Development of Variable Stiffness Joint Module to Achieve Safety Collision of Robot Arm

Yeon Taek Oh
Department of Robot System Engineering, Tongmyong Univversity
428 Sinseon-ro, Nam-gu, Busan, Korea
yeonoh@tu.ac.kr

Abstract **— The robots are interacting with humans in various aspects. Safety issues are increased in various robot applications. Many robot arms have been introduced for safety. The passive compliance methods have faster and high reliability than active methods. In this paper, a new safety mechanism based on passive compliance is proposed. The variable stiffness joint employed spring and roller is economical safety joint for robot arm. Also the mechanism works only when the robot arm exerts contact force much more than the human pain tolerance. In order to evaluate the performance of the safety joint, the variable stiffness joint is mounted on robot arm and verified by HIC experiment. It is shown that safety arm using the variable stiffness joint provides higher performance and safe than these using other passive compliance mechanism or active methods.**

Keyword-Variable stiffness joint, Passive compliance, Head injury criteria (HIC), Collision test, Safe mechanism

I. INTRODUCTION

As robot technology is rapidly developing, robots are expected to share activity space with human. Such sharing may lead to unintended collision and accident. Because of the possibility, preparing method to prevent accident has become an important matter [1]. Achieving a stable physical interaction between human and robot is critical both in practicality and human perspective.

Developing process a very safe robot to solve the issue is complicated as it requires close cooperation among all engineers including system design to hardware/software design. Building the way to test safety is also perceived vital [2].

The robot manipulator can be given two methods of passive and active compliance to assure its safety and performance at the same time. The active method controls external force or impact actively with control algorithm by sensing the feedback signal from multiple sensors (force/torque sensor) attached to the robot manipulator. However, the passive method mechanically realizes safety with equipment in the form of variable stiffness or passive compliance based on physical factors such as a spring or damper react to outside force.

Hippocrate, a French surgical robot, achieved safety by controlling its arm with the information from the force/torque sensor attached to its end effector. DLR, the German aerospace center, developed the technology that controls the robot arm for the force coming from outside by sensing the force and torque of the robot finger joints in real time [3].

The active control method needs expensive sensors and control algorithm by feedback signal and its reaction speed relies solely on sensitivity of the sensors and actuator, imposing a limit to achieve safety. It is also pointed out the robot manufacturing cost is relatively high. For example, using a sensor with low resolution can complicate instant reaction to a fast external impact. Noise added to the sensor can also cause malfunctioning.

Hence, variable stiffness mechanism or passive compliance that use a physical mechanical device have been studied as they can react to external force quickly and provide easy controllability. Some university studies applied passive compliance shoulder that consists of rotating spring and MR damper to the arm joint of research service robot [4]. The study on force transmission characteristics based on transmission angle of 4-bar linkage as well as the study to achieve the passive compliance mechanism with design of joints where the spring and electronic damper are laid out in circle have been performed [5]. Also Variable stiffness joint was studied using ball transfer and kinematic coupling [6].

The existing safe arms listed above applied damper in common. Although it reduces vibration of the joint system, it makes the joint bulky and needs application of a complex active control algorithm. Also, its size, weight and complicated controllability make it hard to apply to commercialized robots. The development of a new variable stiffness device that can promise low cost and simple structure is demanded.

The study designed the safe joint mechanism by using the spring and roller and checked performance before manufacturing the prototype to develop a small and light variable stiffness safe joint. It also conducted collision test against the variable stiffness safe joint and shows the result of its shock absorption performance.

II. STRUCTURE OF VARIABLE STIFFNESS JOINT

The developed variable stiffness joint in this study was shown rigid characteristics under normal operation, and designed flexible characteristics against unexpected impact. Figure 1 shows a horizontal variable stiffness joint the study developed. The variable stiffness joint comprises outer race, inner race, spring and roller. When the variable stiffness joint attached to the robot arm is operated normally, the roller is inserted into outer race groove. As the roller fixed to the inner race interrupts the relative rotation of the inner race to the outer one, both races operate as one under normal operation.

When there is unexpected impact to the robot arm while in motion, the roller breaks away from the groove and moves along the outer race profile. That is, if torque occurs stronger than the force of the spring pushing the roller, the impact is detected and the roller gets out of the outer race groove. Then, resilient spring with removed impact sends the roller back to the groove automatically.

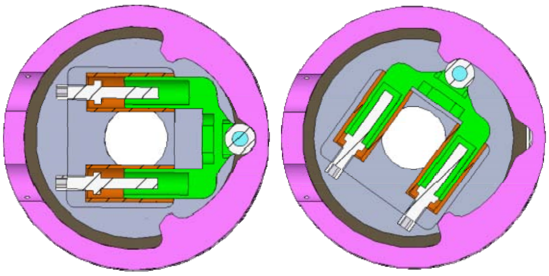


Fig. 1 Variable stiffness joint (horizontal type)

Figure 2 is shown the vertical variable stiffness joint, which also has the same operation mechanism with the horizontal joint. The horizontal structure has the roller in the groove placed at the inside diameter of the outer race while the vertical one has the roller in the groove placed outside of the outer race. Attaching these two different structures to the robot arm can ensure its flexibility regardless of where unexpected external impacts come from.

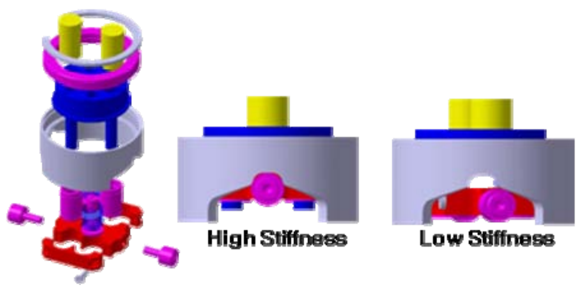


Fig. 2 Variable stiffness joint (vertical type)

Operation range of the variable stiffness joint was designed considering operation range of the robot arm joint. Adjusted length of the outer race profile of the variable stiffness joint can be applied application to wide operation range of the robot arm joint. Separation torque of the variable stiffness joint was made adjustable with the spring. Table 1 illustrates specification of the variable stiffness joint. It weighs about 410 g, with adjustable separation torque of 14 Nm, adjustable stiffness range of 12~2,000 Nm/rad and operation range of -60~+60 deg.

Table 1 Specification of Variable stiffness joint

Spec.	Result
Weight	410g
Size	70 × 70 × 25 mm
Separation toque	14Nm (Adjustable)
Adjustable stiffness range	14~2000Nm/rad (0.06~8.0kN/m)

Figure 3 shows the manufactured prototypes of the horizontal and vertical variable stiffness joint. Besides, operability and feasibility test for the manufactured variable stiffness joint module was conducted using torque wrench. Figure 4 tests the operation of the horizontal variable stiffness joint module. The operability test using torque wrench was successful and found operable within the designed torque range.

(Horizontal) (Vertical)

Fig. 3 Prototype variable stiffness joint

Fig. 4 Test of variable stiffness joint

III. SAFE ARM APPLYING VARIABLE STIFFNESS JOINT

The study determined the robot arm driving modeling through CAE by using the first version of the safe arm that the lab had as Figure 5 shows.

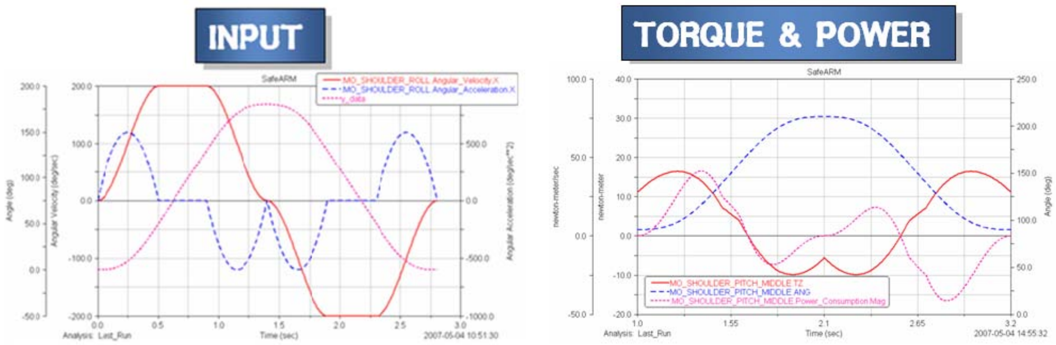


Fig. 5 Determination driving modeling using CAE

CAE simulation helped decide the robot shoulder pitch specification at Max. Load torque 16.4 N-m, Cont. load torque 10.9 N-m and Max. Power 41.4 W. Based on the simulation result, the study modified the design so that the variable stiffness joint can be connected to the first safe arm owned by the lab.

The modified design is shown at Figure 6, based upon which the safe arm final version was created. The final version weighed 4.8Kg, with each link length at 250 mm, maximum joint speed at 200deg/s and 7 DOF. Figure 7 and 8 show that vertical and horizontal variable stiffness joints are attached to the safe arm shoulder, respectively.

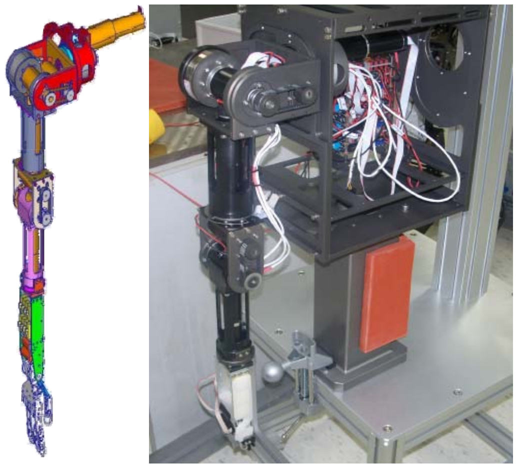


Fig. 6 Safe Arm having variable stiffness joint

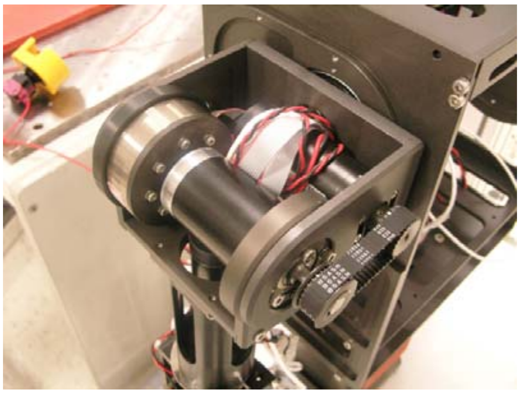


Fig. 7 Variable stiffness joint in shoulder roll

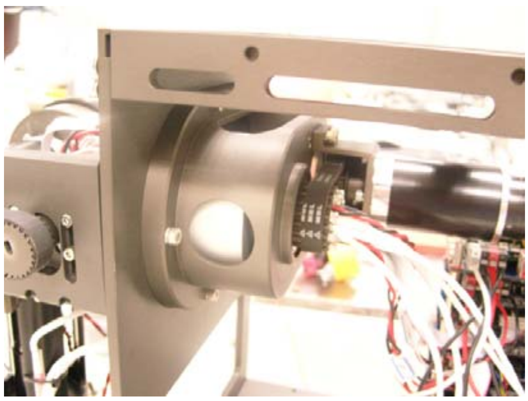


Fig. 8 Variable stiffness joint in shoulder pitch

IV. COLLISION TEST OF SAFE ARM

Safety test was performed using the safe arm. Standard for robot arm safety test has yet to be well established. Thus, this research conducted Head Injury Criteria (HIC) safety test that represents the degree of impact on human in case of car collision.

HIC, quantitative data of impact that can be given to human by car collision, can be obtained measuring acceleration of a driver’s head from the colliding moment until the end. In general, HIC of 100 or lower is considered not deadly while 10 or lower is known rarely injured. HIC can be expressed as the equation below [7].

$$HIC = \left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a dt \right)^{2.5} \left(t_2 - t_1 \right)$$

HIC can be classified into two categories. One is the structural HIC, for which collision test was performed under assumption that the system was not recognized to perceive collision. On the other hand, collision test was done for the control HIC under the condition that the system perceives collision and takes a proper take action against it. This research applied the structural HIC method that suits the robot’s feature for the test.

Dummy head used for collision test wore three-axis acceleration sensor to measure acceleration of the dummy head at the colliding moment. Figure 9 shows the experiment equipment. At the initial collision test, the dummy head was attached by the linear guide, resulting in irregular impact data. As Figure 9 shows, the dummy head was changed to the pendulum type that minimized the impact coming from its motion confinement to secure an accurate result. The test condition is listed in Table 2.

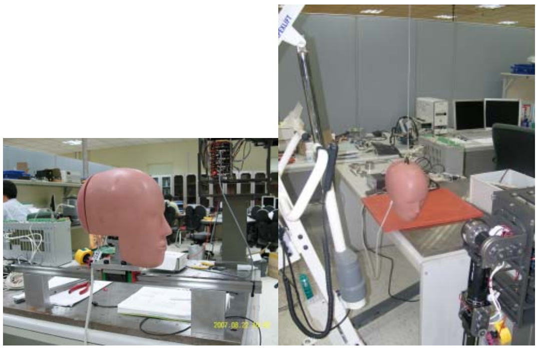


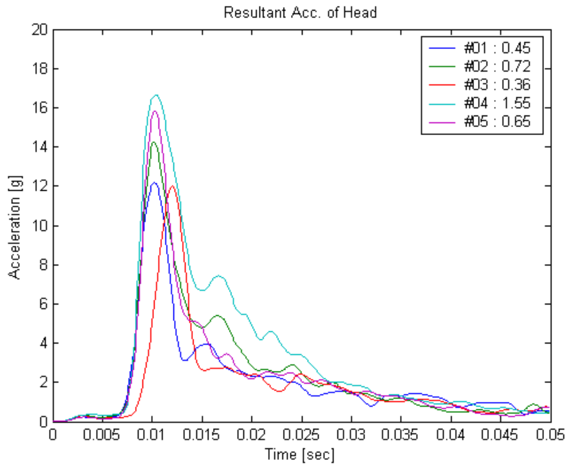
Fig. 9 Experimental equipment (Dummy Head)

Table 2 Test Condition

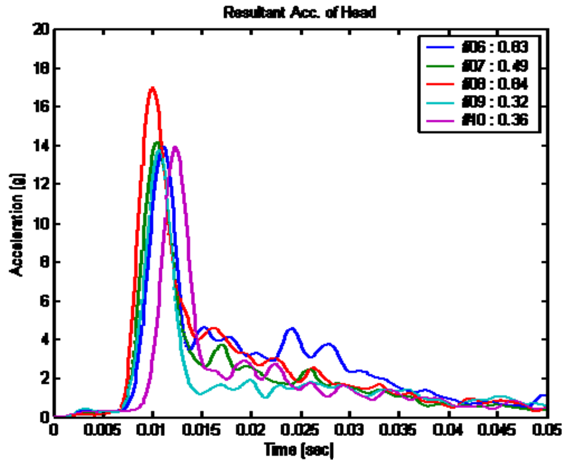
Test Condition	Setting Value
Weight Dummy	4.9 kg
Impact Speed	1.83 m/s
Dummy fixture	Pendulum Type
Impact Radius of Arm	500 mm

Fig. 10 Impact Test with Safe arm having variable stiffness joint

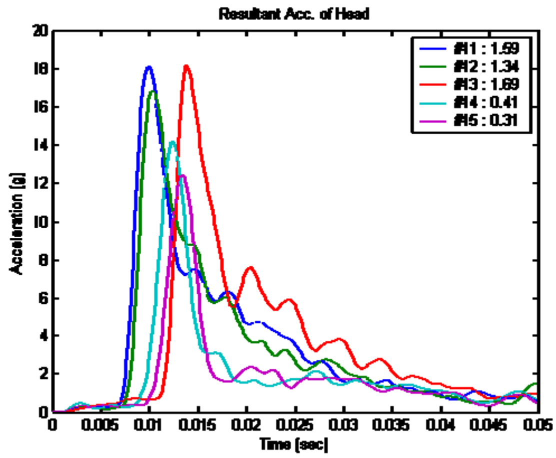
The data measured acceleration with the sensor attached to the head after the safe arm collide dummy head under the test condition of Table 2. The test was done 20 times to secure data reliability.



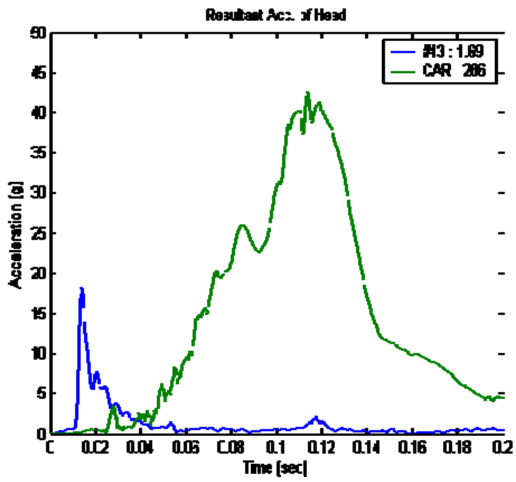
(a)



(b)



(c)



(d)

Fig. 11 Test result of acceleration

Figure 11 display the acceleration result from the collision test. The acceleration suddenly increased the moment the safe arm struck the dummy head. Referentially the green line of Figure 11 (d) is of HIC 286, one of the best vehicles that received five stars from driving safety analysis. The variable stiffness joint that safe arm was applied to demonstrate a high level of safety even when it was compared with the best safety rated cars.

Table 3 HIC value

Test No	HIC	Test No	HIC	Test No	HIC	Test No	HIC
1	0.45	6	0.83	11	1.59	16	0.72
2	0.72	7	0.49	12	1.34	17	0.25
3	0.36	8	0.84	13	1.69	18	1.57
4	1.55	9	0.32	14	0.41	19	0.45
5	0.65	10	0.36	15	0.31	20	1.19

As Figure 11 and 12 show, HIC was calculated with the measured acceleration data and the result of HIC show at 0.45~1.55. Typically, HIC < 10 is the approximate value to almost absolute safety, implying that HIC lower than 10 can be regarded almost not injured.

The following figure shows the level of HIC and injuries. HIC 250 suggests minor injuries. It can be said HIC < 10 is close to absolute safety, and injury level of 0.45~1.55 from the test result implies almost no change to injury.

AIS	Injuries	HIC
0	None	-
1	Minor : Light brain injuries with headache, vertigo, no loss of consciousness, light cervical injuries, whiplash, abrasion, contusion	< 250
2	Moderate : Concussion with or without skull fracture, less than 15 minutes unconsciousness, corneal tiny cracks, detachment of retina, face or nose fracture without shifting	< 750
3	Serious : Concussion with or without skull fracture, more than 15 minutes unconsciousness without severe neurological damages, closed and shifted or impressed skull fracture without unconsciousness or other injury indications in skull, loss of vision, shifted and/or open face bone fracture with antral or orbital implications, cervical fracture without damage of spinal cord	<1250
4	Severe : Closed and shifted or impressed skull fracture with severe neurological injuries	<1750
5	Critical : Concussion with or without Skull fracture with more than 12 hours unconsciousness with hemorrhage in skull and/or critical neurological indications	<2500
6	death, partly or fully damage of brainstem or upper part of cervical due to pressure or disruption, Fracture and/or wrench of upper part of cervical with injuries of spinal cord	>2500

Fig. 12 Correlation between HIC and AIS[8]

It was found from the test that the variable stiffness joint ensures normal operation and effectively reduce the impulsive force from collision, keeping the robot and human safe.

V. Conclusion

This research suggested the variable stiffness joint module to achieve safety collision of the safe arm. The suggested variable stiffness joint prevents human from being injured by sudden impact and damage to the joint itself by quickly blocking torque given to the robot arm joint against it. The study applied the spring and roller to address the problem of the variable stiffness device in previous research. It also performed a highly efficient design that simplified the operation mechanism. This design enabled the robot to sense external impact and disturbance without an expensive sensor, allowing easy safety control. As the variable stiffness joint module operates manually in particular, reaction was fast, malfunctioning risk was nearly zero and safety reliability was very high.

The research also made the prototype of the variable stiffness joint module that was easily applicable to any system, improved a platform to evaluate performance of the designed variable stiffness joint module and evaluated HIC by installing the completed variable stiffness joint module to the improved platform. The test result of HIC was found to be 0.45~1.55. The developed variable stiffness joint module is expected to replace complex control algorithm and all equipment needed for joint, lighten the robot and facilitate easy manufacturing.

This variable stiffness joint module technology will surely have a great deal of spillover effects as a unit technology instead of simply being a robot with its application to environment-adaptive assembly robots at unmanned factories that future industries require and supporting robots that will closely cooperate with workers.

References

[1] Yamada, Y., Suita, K., K. Ikeda, H. and Sugimoto, N., 1996, “A failure-to-safety robot system for human-robot coexistence”, Robotics and Autonomous System, Vol. 18, No.1-2, pp. 283-291,
[2] Santis, A. D., Siciliano, B., Luca, A. D. and Bicchic, A., 2008, “An atlas of physical human-robot interaction “, Mechanism and Machine Thery, Vol. 43, No. 3, pp. 253-270
[3] Liu, H., Meuse, P., Seitz, N., Willberg, B., Hiirzinger, G., Jin, M. H., Liu, Y. W., Wei, R. and Xie, Z. W., 2007 , “The modular multisensory DLR-HIT-Hand”, Mechanism and Machine Theory, Vol. 42, No. 5, pp. 612-625
[4] Kang, S., and Kim, M., 2002, “Safe arm design for service robot”, Proc. of international conference on control, automation and system”, pp. 88~95
[5] Park, J. J., Kim, B. S. and song, J. B.,2004, “Shock absorbing safe mechanism based on transmission angle of a 4-bar linkage”, Proc. of KSPE autumn conference, pp.94-99
[6] Jeong, J. J. and Chang, S. H.,2009, “Design of a variable-stiffness type safety joint for service robot”, Journal of the Korean society for precision engineering, Vol. 26, No. 5, pp. 128-134
[7] http://www.intmath.com/applications-integration/hic-part2.php
[8] M. Shojaati, 2003, “Correlation between injury risk and impact severity index AIS”, 3rd Swiss Transport Research Conference, March 19-21
[9] Ikuta, K and nokata, M, 2003, “General evaluation method of safety for human-care robots”, The international journal of Robotics Research, Vol.22, No 5, pp 281-293
[10] Jung-Jun Park, Byeong-Sang Kim and Jae-Bok Song, 2005, “Shock absorbing safe mechanism based on transmission angle of a 4-bar linkage”, ," Trans. Korean Soc. Mech. Eng. A (or) B, Vol. 29, No. 11, pp. 1534~1541