論文の内容の要旨

論文題目　Development of Small and Light-Weight Electro-Hydrostatic Actuators and their Integration to the Whole-Body Drive System of Humanoid Robots
（小型軽量電気静油圧駆動系の開発とそれを用いたヒューマノイドロボット全身駆動系の実現）

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For the next generation of robots which try to move from the well-defined environments such as factories or labs to an unstructured environment closer to or extremely far from our lives, the backdrivability of the actuators has been an important requirement. While actuation by the servovalve controlled hydraulic systems or the combination of electric motors and high reduction ratio gear train have high performance on the response and torque density, their backdrivability is limited by the large friction in the force transmission process. For the intrinsically backdrivable actuators, which are the direct driven systems, pneumatic actuators, and series elastic actuators, it is still difficult to simultaneously realize both of the high torque density and control bandwidth. Actuation by Electro-Hydrostatic Actuators(EHA) has the possibility to solve the problem since its high backdrivability is realized by the low friction property of the transmission and not relying on the series elasticity. However, while its property of high backdrivability and energy efficiency was studied in the previous works, both of the torque density and response were not deeply discussed and the performance presented in the existing works was not advantageous compared to other types of backdrivable actuators. Its integration into an articulated robot was also not accomplished. In this dissertation, we establish a generalized hardware design, control, and system integration framework to realize a hydrostatically driven humanoid robot and evaluate its whole body control and locomotion performance.

In most case the hardware development of an actuator and its controller design are conducted separately. The fundamental improvement of the control performance, however, is achieved by the hardware improvement. The effect of a hardware modification on the control performance, on the other hand, should also be evaluated from the control perspective in advance. Therefore, we first derive a simplified linear model of EHA from the fluid dynamical and material mechanical principle in chapter 2. This approximation was possible with the assumption that the flow inside the pump is

laminar, the pump is a rotary one, and all values such as pump torque/velocity and fluid pressure/flow-rate are expressed in the equivalent value seen from the actuator. From the model, it is made clear that the actuator output force is affected by both the motor torque and the actuator output velocity, as the second order lag system. The output velocity of the actuator is a third order lag system from the motor torque input.

The currently available miniature backdrivable actuators have only limited torque density, therefore, they are difficult to be adopted in legged robots, which need to support their own bodyweight with the active torque. In chapter 3, we propose a systematic mechanical design approach to improve it. It is made clear that the miniaturization of the system size has the effect of increasing internal leakage and therefore impair the output force. To encounter it, the key is to attain a small internal gap and high fluid viscosity, while maximizing the effective pressure receiving surface in the limited overall weight or size. To reduce the gap inside the pump, we experimentally show that the optimization of bearing arrangement or type, and reinforcement of the pump casing are effective. To reduce the gap in the actuator, we present the design of a light-weight cylinder and a vane motor with reinforced casing rigidity. To maintain the fluid viscosity, we propose a direct pump casing water cooling approach. Lastly, we show the integrated tie rod cluster cylinder to maximize the effective pressure receiving surface.

To maintain or even improve the backdrivability of the torque-enhanced EHA, in chapter 4 we present the approach from both the mechanical design and measurement perspective. To minimize the viscous friction, double rod cylinders are more suitable since the closed circuit volume is invariant. We proposed a double rod cylinder design with the beam structure to minimize the piston rod diameter, therefore minimize the friction due to the piston rod oil seal. We also presented an active friction compensation of the rod oil seal with the merged information of the pressure sensor and strain gauge by a complementary filter.

While the possibility of fast response is a key property of EHA compared with other elastic actuators, little attention was paid to it in the existing works. In chapter 5, from both the hardware and control perspective, we present the enhancement of the fast response property of EHA, proving their superiority over elastic actuators in the sense of the closed-loop control bandwidth. From the hardware side, to reduce the series elasticity between the pump and the load, we filled the dead volume in the chamber and selected the high bulk-modulus fluid since the fluid compressibility is a large source of elasticity. We also applied the reinforcement on the force transmission structure, with which a clear improvement in the response was seen. From the control side, we introduced the current-pressure-position triple-loop feedback controller. The idea is to distribute the controller in three layers with different framerate processing device and control faster behavior in a faster device, instead of treating the large number of internal parameters as a single state vector. The pressure control bandwidth in the fixed piston configuration was 100 Hz, which is a higher value compared with those by the existing works on EHA and series elastic actuators.

With the actuators developed above, in chapter 6, we present our approach to integrate the complex EHA system into a whole-body humanoid, in each of the hardware, electronics and software level. The hydrostatically driven humanoid “Hydra” has 40 joints driven by 24 double rod linear cylinders with the beam structure and eight casing-reinforced vane motor, powered by 36 water cooled trochoid pump in addition to the two five-DoF cluster EHAs for the hand. The full version robot has 130 kg weight and is 180 cm tall. Due to its high joint control bandwidth, Hydra can be controlled to be stiff enough for a position control based locomotion. With the Capture Point Tracking control, Hydra could conduct a walking motion with 0.2 m stride, 30 mm step height and 1 second stepping time. With its high joint backdrivability, Hydra can be compliantly controlled to prevent a disturbance force applied on a distal link to be transferred to other links. Simultaneously realizing both of the moderate stiffness of the COM and compliant motion in the nullspace by the resolved viscoelasticity controller, it was experimentally confirmed that Hydra could conduct a stable balancing and locomotion while absorbing external force by the nullspace motion.