1}(jw)$ for all $w \in \mathbb{R}_+$.

Based on the experimentally obtained $W(s)$ in (6), a $Q$-filter can be designed such that its magnitude is smaller than that of $W^{-1}(jw)$ at the entire frequency range. A possible $Q(s)$ is

$$Q(s) = \frac{0.218}{s^2 - 1.067s + 0.285}$$

FIG. 4. The upper bound of the multiplicative uncertainties.

FIG. 5. The block diagram of the disturbance observer.

4. EXPERIMENTAL RESULTS

4.1 Reference Tracking Performance Evaluation

Figure 8 shows the experimental results of the PD controller without the DOB; the reference trajectory and the controlled joint angle are shown in the figure. The locomotion speed was increased gradually in the experiment. Recall that, since the reference trajectory has drastically changing moments, the derivative controller was designed such that it calculates the control input by using only
Box and the timing belt were significantly rejected by the gear-wheel. Since disturbances and model uncertainties by the gear-wheel significantly increased the response time during force transmission. The PD control, because the gear-box and the timing belt were difficult to obtain the desired performance only with the PD controller. Nevertheless, the tracking performance of the PD controller was insufficient to realize successful locomotion. It was difficult to obtain the desired performance only with the PD controller, because the gear-box and the timing belt increased the response time during force transmission. The backlash of the gear-box and the timing belt significantly affected the tracking performance. Moreover, the tracking performance was more deteriorated as the locomotion speed of the Cheetaroid-I increased. This is because the reduced stance period made the change of the reference trajectory more drastic.

The tracking performance with the proposed control method is shown in Fig. 9, where the performance was remarkably improved than the PD controller by the proposed control method. In both experiments in Figs. 8 and 9, the same gains were used in the PD controller. Since disturbances and model uncertainties by the gear-box and the timing belt were significantly rejected by the proposed control method, i.e.,

\[ \hat{d}_{GND}(t) = f_L(s) \left[ \max(d(t) - d_0, 0) \right] \]  

(10)

In this paper, the ground contact detection is conducted through the estimated disturbance by the DOB. The artificial experimental environment was set for the verification of ground contact detection by the DOB. The sinusoidal reference trajectory was used, and the feet contacted the ground slightly for checking the accuracy of the proposed method. Figure 11 shows the estimated disturbance by the DOB, where the estimated disturbance is periodic, and the peaks occur in the estimated disturbance at the ground contact moments. Therefore, the estimated disturbance can be used as the estimate of the ground reaction force with a proposed filtering law, i.e.,

\[ \hat{d}_{GND}(t) = f_L(s) \left[ \max(d(t) - d_0, 0) \right] \]  

(10)

4.2 Ground Contact Detection

Snapshots of a video of a gait experiment are shown in Fig. 10; the right hand side of the Cheetaroid-I was the front direction. The whole motion is divided into two periods based on the motion of right hind leg: (a)-(c) represent the swing period, and (d)-(f) are the stance period. In the stance period, since the feet contact the ground, the ground reaction forces occur and can be measured by appropriate sensing mechanism. Measurement of the ground reaction force is important in the locomotion control because the gait stability is closely related to the ground reaction force.
In (10) $\hat{d}_{\text{GND}}$ is the estimated ground reaction force, $f$ is a scaling factor, $L(s)$ is a lowpass filter, $d$ is the estimated disturbance by the DOB, and $d_0$ is a threshold value. The estimated disturbance is regarded as the ground contact when it is larger than the threshold value.

Figure 12 shows the ground contact detection results during the sinusoidal tracking experiment, where the estimated ground reaction force and the measured ground reaction force are shown together. The tendency of the estimated ground reaction force was similar to the ground reaction force measured by a force sensor. The error between estimated ground reaction force and force sensor measurement was 0.592N in the root-mean-square (RMS). The error was mainly caused by the lowpass filtering, since the high frequency component of ground reaction force was filtered twice by Q-filter and $L(s)$. The estimated ground reaction force preceded the measurement of the force sensor occasionally, and the estimated ground reaction force held longer than the ground reaction force measured by the force sensor as shown in Fig. 12. This is because a force sensing resistor (FSR) sensor was used to measure ground reaction force in the experiment, and the FSR can measure the ground reaction force applied to the sensing area of FSR only (in this case, the diameter of the used FSR was 25mm). Therefore, the FSR sensor could not measure the ground reaction force even when the feet contacted the ground. On the other hand, the sensing area where the DOB can estimate was not constrained, since the DOB could estimate the total external force that acts on the entire area of the foot. Therefore, wider and faster ground contact detection could be achieved when the ground reaction force is estimated by the proposed DOB-based algorithm.

5. CONCLUSIONS

In this paper, the dynamic model of a Cheetaroid-I leg system was analyzed, and the nominal plant model and the range of model variations were obtained through extensive experiments. The parameters of the nominal plant model were further optimized considering the closed-loop stability of the DOB, as well as the closed-loop performance. Also, the ground contact detection was conducted through the magnitude of the estimated disturbance by the DOB. The proposed control system was verified by the experimental results. The tracking performance was remarkably improved by the DOB, and the ground contact detection was available by monitoring the magnitude of the disturbance estimated by the DOB. Consequently, the proposed control system enabled both effective control of a Cheetaroid-I leg system and removal of force sensors for detecting the ground contact. The DOB design was only limited to the distal joint in this paper. The extension of the DOB to the proximal joints is the future work.

REFERENCES


