論文の内容の要旨

論文題目　　Study on Electro-Hydrostatic Actuators for
Force Sensitive Robot Systems
(力感応ロボットシステムのための電気静油圧アクチュエータの研究)

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Robot actuators play crucial roles in robots as its processors and software. Time to time, different type of actuator was tested, some of them successful and some of them are not. Looking back at the history of humanoid robots, there were similar trends. In early years, due to its advantage in power to weight ratio, fluid power actuators were used. Those actuators had external power source as pumps and compressors, which restricted the mobility of the robots. Due to the improvement of battery and magnetic materials, about last 10 years were era of servo motors and gear drives.

Servo motors have many advanced features; wide control bandwidth, light weight, and simple power circuitry. However, they still have many unsolved problems. Many of them reside on the gear transmission. Two big examples of them are force sensitivity and backdrivability. These issues are intertwined: loss of backdrivability results in loss of force information, thus force sensitivity. The system without force sensitivity can produce large force when it comes into contact with unknown obstacle. This is undesirable character for the robots to operate in our daily life.

To overcome such drawback, traditionally two approaches were taken; software and hardware. Examples of software approaches are force/position hybrid control [Raibert and Craig 1981] and impedance control [Hogan 1985]. Hardware approach is mainly series elastic actuation [Pratt and Williamson 1995]. However, impedance control has issue in control bandwidth that it has restriction in reproducing low impedance in high frequency range. In contrary, series elastic actuation has issue of low controllability in high frequency range due to mechanical natural resonance frequency. Recently there are approach of enhancing high frequency behavior of impedance control by increasing servo loop frequency and improving manipulator performance [Hirzinger et al. 2002]. There is an approach called distributed macro-mini actuation, that improves behavior of series elastic actuation in higher frequency range by mechanically distributing actuator compliance and weight [Zinn et al. 2002].

Hydraulic actuators have force sensitivity that it can measure output torque by measuring the hydraulic pressure, but traditional hydraulic drives are mostly used for power applications that do not require backdrivability, such as construction machines. EHAs (Electro-Hydrostatic Actuators) are a class of hydraulic actuator that controls the motion of hydraulic motor by controlling hydraulic pump, not the valve.

Since no valves are used, under some condition, the system becomes backdrivable. Since this type of hydraulic drives use motor as torque generator, so in some sense, they are replacement technology of gear transmissions. EHAs have advantage of servo motor actuation as simple power supply, and advantage of hydraulic drive such as force sensitivity and high durability and reliability. In addition, they have backdrivability.

In this thesis, the dynamic characteristics of the EHA were modeled in symmetric way. This formulation enables the analytical treatment of backdrivability. Using this formulation, condition on backdrivability, torque sensing theory, and control strategies are derived. Based on this theory, design methodology on backdrivable EHAs are presented. As extreme examples in the actuator size, miniature and large capacity EHAs were developed and applied to humanoid robot systems. Miniature EHA is more difficult to obtain total backdrivability (explained in chapter 2). Large scale EHA is more strict in performance evaluation during design phase.

Miniature EHA was applied to anthropomorphic robot hand. The hand is equipped with 20 joints with 16 DOF. Detail of the hand design in discussed in chapter 3. From the evaluations, issues on designed EHA arose. One was mechanical issue as leakage and cavitation, the other was system weight. To make a fundamental improvement, change in actuator material and operating pressure was necessary. First part in chapter 4 explains the improvement of vane motor and second half of chapter 4 explains hand system design. Large capacity EHA was applied to humanoid robot's knee joint. Design methodology of the EHA with inverse dynamics computation is explained in chapter 5. Chapters until chapter 5 form the scalable design methodology of backdrivable EHA.

Chapter 6 is the extension of EHA design methodology to the wearable robotics, namely lower extremity exoskeleton. The technique to decide specification of the robot that interfaces and interacts with human in quantitative way is discussed together with mechanics and hydraulics design.