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Bilateral Nonlinear Control of a Master-Slave Manipulators System

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A master-slave system is one of a teleoperating systems for extending a human sensing and manipulation capacity to remote locations. It has been often useful with human decision for unfixed tasks in the handling of radioactive materials, in deep-sea exploration and servicing, in treating under narrow environments where it is impossible for people to work directly. Recently, a concept of "tele-existence" attracts a great deal of attention in research about master-slave system. Bringing into tele-existence, an operator feels that he/she directly treats the objects around the slave manipulator with haptic feedback. The ideal of master-slave system is to achieve "transparency" which reproduces complete human skills with a slave manipulator. In master-slave system, usual position feedback controller's leaves something to be desired performance as controlling interference force between slave and environment. Hence it is necessary to perform bilateral control which communicates both position errors and force/torque errors as a transition of environment between master and slave manipulators. It is also necessary to be robust for uncertainties of robot dynamics and to consider interactive forces between slave and environment. Some nonlinear robust control methods for master-slave systems were studied by Strassberg, Goldenberg, Leung and Francis. Their laws are an application of robust control method for single manipulator, based on the earlier work of Spong and Vidyasagar. In this law, given the nominal models of the master and slave dynamics, and using an approximate feedback linearization control, a robust closed-loop system (position and force) can be obtained with a multiloop version of the small gain theorem under the assumption that the deviation of the models from the actual systems satisfies certain norm inequalities.

However their computations are too complicated to apply their method to master-slave system with more degrees-of-freedom.

In this thesis, we propose a control method which is robust for fluctuations of operator and environment. This method is an application of a tracking control method called Lyapunov-based method proposed by Slotine and Li. The characteristics of Lyapunov-based method are to use the structural properties of the manipulator dynamics, to achieve asymptotic convergence of the tracking error. In this method, a robust version of the control law can be obtained with small modification.

On the assumption that we can obtain the exact model of n degrees-of-freedom master-slave systems, we consider control of to achieve asymptotic transparency, that is, asymptotic agreements in positions, velocities and forces between master and slave manipulators. We derive a control law of master-slave systems consists of two parts, one part is tracking controller and the other part is compensator for external force. To use this structure, we can extend a tracking control law of single manipulator based on Lyapunov-based method to control master-slave systems. Then we proved asymptotic stability of the master-slave system under this control law, using same process of a single manipulator, so that we can showed position, velocity and force errors between master and slave manipulators are equal to zero.

To consider the structure of above control law, it consists of two tracking control loop which compare master's angle and slave's angle with each other, and additional force control loop to cancel external forces, so that we can apply same process of a single manipulator to those tracking loops. Because the computing order is only n to control Lyapunov-based tracking law of n degrees-of-freedom, the order is advantageous to extend multi-degrees-of-freedoms systems. It is unwelcome to use acceleration signal of manipulators' joint because of it's noise, but the goal of our control law, that is well agreement in position, velocity and force errors between master and slave, can not be achieved without acceleration signal. Our control law only shows that the difference of position go to zero, so there is a danger that the position of master and slave go to infinity at the same time. Therefore, in order to realize of transparency, we shall have to consider again the goal.

Furthermore, we consider robust control problems. We can derive control laws only with obtained parameters of manipulators, because it is difficult to know exact robot parameters of actual systems. Solution of robust control problems satisfies desired performance to control systems with parametric uncertainties. On the assumption that we can obtain the upper bound of parametric uncertainties, we aim the tracking errors at uniformly ultimate bound, which means the tracking error goes no further than the designed bound for all time, after it entered into the bound.

It is known that Lyapunov-based tracking control of single manipulators can easily extend to have robustness about parametric uncertainties. For the purpose of deriving robust control law of master-slave system, we extend the above nominal control law of master-slave system to have robustness with the same style. Then we prove the closed-loop of master-slave system is uniformly ultimate bounded under this control law. However this proof only shows the upper bounds of position and velocity errors, we can not find that force error between master and slave manipulator is uniformly ultimate bounded. Therefore, we will have to propose additional force controller with robustness.

In order to illustrate performances of the control laws, we simulate 2 degrees-of-freedom master-slave manipulator on an analysis program. Firstly we compute to confirm of a performance of our nominal control law of master-slave manipulator. Secondly on the assumption of the deviation of the mechanical parameters from the actual system, we compute tracking error on two cases, without and with loads on the hand of the slave manipulator, as an example without and with uncertainty of the systems. This simulation shows our nominal control law can satisfactorily control systems without uncertainties, but it can not make errors to stay desired state when uncertainty exists. In the proposed control law, uniformly ultimate bound is achieved for tracking errors with uncertainties, but not done for force errors. It will be expected to derive robust control law with improved force feedback loop.