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Stiff and Safe Task-Space Position and Attitude Controller with Noise-Reduction Differentiator for Robotic Manipulators

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論　文　名　：Stiff and Safe Task-Space Position and Attitude Controller with Noise-Reduction Differentiator for Robotic Manipulators

（多関節ロボットのための高剛性かつ安全な作業空間位置・姿勢制御器とノイズ低減微分器 ）

区　　分　：　甲

論　文　内　容　の　要　旨

Recently, robotic applications involving human-robot physical interactions in unknown environments have received much attention from various areas such as power assisting, surgery, rehabilitation, robot teaching, and etc. When robotic manipulators work in contact with humans, an appropriate controller is necessary to control the contact force between the robot's end effector and the human operator. One of the force control schemes is admittance control where a virtual object with simple dynamics is considered in the controller, in which the contact force is used to simulate the virtual object's motion. It may require a stiff task-space position/attitude controller as an internal position/attitude controller to track the virtual object's motion accurately in the three-dimensional task space. One problem of the admittance control combined with the stiff task-space position/attitude controller is that it can cause unsafe behaviors such as repeated overshoot from large error between actual position/attitude and position/attitude determined by the virtual object's motion. It is not suitable when the robots work together with human operators in the shared workspace. On the other hand, detecting the contact force in admittance control is also an important issue. In situations where a force sensor is not available, a reasonable choice is to use force estimation algorithms for detecting the contact force. It requires an appropriate noise-reduction differentiator for estimating first and second-order derivatives of optical encoder signals including noises. Motivated by the above problems, this thesis proposes some techniques for robotic manipulators such as task-space position/attitude controller, noise-reduction differentiator, and task-space admittance controller combined with external force estimator.

Chapter 2 proposes a stiff and safe task-space position and attitude control scheme for robotic manipulators. This study extends the work of Kikuuwe et al.'s. (2006) velocity-bounding proxy-based sliding mode control by explicitly addressing the attitude part. The proposed controller has a Jacobian-based structure, which realizes smooth trajectories when the desired attitude is far rotated from the actual attitude. It also imposes arbitrary magnitude limits on the end-effector velocity, angular velocity, and each actuator force without sacrificing stiffness, which is the same level as a high-gain PID position control below the limits. The benefit of the proposed controller becomes apparent after the robot yields to external forces due to force saturations, when the robot makes contact with obstacles.

In such a situation, if the external forces disappear, the controller generates overdamped resuming motion from large tracking errors. The proposed controller can be expected to enhance the safety of robotic applications for the human-robot interaction. This method is validated by experiments employing a six-DOF industrial manipulator.

Chapter 3 proposes a new sliding mode differentiator combined with a sliding mode filter for estimating first and second-order derivatives of noisy signals. The proposed differentiator can be seen as a version of Slotine et al.'s sliding mode observer extended with an additional non-Lipschitz property, which is intended to realize a faster reaching to the sliding mode. It behaves as a noise-reduction filter that is composed of first, second and third-order LPF in the sliding mode, but also employs the filter that is composed of second, third and fourth-order LPF out of the sliding mode. Moreover, the differentiator effectively removes impulsive noises by combining a sliding mode filter and its discrete-time implementation is based on the implicit (backward) Euler discretization, which does not result in chattering and realizes the exact sliding mode. Experiments show that the proposed algorithm has a better balance between the noise attenuation and small phase lag than the linear-filtered Euler differentiation and previous sliding mode differentiators. It is validated through experiments using optical encoder signals of industrial robots.

Chapter 4 proposes a task-space admittance controller combined with an external force estimator for robotic manipulators. It is developed using two improved methods in order to guide the robot's end effector, of which an attitude rotates according to a force applied by human operators with maintaining a position. Specifically, first, the proposed control scheme contains a task-space position and attitude controller presented in Chapter 2 for the use as the internal position and attitude controller of the admittance control. The internal position and attitude controller quickly responds to change in the applied force as much as a high-gain PID position control, and is capable of smooth and overdamped motion when an output of desired admittance is far separated from the actual position and attitude. Secondly, the proposed control scheme employs an external force estimator using a noise-reduction differentiator presented in Chapter 3 for estimating robot joint's velocity and acceleration. It produces smaller phase-lag and noisiness than linear filters. Moreover, the proposed external force estimator is combined with a dead-band filter where uncertainties and unmodeled dynamics are hidden under the dead-band threshold. It effectively distinguishes contact environments from free space. Due to such combination, enhanced safety and operability of the task-space admittance control is achieved without force sensors. The proposed algorithm is validated through experiments using a six-DOF industrial manipulator.

Finally, concluding remarks and future studies are stated in **Chapter 5**.