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題目(和文)	ロボット関節のための瞬間的に切り替わる負荷感応型変速機
Title(English)	Load-sensitive Rapidly-switchable Transmission for Robot Joints
著者(和文)	PHLERNJAI Maroay
Author(English)	Maroay Phlernjai
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種別(和文)	論文要旨
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論 文 要 旨

THESIS SUMMARY

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申請学位（専攻分野）： 博士 （Engineering）
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学生氏名： PHLERNJAI MAROAY
Student's Name

指導教員（主）： 教授 小俣 透
Academic Advisor(main)

指導教員（副）： 准教授 高山 俊男
Academic Advisor(sub)

要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

This study proposes a load-sensitive transmission concept that can rapidly switch its reduction ratio with a high-compliance during the switch. This thesis is organized into five chapters.

Chapter 1 [Introduction] describes the need for high output speed and torque in robot joints. Advantages of variable transmissions that can rapidly change their reduction ratio are discussed to improve joint performance. Also, the importance of joint compliance and its use for safety in human and robot interaction, especially during high-speed motion of the joint is discussed. This research objective is set to develop a concept of singularly actuated transmission that can rapidly switch its reduction ratio load-sensitively. The transmission needs to be compact enough to be used in robot hand and arm joints. Passive compliance of the joint for safety during high-speed motion is also included in the research objective.

Chapter 2 [Load-sensitive Rapidly-switchable Transmission (LRT)] discusses serial and parallel actuation schemes that were used in previous studies on rapidly-switchable transmissions with two motors. The discussion shows that the parallel actuation and a clutch mechanism are required to get a switchable reduction with high compliance. With the addition of a differential mechanism and a load-sensitive clutch, the proposed transmission can be driven by a single actuator. The transmission enables robot joints to move in high-speed during low load. Once the load exceeds a preset threshold, the load-sensitive clutch moves and connects the high reduction path to the output, producing high output torque. The passive compliance for safety is achieved by adjusting the clutch spacing, allowing the output joint to be back-drivable until the clutch fully engages. Mathematical models of the effective reduction ratio, output torque, and stiffness are introduced. The design trade-off between the high compliance range and the reduction switching speed is addressed together with other design considerations of the proposed LRT.

Chapter 3 [Cable-driven LRT] first explains that cable actuation is widely used with many existing robot hands. The chapter introduces a cable-driven LRT concept that can be applied to such cable-driven robot hands. The analogy between a movable pulley system and the differential unit of the LRT concept is described. The novel idea of using a split pulley as both the differential and load-sensitive clutch is examined. However, a limitation exists as the split pulley damages the cable after several uses. Therefore, an improved concept using a rack-gear clutch is proposed. During low load, the cable directly drives the output joint without reduction, producing high output speed. Once the load exceeds the preset threshold, the movable pulleys move the rack clutch into engagement and produce high output force. A 2-DOF underactuated robot finger and LRT prototype were developed for pinching operation. The LRT unit, including the frame, is 80 mm × 50 mm × 22 mm in size and weighs 156 g. The unit is compact enough to fit in a human palm. The reduction ratio increases 14.5 times when the clutch is engaged. With a 50 mm long robot finger, the finger/LRT pair produces a no-load joint speed of 372 deg/s and maximum fingertip force of 24.6 N. The clutch spacing was designed to allow the finger to be backdrivable for its whole flexing range. The time used to switch the reduction ratio was 0.25 s. The finger/LRT exhibits high performance when compared to an existing cable-driven robot finger with a fixed reduction ratio.

Chapter 4 [Gear-driven LRT] discusses a limitation of the rack clutch, which occurs when the joint has to exert high torque over a large stroke. The lengthy space claim makes the rack clutch not suitable for use in some applications such as elbow and knee joints. Therefore, this chapter proposes a novel gear-clutch mechanism using a rotary motion of a D-cut gear which is potentially more compact than the linear motion of the rack clutch. As jamming between the engaging gears may occur, a link mechanism is introduced, allowing the teeth to tilt away from the jamming point and properly mesh when the clutch is engaged. The clutch design criteria on jamming and meshing are analyzed and experimentally verified. An elbow joint prototype with LRT and the proposed gear clutch was developed. The LRT unit is 77 mm × 95 mm × 58.5 mm and weighs 650 g. The unit is approximately the same size as a human elbow joint. The reduction ratio increases 22.1 times after the clutch engages. The joint prototype can produce a no-load speed of 230 deg/s with low reduction and a maximum torque of 4 Nm with high reduction. With the clutch spacing designed to allow 90 deg safety back-drivable range, the time used to switch the reduction ratio was 0.45 s. The joint prototype exhibits high performance when compared to existing robot elbow joints.

Chapter 5 [Research conclusion and future work] concludes the study and performances of the developed prototypes. The practicality of the proposed LRT concept, considerations for possible applications, and future works are also discussed in this chapter.