論文の内容の要旨

論文題目　「Whole-Sensitive Anthropomorphic Robot Arm Based on Optical Torque Sensing Technique and Its Control Algorithm Providing Compliant Interaction with Environment」

（光学式全軸トルクセンサを有した人間型ロボットアームと外界とのコンプライアントなインタラクションが可能な制御アルゴリズムの研究）

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（本文）Many operations in specific environments are dangerous for human（e.g. nuclear, in-space, underwater）or difficult to access（e.g. micromanipulation）. Recently, teleoperation has been gaining the increased attention by researchers interested in studying the possibilities to overcome the limited functionality of autonomous robots performing specific tasks, and to improve dexterous operations.

Our research is mainly devoted to realization of teleoperated robot enabling safe interaction with humans. The line of master-slave robot systems（TELESAR I and TELESAR II）was successfully developed in our laboratory. A slave robot controlled by the operator mainly performs the manipulations in unknown and unstructured human environment. The operator has to move the slave robot arm to target position, and to perform manipulations while simultaneously avoiding obstacles. However, operators cannot accomplish these tasks in real time. Besides, they are not perfect in planning the collision-free motion in dynamic unstructured surroundings. To lighten the operator’s work, safe area of interaction with environment was provided around the wrist of the robot arm through impedance control. Nevertheless, collision or expected contact with an environment may occur on the entire surface of the robot arm（e.g. forearm, elbow, upper arm, shoulder）producing interactive forces. Moreover, teleoperated robot in rescue and some other applications has to interact with human being in various cooperative tasks. In these fields, human-robot interaction represents a crucial factor for a robot design and imposes very strict requirements on its behavior and control in order to ensure safe interaction with environment and effectiveness while target task execution.

To realize the safe physical contact of entire robot arm structure with human and to guarantee the collision avoidance, our primary idea is concentrated on the design of a whole-sensitive robot arm（see Fig. 1）by using distributed torque sensors in each joint（Fig. 2 and Fig. 3）. When contact with environment occurs, manipulator automatically adjusts its dynamic parameters（stiffness and damping）according to the measured external torque and time derivative of torque.

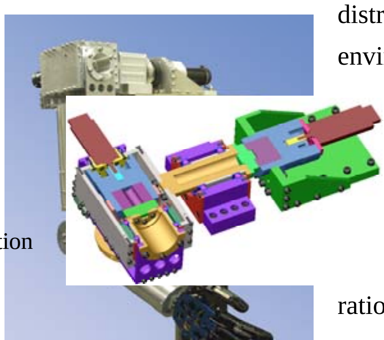

Fig. 1 Developed

Fig. 2 Cross-section

Fig. 3 Implemented optical torque sensor

The straightforward solution of torque measurement is integration of commercially available compact force/torque sensors in each robot arm joint. The main issues here are the cost of the sensors, their low signal-to-noise ratio, and difficult installation procedure. In order to facilitate the realization of local impedance control in each arm joint, we developed new optical torque sensors having high reliability, high accuracy（even in electrically-noisy environment）, easy mounting procedure, and low price. In the thesis, we describe the techniques of the torque measurement; discuss their advantages and shortcomings; and point out the motivations behind using an optical approach.

The novelty of our method is employment of the ultra-small size photointerrupter（PI）RPI-121 as sensitive element to measure the relative motion of sensor components. The linear section of the transferring characteristic corresponding approximately to 0.2 mm can be used for detection of the relative displacement of the object. The dimensions of the PI（RPI-121: 3.6 mm × 2.6 mm × 3.3 mm）and its weight of 0.05 g allow realization of compact design. Furthermore, PI also has small influence from the electromagnetic field and stray light. We developed several sensor prototypes with cross-shaped, hub-spoke-shaped, ring-shaped, and semi-circular-shaped flexure on the basis of FEM analysis results in order to find the optimal solution. Because of sufficient stiffness, high natural frequency, and small influence of bending moment and axial force on the sensor accuracy, the spoke-shaped spring was chosen as deflecting part of the optical torque sensor.

Finally, the optical torque sensors with spoke-hub structure directly connected to the driving shafts of the harmonic transmissions were developed. To eliminate hysteresis, the sensors were manufactured from one piece of steel using wire electrical discharge machining cutting. Spring members of the optical torque sensors were made from AISI 4135 steel with tensile yield strength, providing thus high loading capacity. The test rig for calibration of the optical sensor was developed. Loading torque was created by means of attachment of reference weights to the lever arm. Calibration results for the torque sensor attached to the elbow joint are presented in the thesis. Based on the comparison of the developed sensors with commercially available analogues, we concluded that our sensors are better solution for torque measurement in robot arm joints.

In addition to contact force, torque sensor continuously measures the gravity load. To extract the value of the contact force from sensor signal, we elaborated the gravity compensation algorithm. Using gravity compensation algorithm we can easily determine the occurrence of contact of robot arm with environment.

The anthropomorphic manipulator having 4-DOF arm and 8-DOF hand enabling safe interaction with environment wherever contact occurs on the arm surface was developed. From the safety point of view, to minimize injures in case of collision, most of the robot arm parts were manufactured from aluminium alloys to obtain as much lightweight structure as possible. The robot links were designed in round shape to reduce impact force. The distribution of the arm joints replicates the human arm structure in order to make it easy to operate using kinesthetic sensation during teleoperation. Each joint is equipped with optical torque sensor directly connected to the output shaft of Harmonic Drive. The sizes and appearance of the arm were chosen so that the sense of incongruity during interaction with human is avoided. To protect the sensor against influence of bending moment and axial force, the simple supported loaded shaft configuration was implemented using two sets of bearings.

To achieve skillful human-like behavior, the robot has to be able to change its dynamic characteristics depending on time-varying interaction forces. The most efficient method of controlling the interaction between a manipulator and an environment is impedance control. To improve the service task effectiveness, we decided to implement position-based impedance control. In this case, compliant trajectory generated by the impedance controller is tracking by the PD control loop. Thus, inherent dynamics of the robot does not affect the performance of target impedance model. To verify the theory and to evaluate the feasibility and performance of the proposed impedance controller, the experiments were conducted with newly developed teleoperated robot arm. The experimental results showed the successful realization of the joint impedance control. While contacting with human, the robot arm generates compliant soft motion according to the sensed force. The larger force applied to the robot arm, the more compliant trajectory is generated by impedance control. The conventionally impedance-controlled robot can provide contacting task only at the tip of the end-effector with predetermined dynamics. By contrast, our approach provides delicate continuous safe interaction of all surface of the arm with environment.

In order to provide soft and natural human-robot interaction, the intelligent variable impedance control was devised. The research on impedance characteristics of human arm shows that, while pushing or pulling the object naturally, human arm stiffness and damping behavior can be approximated by exponential curves. The first essential peculiarity of the proposed control method is that we introduce the exponential functional dependency between sensed force and stiffness to impart the human-like damping and stiffness behavior to the robot arm interacting with environment. The second main feature originates from the fundamental conflict in impedance selection with regard to current working conditions. We consider the threshold of external disturbance torque value to distinct the service task（with high stiffness and damping of joints） from human following motion tasks requiring low stiffness. This value can be chosen depending on the force necessary to accomplish the service task. We assigned the specific magnitude of threshold to each joint of robot arm. When sensed value of the torque is larger then threshold level, robot recognizes this condition as human following motion mode, and adjusts its dynamics parameters（stiffness and damping） in the same way as humans in order to provide smooth natural interaction. The desired damping is adjusted to prevent force responses from being too sluggish while changing stiffness values, and to ensure contact stability. Proposed control algorithm comprehensively distinguishes and successively processes the service tasks（torques under threshold level） and co-operative human following tasks（torques above threshold level）. The experimental results showed that the variable impedance control provides softer trajectory to accomplish human following motion than the impedance control with constant coefficients.

While working in human daily environment, robot has to recognize the collision condition, and its control system should be able to quickly and smoothly guide manipulator to avoid excessively large impact force. We realized the robust impact control inspired by human reflex system. When an unexpected collision is detected, the impact control algorithm provides the pre-programmed reflex action of the robot arm. After accomplishment of a safe and smooth collision, the control system is returned to the original mode aimed at distinguishing the service and co-operating tasks. While analyzing the results of collision experiments, we came to conclusion that the large contact forces, mainly used as criterion of collision, do not indicate the impact, while the time derivative of force value does. In the developed impact control system, the value of the time derivative of torque exceeding the assigned threshold is interpreted as the indicator of collision state. To realize reflexive human-like behavior, the stiffness of the impedance model of the robot arm on the first stage of contact transient is reduced drastically according to the exponential law. In the second stage of contact transient, while time derivative of torque is negative, the high damping value reducing arm inertia effect is defined, taking into account the dynamic stability ensuring. The experiment was conducted to validate the theoretical approach. As impact was recognized（time derivative of torque became larger than threshold value）, the stiffness and damping were decreasing drastically. Thus, safe behavior of the robot arm while impact transient was successfully achieved.

To conclude, the newly developed anthropomorphic manipulator is capable to safely interact with environment wherever contact occurs on the arm surface. The developed control algorithm can recognize and process the service tasks, co-operative human following tasks, and impact state without involving the operator actions. Therefore, achieved compliant interaction with environment results in considerable increase in human-robot interaction safety.