論文の内容の要旨

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High-Performance Robot Motion Control Based on Wideband and Friction-Free Force Sensation

広帯域と摩擦フリー力覚情報に基づく高性能ロボットモーションコントロール

Force sensing method plays a very vital role in robot motion control systems. The measurement of force in a force control system is of greatest importance since the accuracy of the force measurement affects the performance of the system directly. Wideband force sensing is necessary to achieve a high-performance force control system. Generally, force measurement is realized using force sensors. However, force sensors are susceptible to the noise effect that results in a narrow force-sensing bandwidth and are not usually suitable for all environments or applications. Moreover, in many control systems, the drive motor is connected to the load through a ball screw or gear mechanism. Due to mechanical imperfections in these connections, there always exists some friction. Friction is one of the greatest obstacles in high-precision control systems. In a force control system, friction can deteriorate the force-sensing performance as well as the control performance. Many model-based friction estimation and compensation methods have been proposed. The inherent disadvantage of the model-based technique lies in the model complexity and accuracy. Therefore, to achieve the high performance robot motion control system, it is vital to develop a wideband force sensing method with effective friction reduction in force estimation.

This research proposes a methodology to attain the high performance robot motion control system based on the superior wideband force sensing and the friction-free force observation. The Kalman-filter-based disturbance observer with muti-sensor is designed for force sensing operation. The Kalman-filter uses position signals and acceleration signals as its inputs to estimate the velocity. By using Kalman-filter with multi-sensor integration, the noise in velocity estimation is suppressed effectively and the improved velocity information is obtained, especially during the impact motions with high acceleration. As the result, the force estimated by disturbance observer is markedly enhanced. The bandwidth of force sensing is widened to 62800 rad/s (≈ 10Khz) using the proposed method. This bandwidth is superior to human bandwidth of tactile sensation and is useful for human support techniques.

To deal with the effect of friction, a novel force sensing method named as friction-free disturbance observer is proposed to achieve a wideband force control system with friction-free observation. The effect of friction on force observation is eliminated owing to the addition of a dither signal to the desired reference signal. The disadvantage of the dithering method is that it generates an oscillatory disturbance that can affect the performance of the control system. The proposed friction-free disturbance observer is designed for force sensing operation and elimination of periodic disturbance in force estimation. To make the design practical, the problem of noise in the measurement is taken into account. A Kalman filter is used in combination with the friction-free disturbance observer to reduce the effect of noise on the force estimation. The influence of the periodic signal on force estimation is effectively rejected by the friction-free disturbance observer. The force-sensing bandwidth is widened to 1000 rad/s due to the effective noise suppression by using a Kalman filter.

This research also presents a new force sensing approach based on the friction-free disturbance observer to improve the performance of a bilateral control system with different mechanisms of the master and the slave sides operating as a power assisted control system. A linear shaft motor and a ball screw perform the roles of the master and the slave, respectively. The proposed bilateral control is based on acceleration control and consists of a conventional disturbance observer and a friction-free disturbance observer for the master and slave, respectively. Using the proposed method, the oscillatory disturbance in the force responses is reduced effectively on both master and slave sides; the good tracking in the position and force responses of the master and the slave devices is achieved, even when the mechanisms of the master and the slave are different; the human operator is assisted to manipulate the device with a small operational force, while still perceiving the impedance of the remote environment. Additionally, the friction-free DOB effectively suppresses the harmonic disturbances in the force estimation in both the master and slave. The proposed method is feasible for application to human assist systems or in industrial applications.

Furthermore, in this research, all control algorithms are implemented in FPGA to improve the control performance. Since the force sensing bandwidth is inversely proportional to the sampling period of the control system. In order to increase the bandwidth of force sensation, a shortened sampling period is necessary. The feature of parallel processing enables FPGA to significantly shorten the sampling time of control algorithms. The shortened sampling time of control system is 5 μs that enables widening force sensing bandwidth and ensures the high performance of control system when the control algorithm is highly complex.