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FUSION CLUTCH: A BI-STABLE LATCHING MECHANISM FOR HUMAN-SAFE ROBOTS

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ABSTRACT

As the role of robotics continues to expand beyond highly structured manufacturing applications to other domains, including medical and service applications, safe operation in the presence of people is becoming increasingly important. Many existing safety systems rely on fragile and sophisticated joint torque sensors and control models that greatly add to the expense and complexity of the robot system. This paper presents the "Fusion Clutch", a mechanical system for decoupling high-impedance actuators from the output, such as a robot arm, in the event of a collision. In its nominal configuration, the clutch couples the transmission to the output via a spring-loaded bi-stable mechanism that is able to quickly decouple the two in the event of a collision with very low activation force. After the actuator is disengaged, the clutch also applies a brake to the output that prevents it from falling under the force of gravity but allows the operator to still reposition it. This prevents a robot arm from pinning the operator after the mechanism had been activated. Experimental results validate the small force required to activate the mechanism, along with a substantial decrease in force impulse during impact.

INTRODUCTION

According to the Occupational Health and Safety Administration (OSHA), there is on average 1 death per year due to accidental robot impact or crushing [1]. Many other serious injuries also occur, including head contusions, broken bones, or other trauma. Due to the danger associated with industrial robots, they are typically enclosed in workcells. Humans can only enter if the robot is powered down or if the operator is carrying an emergency stop button. Although many safety precautions are taken to prevent injuries by ensuring that the robot does not operate when a human is in the vicinity, the operator must still be vigilant and ensure that all safety interlocks are in place before proceeding to use the system.

In order to increase the safety of industrial robots, allow cooperative human-robot interaction, and expand the applications of robots further, researchers in both industry and academia have sought new solutions to increase safety and performance. Decreasing the weight of the links and placing a soft coating on the robot will, by default lower the impact force [2]. Yet, this alone does not make robots safe enough for direct interaction with humans, as mass/inertia can only be decreased a small amount within practical limitations. Other straightforward solutions generally involve reducing the stiffness and/or speed of the system, which introduces at the cost of precision and performance.

Controls researchers and robot manufactures have implemented "active" safety systems usually involving sensing the applied force/torque and varying applied motor currents [2][3][4]. While these solutions can result in high-performing and functional robots, they still suffer from delayed response, increased cost and control complexity, and decreased system

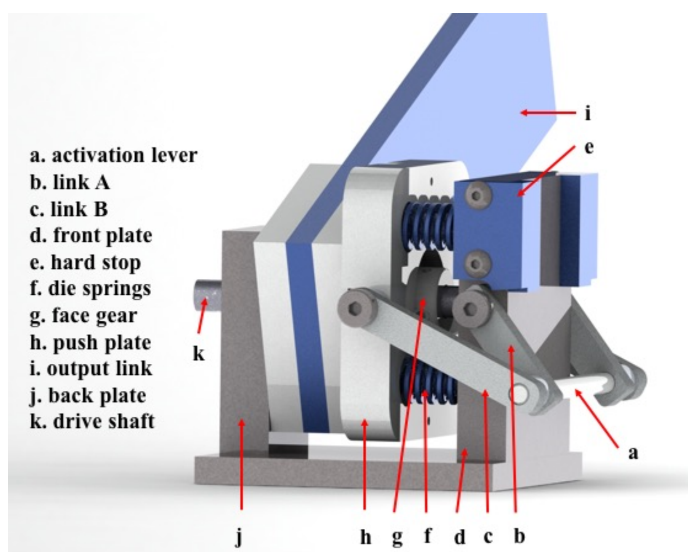

Figure 1. Annotated CAD rendering of the Fusion Clutch mechanism without the motor.

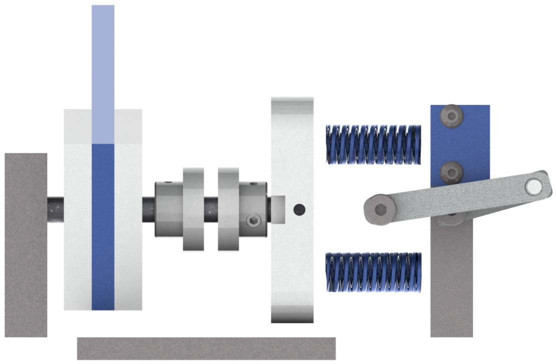

Figure 2. Exploded view of Fusion Clutch. The face gear on the left is securely attached to the output link, and the face gear on the right is coupled with the drive shaft.

reliability due to the fragile sensors. Other approaches combine mechanical design and controls in close concert. These include the Distributed Macro Mini (DM2) actuation approach [5], which uses one larger actuation unit responsible for low frequency actuation near the base and a smaller motor for high frequencies at the joint to reduce the arm inertia and thus reduce the impact force [6]. Other hybrid approaches include using a series elastic actuators (SEAs) [5] or variable stiffness actuators (VSAs) [7][8], which can decouple the inertia of the actuator from that of the link when an impact occurs [1].

Various mechanical clutches, brakes, and locking/unlocking mechanisms have also been proposed to improve robot safety [9]. Clutches are generally used in robots to protect the end effectors [10], increase positioning accuracy [11] and limit torque [12] [13] [14]. The clutches specifically for end effectors are used to protect the tool rather than the operator. They only allow for detection of force at the end of the robot arm rather than anywhere along it. Torque limiters placed in series with the actuator at each joint, slip or fail when a certain joint torque is exceeded. The deflection of a torque limiter disconnects the actuator and output similar to a SEA. Detecting the slip of the clutch can also be used to send the motor currents to zero. The thresholds for each joint are set such that the end effector force does not exceed a preset value.

In this paper, we propose a new type of safety clutching mechanism, named Fusion Clutch that combines a number of design features in a compact package. The main concept involves decoupling the input (actuator and transmission) from the output (e.g. robot arm) to reduce the overall inertia, while simultaneously dissipating energy using a brake. The brake allows for passive movement of the output to avoid pinning an operator. The mechanism is activated via a bi-stable mechanism that requires minimal force from an external collision detection device. Before activation, the actuator is rigidly connected to the output link. This avoids some of the problems associated with SEAs and VSAs, such as oscillation around a goal position and large settling times [6].

In the remainder of this paper, we first describe the design of the Fusion Clutch and present a hardware prototype. We then describe the experimental methods used to measure theactivation force and peak impact force. Finally, we analyze the results and discuss how the device may be improved.

DEVICE DESIGN

The Fusion Clutch (Fig. 1) seeks to address some of the issues with current human safe robots by combining features from various locks and brakes to create an exclusively mechanical device that prevents high force impacts and continued application of force after collision. The clutch is designed to receive mechanical input from a collision detection mechanism (to be developed later) that encapsulates the output link. To minimize the force applied to the human during a collision, the input force required to activate the clutch must be small. After the clutch has been activated, the output link is decoupled from the motor, but it is important that the arm does not swing freely since this could further injure the person. It is also undesirable for the arm to be rigidly locked in place after collision since it could be pinning a person down while continuing to apply large loads. Therefore, the clutch must feature a semi-locking mechanism that supports the arm weight, but also allows the human to move the arm out of the way. The mechanism must accommodate various motors sizes so that it can be used on different robot arms. Furthermore, Fusion Clutch must be robust and compact for future integration into a fully functioning robotic system.

During normal operation, the motor output is rigidly coupled to the output link. A face gear embedded in the output link is engaged with a face gear that is coupled to the motor shaft (Fig. 2). A spring between the back plate and one face gear engages the face gears. The push plate is retracted by a set of links during normal operation. The links resist forces from the two compressed die springs by pressing up against the hard stops. The hard stops determine the angle of the linkage and the amount of compression of the die springs.

The activation lever is positioned near the point of unstable equilibrium that lies 180 degrees away from the mechanism, in a horizontal configuration. The mechanism is at an unstable equilibrium configuration when the lever itself, the attachment point of the short link (link A) to the front plate, and the attachment point of the long link (link B) to the push plate are aligned. The lever configuration is stable during normal operation because it rests a few degrees from 180 and is constrained by the hard stops.

Past the unstable equilibrium point, the lever does not restrict the motion of the push plate and it can translate until it contacts the output link and pushes it against the back plate. The activation force is minimal since the level is held only a few degrees away from the singularity. In practice, however, there is a small discrepancy between the positions of the theoretical and the actual singularity points due to the slight, vertical displacement of the push plate. Therefore, the lever is positioned 5 degrees above horizontal during the normal operation in order to prevent false activation of the switch. Figure 3 shows the two stable configurations of the mechanism, one during normal operation and one after the mechanism has been activated.

After a collision is detected, the lever is triggered across the singularity point, releasing the push plate to pin the output link against the opposite back plate. This contact can be seen in Fig. 3. In this configuration, the friction at the interface between the output link and the back plate (μ_{static} = 1.05 – 1.35; ($\mu_{sliding}$ = 1.4) aids in decelerating the output link after it is

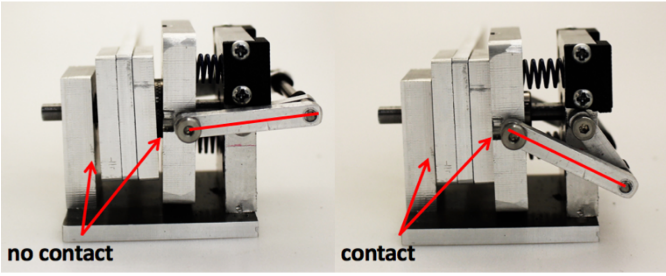

Figure 3. During normal operation (left) the lever is above horizontal, or zero degrees, and after collision (right) the lever is below. After collision the output link is pressed against the back plate and restricts movement.

disengaged from the motor. The force due to friction is proportional to the loading of the die springs, which can be modified by changing the distance between the front plate and the back plate. The friction between the aluminum-aluminum interface could also be modified by changing the material. Currently the friction has been adjusted so that it is sufficient to hold the output link in position but can be easily overcome by a human operator.

The mechanism was machined out of aluminum, and weighs 400g including the output link. The hard stops were 3D-printed to allow for different angle settings. Currently, a Maxon 24V brushed DC motor (Part no. #310007) has been used for testing, but the mechanism can be easily integrated with other actuators.

EXPERIMENTAL METHODS

Force Input Threshold

The clutch must be easily activated by the external mechanism in the event of a collision. Therefore, the position of the lever during normal operation must be close to the singularity to ensure small activation forces, but not result in false disengagements. The force required to push the lever across the singularity point, and disengage the two face gears is measured using a universal testing machine (Instron model 5542). The lever was placed in the upright position before the singularity and the force required to push the lever through the singularity and trip the mechanism was recorded as shown in Fig. 4. The lever was pressed down at 1 mm/min and the output link was not bearing a load. This procedure was repeated for initial starting angles from 9 to 6 by changing the position of the hard stops on the device.

Force Output

The force output experiment seeks to demonstrate the difference in peak force during an impact when the mechanism has been activated versus when it has not. Peak impact force is a function of the system's effective inertia, interface stiffness, and velocity of the output link [15]. When the mechanism is activated, the output link movement is decoupled from the motor, preventing its inertia and kinetic energy from contributing to the impact event or crushing force from that point in the arm trajectory and forward. Instead, only the inertia and angular acceleration of the arm contributes to the impact. Furthermore, due the friction between the back plate and the output link, the output link decelerates before impact, further reducing the impact impulse.

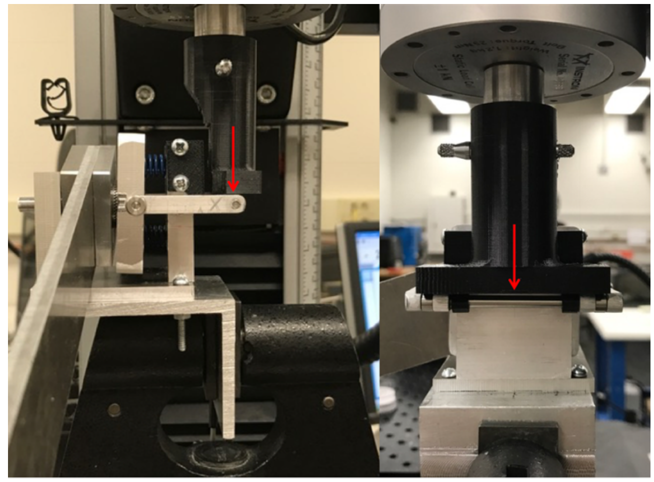
Figure 4. Force input testing. The arrow shows direction the Instron applies force on the activation lever.

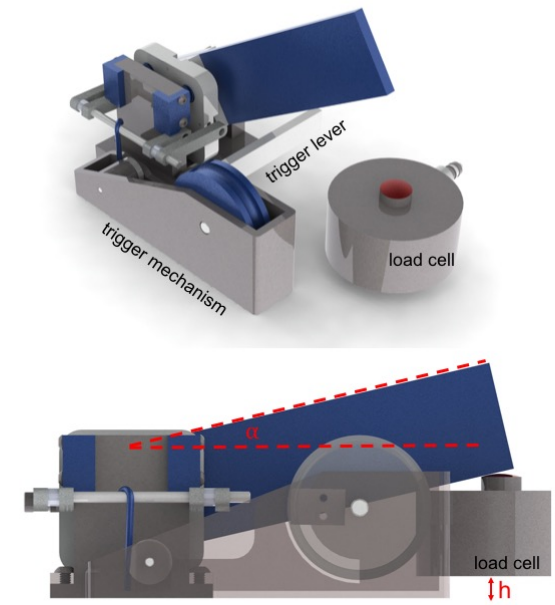

Figure 5. CAD rendering of the force output experimental setup. The angle, α, above horizontal is the angle of the output link at impact.

The collision detection mechanism that will activate the clutch will surround the output link so that when an impact occurs, this shell will make contact first and activate the clutch before the center link impacts the person. To simulate this detection mechanism, a lever was placed such that the output link makes contact with it before impacting the load cell (Fig. 5). The lever is attached to a pulley that pulls a tendon to activate the mechanism. As discussed previously, the force required to activate the mechanism is small especially in comparison to the overall impact force. Since that the mechanism can be triggered prior to the main impact, it will reduce the effective inertia, link velocity, and peak force associated with the impact.

To determine the reduction in peak force the mechanism provides, the impact force is measured with and without the mechanism being triggered. The link is initialized in a vertical

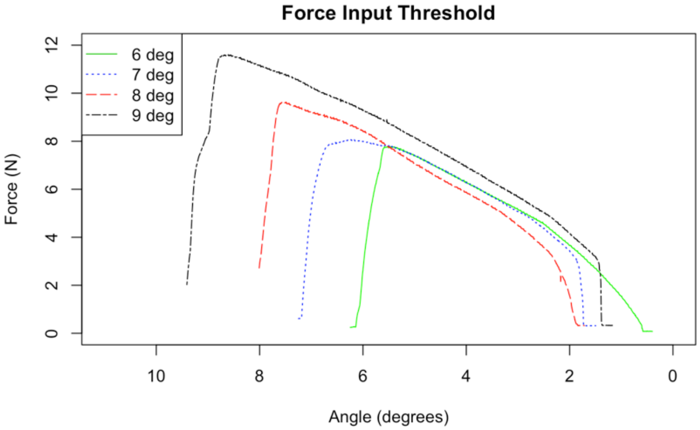

Figure 6. The graph displays force required to activate the mechanism versus angle of the lever. Zero degrees corresponds to the horizontal position or singularity point of the activation lever.

orientation and 5V is applied to the motor. The link is then released and strikes a load cell (Transducer Techniques MLP-200) that records the impact event at 10 kHz. The time between when the detection mechanism is tripped and the impact occurs will translate into the distance between the collision detection mechanism and robot arm within it. To simulate this, the height of the load cell is varied so that impact occurs at different times after the mechanism has been triggered. This is expressed in terms of α, the angle of the output link during impact (Fig. 7). This distance is critical as it must be large enough to ensure that the motor disengages before impact to reduce the effective inertia and therefore impact force. The distance must also be large enough to ensure the output link velocity decreases a sufficient amount before impact to further aid in decreasing impact force. However, the distance cannot be unreasonably large as it will translate to the overall radius of the robot arm and its collision detection sleeve. The experiment is conducted with and without the activating mechanism in order to compare the two cases.

RESULTS

Force Input Threshold

Figure 6 shows the profile of the load required to change the lever angle and activate the mechanism from various starting positions. Overall, the required activation force is sufficiently low (<8 N for a 6-degree angle) and could be easily tripped by a secondary collision detection mechanism. Zero degrees corresponds to horizontal and the other values correspond to an angle above horizontal before the singularity point. The angle of deflection was calculated based on the geometry of the system and the extension data from the Instron. From left to right on the graph, the force increases as the Instron begins to press on the activation lever. Due to compliance in the assembly, there is a small displacement during this initial loading process; ideally these would be vertical lines. Once the force overcomes the initial compliance, the lever begins to move toward horizontal and the force required to move the lever decreases linearly until around 2 degrees. At small angles close to the singularity, the activation force is very small causing the lever to swing past singularity; otherwise the linear trend would have passed close to 0 degrees

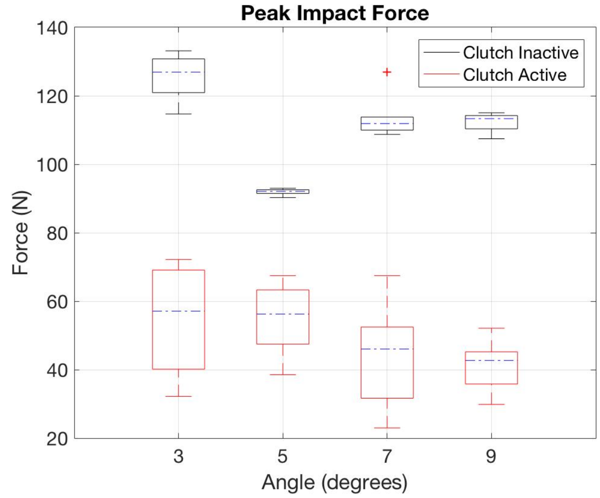

Figure 7. The graph displays peak impact force when the output link impacts a load cell at different link angles.

at zero activation force. The separate lines correspond to the different hard stops angles used to set the lever's initial position. Note that the initial loading value varies across trials, which is solely due to different initial pre-loading values.

Force Output

The Fusion Clutch significantly reduces the peak impact force during a collision. The reduction of the effective inertia by decoupling the motor and slight decrease in velocity after the mechanism has been activated is responsible for this decrease. Figure 7 shows this force for different angles of the output link when it strikes the load cell. The red and black boxplots show the peak force exerted on the load cell when the mechanism is active and inactive, respectively. Outliers are shown in red. The angle of the output link (α in Fig. 5) upon impact is varied and the height of the trigger mechanism remains constant. Again, this is analogous to the radius of the collision detection sleeve on a robot arm.

The range of angles is based on the limits of motion of the activation method used for the experimental setup. When the output link is at ten degrees above horizontal, the mechanism is triggered unreliably. Therefore, nine degrees is used as an upper bound to ensure that the mechanism triggers every trial. The upper bound corresponds to the shortest time between triggering of the mechanism and impact on the load cell whereas the lower bound at three degrees relates to the longest time between trigger and impact.

The peak force values are reported as an indication of the clutch's ability to reduce the impact force as seen by the large difference in the two data sets. The force is also dependent on the distance traveled between the trigger and load cell, yet those results are highly dependent on the experiment's provisional collision detection mechanism. This preliminary mechanism uses a tendon that can stretch and slip, thereby changing the activation position. This variability contributes to the larger interquartile range in the data for which the Fusion Clutch is active. When the mechanism is not active, the impact force is not dependent on the trigger timing, resulting in a smaller variance.

When the mechanism is inactive and the output link approaches horizontal from its starting position, it continues to accelerate. The velocity and therefore, impact force are larger for smaller angles. This trend is evident in the dataset where the mechanism is inactive. When the mechanism is active, it is expected that the force is smaller for smaller angles because the brake has a longer period of time to decelerate the arm. The data contradicts this idea, which is likely due to the lack of reliability associated with tendon use, e.g. stretching in the tendon, in the trigger mechanism. Consequently, a more robust experimental setup in which the trigger location rather than the angle of impact is modified is necessary to better characterize the mechanism's force attenuation capabilities.

CONCLUSIONS AND FUTURE WORK

The Fusion Clutch has many advantages in comparison to other locking devices for human safety applications. Because it is purely mechanical, the Fusion Clutch does not require any external energy input other than the force supplied from the collision itself in all of the following cases: during normal operation, when the lever is activated upon collision, and when the arm is semi-locked into place. This feature differentiates it from the electromagnetic brakes, which consumes electricity during operation.

The use of a bistable mechanism with low activation energy also ensures that low activation force is needed to trigger the mechanism. Therefore, the output link can be made to be very sensitive to collision with humans. However, to prevent it from accidentally activating, the switch can be positioned at numerous positions above the actual singularity to increase the threshold for the trigger force. This adjustability adds to the Fusion Clutch's adaptability to various applications.

The friction brake applied to the output link after collision enables the user to move the link while still constraining motion. Furthermore, the Fusion Clutch is very compact due to the minimal travel distance of the push plate in order to make contact with the output link and secure it against the back plate.

However, these advantages are not without costs. One of the Fusion Clutch's limitations is that the force balance between the opposing springs is sensitive to the distance between the plates given the spring lengths and constants, and thus requires a precise positioning of the mechanism components. Due to the small size and the triangular shape of the face gear teeth, the gears can slip if not engaged with a proper amount of force. This force is supplied by a compressed spring, around the axle. The spring presses against the back plate and the back of one face gear. However, to hold the pulley away from the gear when disengaged, the die springs must apply significantly greater force to the push plate to compress the opposing spring further. This force balance between the springs in series is critical to proper device operation and was determined empirically in this work. In our current design, there is no mechanism to automatically reset the switch position once it is released. This feature, along with the collision detection mechanism, will be developed in our future work.

Further improvements can be made to the design and evaluation of Fusion Clutch as well. The semi-locking mechanism must be made more resistant to wear and tear and have a higher coefficient of friction to better decelerate the output link after the mechanism is triggered. Integrating a rubber layer between the output link interface and the back plate may be sufficient. Finally, the collision detection half of the human-safety mechanism remains to be designed. Once the collision detection method is in place, testing the difference in force output with and without the overall mechanism will reveal more about the clutches utility. As of now the testing reflects the performance of both the mechanism itself and the simplistic trigger method, that is not part of the mechanism.

The Fusion Clutch successfully decouples the motor inertia from the output link inertia before a collision and only requires a small input force to do so. While the full implementation of the mechanism with collision detection is not yet realized, the preliminary results in terms of activation force and peak impact force are promising.

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REFERENCES

[1] United States Department of Labor. Occupational Safety and Health Administration. Web. 14 Dec. 2016.

[2] S. Tadele, T. J. a De Vries, and S. Stramigioli, "The Safety of Domestic Robots," *IEEE Robot. Autom. Mag. Robot. au*, no. september, 2014.

[3] P. A. Lasota, G. F. Rossano, and J. A. Shah, "Toward safe close-proximity human-robot interaction with standard industrial robots," *2014 IEEE Int. Conf. Autom. Sci. Eng.*, pp. 339–344, 2014.

[4] G. Hirzinger, a. Albu-Schaffer, M. Hahnle, I. Schaefer, and N. Sporer, "On a new generation of torque controlled light-weight robots," *Proc. 2001 ICRA. IEEE Int. Conf. Robot. Autom. (Cat. No.01CH37164)*, vol. 4, pp. 3356–3363, 2001.

[5] M. Zinn, B. Roth, O. Khatib, and J. K. Salisbury, "A New Actuation Approach for Human Friendly Robot Design," *Int. J. Rob. Res.*, vol. 23, no. 4–5, pp. 379–398, 2004.

[6] A. De Santis, B. Siciliano, A. De Luca, and A. Bicchi, "An atlas of physical human-robot interaction," *Mech. Mach. Theory*, vol. 43, no. 3, pp. 253–270, 2008.

[7] M. Grebenstein, A. Albu-Schäffer, T. Bahls, M. Chalon, O. Eiberger, W. Friedl, R. Gruber, S. Haddadin, U. Hagn, R. Haslinger, H. Höppner, S. Jörg, M. Nickl, A. Nothhelfer, F. Petit, J. Reill, N. Seitz, T. Wimböck, S. Wolf, T. Wüsthoff, and G. Hirzinger, "The DLR hand arm system," *Proc. - IEEE Int. Conf. Robot. Autom.*, pp. 3175–3182, 2011.

[8] G. Grioli, R. Schiavi, S. Sen, and a Bicchi, "VSA-II : Variable Stiffness Actuation for Safe and Performing Robots Interacting with Humans," *IEEE Conf. Robot. Autom.*, pp. 2171–2176, 2008.

[9] B. M. Plooij, G. Mathijssen, P. Cherelle, D. Lefeber, and B. Vanderborght, "Lock Your Robot," *IEEE Robot. Autom. Mag.*, 2015.

[10] http://www.ati-

ia.com/products/collision_sensor/robot_
collision_sensor.aspx

[11] K. P. Tan, W. a. Bullough, R. Stanway, N. Sims, a. R. Johnson, and R. C. Tozer, “A Simple One Dimensional Robot Joint Based on the ER Linear Reversing Mechanism,” *J. Intell. Mater. Syst. Struct.*, vol. 13, no. 7–8, pp. 533–537, 2002.

[12] T. Saito and H. Ikeda, “Development of Normally Closed Type of Magnetorheological Clutch and its Application to Safe Torque Control System of Human-Collaborative Robot,” *J. Intell. Mater. Syst. Struct.*, vol. 18, no. 12, pp. 1181–1185, 2007.

[13] M. Lauzier and C. Gosselin, " Series clutch actuators for safe physical human-robot interaction," Proceedings -*IEEE International Conference on Robotics and Automation*, 2011.

[14] W. Lee, J. Choi and S. Kang, " Spring-Clutch: A Safe Torque Limiter Based on a Spring and CAM Mechanism with the Ability to Reinitialize its Position," *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2009.

[15] M. Zinn. “A new actuation approach for human friendly robotic manipulation.” PhD thesis, Stanford University, Stanford, CA, 2005.