SAFETY CONTROL MECHANISM FOR CONSTRUCTION WORKING ROBOTS WORKING IN COLLABORATION WITH HUMAN WORKERS

Hiroyasu Ikeda*, Noboru Sugimoto*, Tsuyoshi Saito And Masanori Onishi*****

**National Institute of Industrial Safety, Tokyo, JAPAN (ikeda@anken.go.jp)*
***Tokyo Engineering University, Tokyo, JAPAN*
****Shinko Electric Co. Ltd., Mie, JAPAN*

Abstract: The principle of safe working based on the safe confirmation is clarified in order to realize such a robot for construction work that can share the working space with human workers. For this purpose, a monitoring system and an intrinsically safe actuator using sensor are prepared for the constructing robot, and a safety control which can allow safe contact with human workers by integrating such system and actuator is realized.

Keywords: Safety Control, Human-robot Collaboration, Ultrasonic Radar Sensor, Bumper Switch, Fail-safe, Intrinsically Safety, Actuator, MR Fluid

1. INTRODUCTION

Recently, it has been strongly required in the construction work, where automation and labor saving have been remarkably promoted, to introduce robots. In actuality, however, the purpose of the robotization in the building and construction field is either of the automation of work completely isolating human attendance or the simple mechanization only of carrying out force support for muscle work, such as furnishing work for buildings. In the future, for example, by introducing robots into the construction work as an application to fill the interval of this two types of robotization, a system in which robots cooperate with human workers are considered. Social needs to develop such a robot that can collaborate with humans are emphasized not only in the construction field but also in many other fields.

In the cooperative work between robot and humans, however, there are problems with the safety. The safe work cannot be realized only by the measures based on the conventional safety standards prohibiting the workers to come close to any dangerous condition. The operational field of robots in current use is extremely limited due to the safety problems. In order to share the cooperative working space with human workers and further expand such space, the robot system itself must have means to ensure the safety of human workers.

On the assumption that the robot is introduced on condition that it shares the working space with human workers, the safety conditions that such robot should satisfy are clarified in this study. Then, assuming that the robot may give impacts or oppressions to human bodies, the safety conditions are considered from the viewpoint of the acceptance ability of the human bodies, and the fundamental safety control mechanism of the robot that can realize such safe conditions is examined. Specifically, such a monitoring system by means of sensor and an intrinsic safety system for actuator that can perform the intended work while ensuring the safety of human workers are proposed for the robot arm having an automatic transfer mechanism.

2. SAFETY REQUIREMENTS OF THE ROBOT COLLABORATING WITH HUMAN WORKERS

"Safety" is understood as a contrary concept of "danger." That is, the danger is recognized in advance, and then a concept of the safety is produced in the process of anticipating and avoiding the danger. When the machine produces an output, the resultant situation is either accident or non-accident. When the accident (danger) is anticipated, this accident can be avoided by stopping the mechanical output. Although the resultant situation is alternative, either "danger" or "non-danger," there is a third situation between these two resultant situations (uncertainty). By judging this third situation as "danger," the anticipated accident can be surely prevented. This third situation is expressed as an uncertain situation in the logic variable $A(t) \in \{ \quad 10$, when the uncertain situation is expressed as 1 and the non-uncertain situation is expressed as 0. As the dangerous situation including the uncertain situation is expressed in the logic variable $H_c(t) \in \{1,0\}$, the following equation is established:

$$H_c(t) = A(t) \vee H(t) \tag{1}$$

Where, the symbol $\vee$ is the logical sum, and $H(t) \in \{1,0\}$ is the apparently dangerous situation. When the denial of the true danger $H(t)$ is $\overline{H(t)}$, and $\overline{H_c(t)}$ is the anticipated safety, the following logical relation should be established from Eq. (1):

$$\overline{H(t)} \geq \overline{H_c(t)} \tag{2}$$

Eq. (2) indicates the principle of safety confirmation that the safety should not be anticipated as $\overline{H_c(t)}=1$ in the unsafe situation.

When $\overline{H_c(t)}$ of Eq. (2) is the sensor output, the sensor is not permitted to report the safety at least in the safe situation as the mechanical output $U(t) \in \{1,0\}$ accompanied by the danger is produced based on the safety confirmation as follows:

$$\overline{H_c(t)} \geq U(t) \tag{3}$$

Eq. (3) is called the principle of safe working [1]. As the accident occurs at least when $U(t)=1$, the worst anticipation is that the sensor becomes out of order and a mechanical output erroneously produces. Contrarily, a stop of the mechanical output is permitted. Eq. (3) means that the sensor reporting the safety should be fail-safe.

Although it is not the very hazard, the mechanical output of Eq. (3) has the characteristics that it may cause an accident through the hazard. The safety secured by preventing the contact between machines and humans by using a sensor is generally called "functional safety". This is the safety required in the coexistence of robots and humans in working. This reduces the opportunity of the mechanical output of robots to be directed to humans, and requires the judgment whether humans can accept the reduced risk.

On the other hand, in the collaboration, the robot requires the safe contact with the human. If a mechanism for restricting the contact force and speed is provided as a safety means and such mechanism becomes out of order, it may cause an accident. However, if such mechanism is so constructed that the contact does not cause any risk and thereby the hazard is eliminated, the dangerous situation is not produced and no accident is caused. That is, the realization of the safe man-machine collaboration requires the guarantee of "safety" in a case where the mechanical output from the robot is directed to the human worker. The hazard elimination to that effect is called "intrinsic safety".

Originally, robots work with a safe distance from humans. Even if the robot contacts the human, it is not permitted at least to give excessive impacts or oppressions over the limit to the human body. The robot, which is the subject of this study, aims at both "functional safety" and "intrinsic safety".

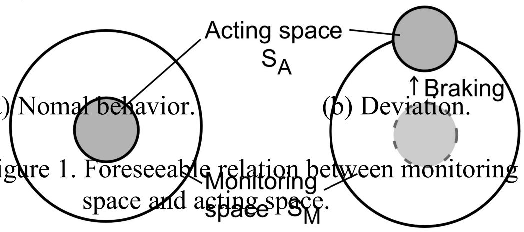
3. SPACE MONITORING SYSTEM BASED ON FUNCTIONAL SAFETY

3.1 Normality confirmation of space.

When the mechanical output of Eq. (3) is speed, it is assumed that the robot moves while monitoring ahead. If the environment in which the robot moves is not completely provided, space into which the robot is not permitted to come, such as a slope or a groove, is produced. If the robot erroneously invades into such space, a heavy damage may be caused. Of course, the robot is placed under restrictions when there is a human in its moving environment. Therefore, it is also anticipated that if the robot invades into the space where there is a human, an accident may be caused. Monitoring ahead by the movement of the robot is called the confirmation of space normality. This concept includes the confirmation of space safety.

When $U(t)$ of Eq. (3) is replaced by the speed $u(t) \in \{1,0\}$, and the speed output is the logical value 1 and no speed (at a stop) is the logical value 0, $\overline{H_c(t)}$ is presumed to indicate the permission of invasion into the space as a result of the confirmation of space normality. The speed output is executed based on the relation $\overline{H_c(t)} \geq u(t)$.

Then, as shown in Fig. 1 (a), when the space where the robot behaves is S_A and this space is determined as a acting space, the monitoring space S_M is provided around the behavior space, and the behavior within the acting space is executed according to the judgment of space normality $\overline{H_c(t)}$, the mutual relation of the space is established as $S_A \subseteq S_M$. When it is supposed that there is a human ahead of the robot in its way, the robot behavior is executed ($u(t)=1$) according to the judgment of normality ($\overline{H_c(t)}=1$) based on the monitoring of the space S_M by the sensor until it comes closer to the human. Generally, as soon as the human is detected in the monitoring space, the sensor output becomes $\overline{H_c(t)}=0$ but the robot cannot stop on the spot. For this reason, as shown in Fig. 1 (b), the acting space deviates from the monitoring space, and the robot may collide with the human. Therefore, the robot



(a) Nomal behavior. (b) Deviation.

Figure 1. Foreseeable relation between monitoring space and acting space.

should have such a braking means that disables the establishment of the space relation $S_A \supset S_M$.

3.2 Hierarchization of space monitoring sensor.

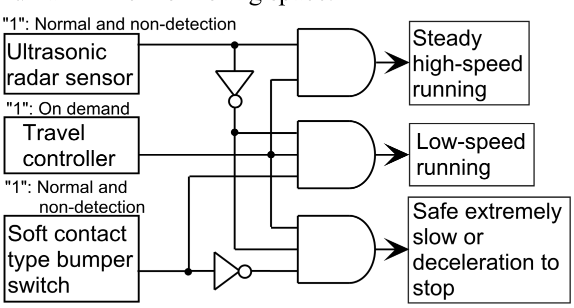
According to the basic stopping pattern of the mobile robot in travel, as generally seen in an automatic guided vehicle (AGV), the robot decelerates from the steady high-speed running to low-speed running and then completely stops. In the AGV, if it suddenly stops, the robot may topple down or its load may be inertially thrown ahead. Therefore, the deceleration from high speed to low speed is controlled by the output signal from a non-contact type sensor, and stopping from low speed is controlled by the output signal from the contact type sensor. In the mobile robot, too, the running speed switching should be controlled from the positional relation between the robot and circumferential human. In the robot for construction work, the speed switching is controlled by the ultrasonic radar sensor and the soft contact type bumper switch.

When the monitoring space by means of the ultrasonic radar sensor is S_{M1} and the monitoring space by means of the soft contact type bumper switch is S_{M2} , their relation to the acting space S_A can be express by the following equation:

$$S_A \subseteq S_{M2} \subseteq S_{M1} \qquad (4)$$

If the normality of the monitoring spaces S_{M1} and S_{M2} as well as the normality of these sensor switches are confirmed, the robot behavior is executed. Therefore, unlike the AVG, in the monitoring space S_{M1} , if the robot has a intrinsically safe actuator as described later and contacts the human, the human permits the behavior of the robot at such a low speed that the human can accept, while in the monitoring space S_{M2} . The human also permits the behavior of the robot in contact with the human at an extremely slow speed (including the deceleration process to the stop). However, the allowable speed of the robot when the robot contacts the human should be separately evaluated and studied.

When these sensor switches are hierarchized for use, the speed switching control of the robot can be realized as a form of travel control interlock as shown in Fig. 2. However, the sensor, the switch and the controller are not permitted to make a mistake toward the danger side, that is, they are not permitted to recognize and report as "absence" when there is a human in the monitoring space.



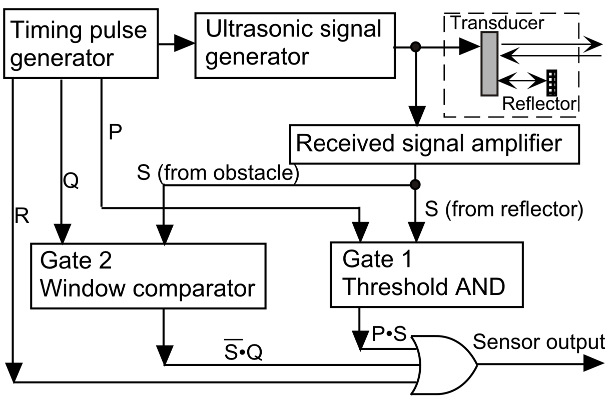
3.3 Construction of space monitoring system.

The ultrasonic radar sensor is widely used, but if it becomes out of order, it may fail to detect the obstacle due to its construction of reflection type. The ultrasonic sensor provided with the dynamic self-diagnosis function [2] can judge the monitoring space to be normal and outputs the ON signal only when the sensor is normal and there is no obstacle in the monitoring space. This sensor also can judge the

Figure 2. Interlock configuration for travel control.

monitoring space to be not normal and outputs the OFF signal when the sensor is out of order or there is an obstacle in the monitoring space. If the sensor outputs the OFF signal, the travel speed of the robot is immediately switched to low speed. As its characteristic, this sensor periodically irradiates ultrasonic wave to the self-diagnosis reflection plate within the transducer and judges of its normality by referring to the ultrasonic wave reflected by the self-diagnosis plate. Fig. 3 shows the schematic construction of the ultrasonic sensor that tests the level of the received signal and performs its AND operation using the fail-safe gate elements [3] 1 and 2.

On the other hand, the soft contact type bumper switch is also required the same output characteristic of the above ultrasonic sensor. The general bumper switch cannot satisfy this requirement because of its mechanical contact. Then, a fail-safe bumper switch is newly constituted using the flexible strain sensor [4]. This sensor with a coating of electro-conductive material on the silicone rubber surface as shown in Fig. 4 has a characteristic that the resistance value varies according to its expansion. A unit stuck this sensor to the inside of a ring-shaped leaf spring is stacked up to form a multi-layer bumper with a buffer



function. As the sensor within the unit is always pre-tensioned, the normality of the sensor itself can be confirmed by monitoring the resistance value of this

Figure 3. Schematic construction of ultrasonic radar sensor.

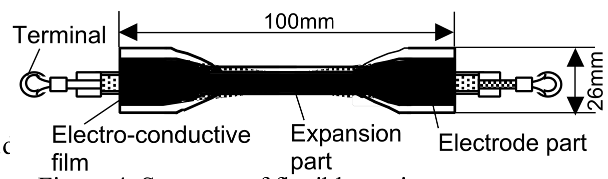


Figure 4. Structure of flexible strain sensor.

pre-tension.

Fig. 5 shows the result of the sudden brake on a vehicle when the vehicle with a prototype bumper traveled and outputted OFF signal upon contacting a human. From this figure, it is understood that the resistance value of the sensor increased when the bumper contacted the human, and that when the resistance value exceeded the preset threshold, the tested output was turned OFF and the brake was applied.

Basically, to control the switching of the travel speed according to the signal from the ultrasonic sensor and bumper switch, all what is required is the interlock function using the fail-safe AND gate [3] as shown in Fig. 3. In practical use, however, a speed monitoring mechanism is also required to check whether or not the robot is traveling exactly at the switched speed. As it is difficult to make this function fail-safe, the functional improvement of the safety level of the speed monitoring mechanism was tried by introducing the diversity redundant controller [5].

This controller has already been used for the control or the like of dangerous press machines. In this controller, three different processors execute a job of the same content on the operating system. Only when the result from each processor is the same, this controller makes output to the outside. With its powerful self-diagnosis function and diversification for preventing common failure as much as possible, this controller has the highest safety level conceivable at present.

For monitoring the speed, by installing two proximity sensors on the wheels, the safety level can be improved by multiplexing. This controller can check the normality of these sensors by managing complementary pulse outputs of sensors, and perform the above interlock function without fail-safe elements. When this controller is used, it is easy to diversify the monitoring and make it multiplex by combining the use of the reflection type ultrasonic sensor and reflection type infrared sensor. As a result, the improvement of the safety level and reliability of human detecting ability is expected.

4. INTRINSICALLY SAFE ACTUATOR SYSTEM

4.1 Force output limiting mechanism using MR fluid.

In monitoring the space S_{M2} by the soft contact type bumper switch, when a human contacts the bumper switch, the robot is not always required to completely stop. In a robot and a human are collaborating, as it is probable that they are working together while contacting each other, the extremely slow behavior of the robot should be permitted. In order for the robot to be permitted to contact the human, it should be guaranteed that the robot outputs the safe force when contacting the human.

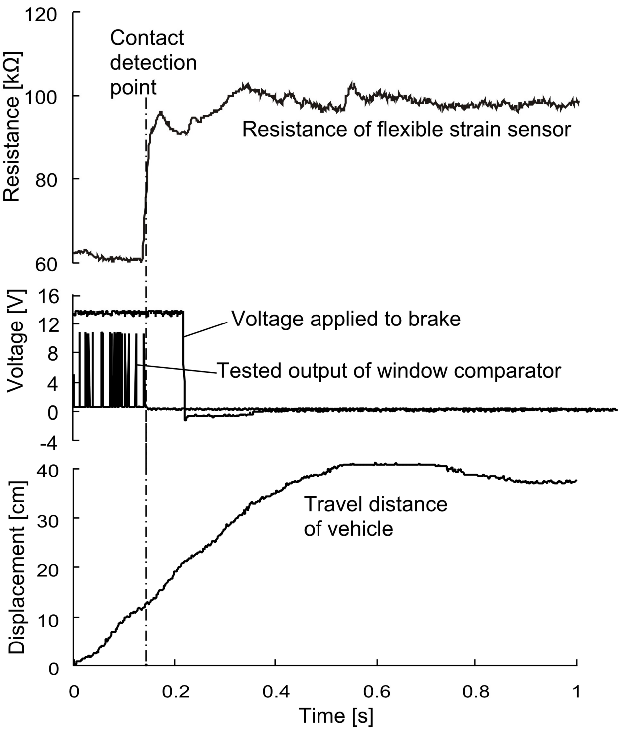


Figure 5. Test result of detectability of soft contact type bumper.

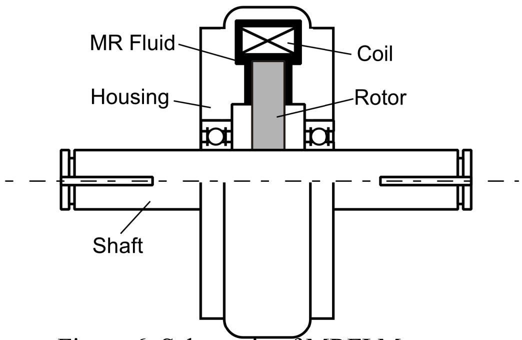


Figure 6. Schematic of MRFLM.

In this study, instead of such a functional technique that the external force acting on a robot arm mounted on a transfer mechanism is detected and the arm force output is dynamically controlled, such a technique that the arm force output is intrinsically limited is aimed at. This is because the functional technique may exert excessive force output on the human due to the failure in control. On the other hand, the force limiter using a spring or the like cannot actively change the restriction according to the positional relation between the robot and the human, and cannot be used for human-robot collaboration.

Alternatively, the intrinsic reduction of the arm force output is tried by inserting a passive force limiting mechanism using the Bingham fluid into the arm joint. Here, the Magnet-Rheological (MR) fluid [6] is a kind of the Bingham fluid which can control its yield shear stress according to external signal. In this paper, the description exemplifies the Magnet-Rheological Force Limiting Mechanism (MRFLM) using the MR fluid controlled by the magnetic field shown in Fig. 6.

When the coil within the MRFLM is excited, the torque is transmitted to the arm according to the strength of the resultant magnetic field. When the exciting current is i, the angular velocity of the input shaft is ω, the rotation angle of the output shaft (arm) is θ and the proportion coefficient is α, the maximum torque τ_M that the MRFLM can transmit can be expressed by the following equation:

$$\tau_M = \alpha \cdot i \cdot \frac{\omega - \dot{\theta}}{\left|\omega - \dot{\theta}\right|} \tag{5}$$

where, $\left(\omega - \dot{\theta}\right)/\left|\omega - \dot{\theta}\right|$ is the direction of the torque in transmission. In the torque transmission using general (Newton) viscous fluid, the transmittable maximum torque receives the effect of the relative rotational speed difference between the input unit and output unit. The On the other hand, the maximum torque that the MRFLM can transmit is completely independent of the amount of the relative rotational speed difference, and therefore it extremely resembles the ideal solid friction clutch model. The characteristics of the MR brake [7] used in the MRFLM are shown in Fig. 7.

4.2 Safe work in contact by the MRFLM.

By controlling the current applied to the MRFLM, the robot arm can realize various functions, including:

(1) Restriction of excessive force output,
(2) Restriction of force transmission from the outside,
(3) Fixation of arm joint, and
(4) Restriction of excessive impulsive force.

When the current applied to the MRFLM is reduced, the function (1) can be realized, and when it is increased, the function (2), i.e., the control of disturbance, can be realized. When the low-torque, low-rigidity actuator is separated from the MRFLM, the current to the MRFLM is increased, and the rigidity of the arm can be increased as the function (3). Furthermore, by controlling the current when the arm collides with the human, the effect of the equivalent inertia moment of the actuator caused by the collision can be shut off, and the function (4) can be realized. Here, it should be noted that if the transmission torque from the actuator is controlled by the function (1), the robot arm may deviate from the normal operation due to the contact with the human. However, if the MRFLM guarantees the safe force output, there is not always the necessity of stopping the control of the arm on the spot.

However, considering trouble in the current

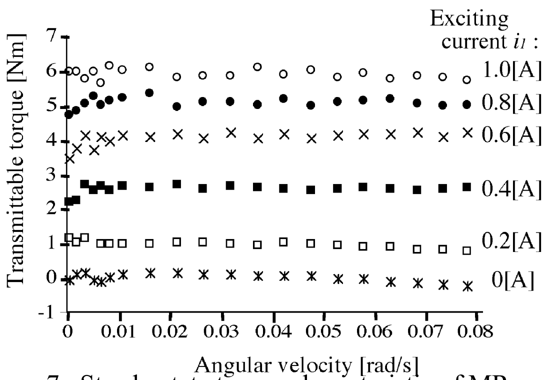


Figure 7. Steady-state torque characteristic of MR brake.

control means of the MRFLM or trouble in the arm control system, if such trouble occurs, the current control should be immediately stopped and the robot arm posture should be locked by any means other than the MRFLM. For this purpose, an electromagnetic friction brake of non-excitation type (normally closed) should be included in the arm joint. This brake can be actively applied to the uses of the functions (3) and (4). However, in applying the brake to the function (4), there would be problems, such as brake heat. In view of this, the brake is applied only to the function (3) and other functions are realized by the MRFLM in this study.

4.3 Impulsive force reduction technique.

As the realization of the functions (1) and (2) is apparent from the characteristics shown in Fig. 7, in order to verify the function (4), a robot arm model which can rotate on the horizontal surface with 1 degree of freedom is supposed. In this model, the MRFLM is inserted in between the output shaft and arm of the servo motor having a high reduction ratio. To assume the worst collision situation, three conditions are provided: (a) the human is bound and static by a hard wall, (b) the arm rotating at the constant angular velocity collides with the human body at a right angle, and (c) the relative speed of the arm and the human becomes zero in one collision.

When the arm rotates at the constant angular velocity $\dot{\theta}_i$, the kinetic energy E of the system can be given by the following equation:

$$E = \frac{1}{2}(\gamma^2 I_m + I_g + I_a)\dot{\theta}_i^2 \tag{6}$$

where, I_m, I_g, I_a are the moment of inertia of the motor rotor, the moment of inertia of the gear and MRFLM rotor and the moment of inertia of the arm and arm base, and γ is the reduction ratio of the motor. It is in the first peak after the collision when the impulsive force becomes the largest in the worst collision situation assumed here. At this time, the surface texture of the human body absorbs all kinetic energy of the arm. Therefore, the condition of the safe collision is that the first impulsive force is not over the allowable limit for the human body.

The impulsive force reduction technique proposed in this study limits the braking force for the actuator by using the MRFLM. On the basis of the characteristic of the MRFLM expressed by Eq. (5), the next balance relation of energy can be established:

$$\frac{1}{2}(\gamma^{2} I_{m} + I_{g})\dot{\theta}_{i}^{2} = \tau_{MR}\int_{0}^{t_{a}}(\omega - \dot{\theta})dt \qquad (7)$$

where, t_a is the time required for the braking of the motor, including the speed reducer, which can be freely selected by changing the transmission torque τ_M of the MRFLM. Especially, it takes the motor a long time to stop as it is achieved by the internal friction alone, but the force transmitted to the human is rather small and on the safety side.

Fig.8 shows an example of experimental result this technique. In the experiment, the arm mounting the force sensor at the arm tip rotated in the constancy at angular velocity of 1.0 rad/s, and the impulsive force were observed when the arm struck instead of the human body at the hard rubber piece. The length of the arm is 300mm, and the mass of the arm is 1.2kg, and the moderating ratio of the gear is 1/200, and the equivalent moment of inertia of the motor is 2.4kgm^2. The exciting current of MRFLM was made to be being constant during the collision, and it compared 2 types of 0.2A and 1.0A. The peak of the primary principal wave of impulsive force is the effect of the mass of the arm, and it is proven that it has not appeared in the collision almost, though the effect by these appears in steady-state characters of the force, since motor, speed reducer do not need the sudden stop. From this fact, it can be judged that the intrinsic safety of the actuator was achieved by this system.

Proposed fundamental system and control means have been applying to the robot for the construction work (Fig. 9).

5. CONCLUSION

In this study, by clarifying the principle of working safely, space monitoring system based on this and composition of the intrinsically safe actuator and the control means were explained. However, the judgment index of permissible ranges of the impulsive force and impact speed applied to the human has not been clarified for the collision between robot and human. In this case, it is rational to entrust the judgment of the acceptance to the human, and human pain tolerance [8] has already proposed. The examination based on such index will be required in the design of actual robot system.

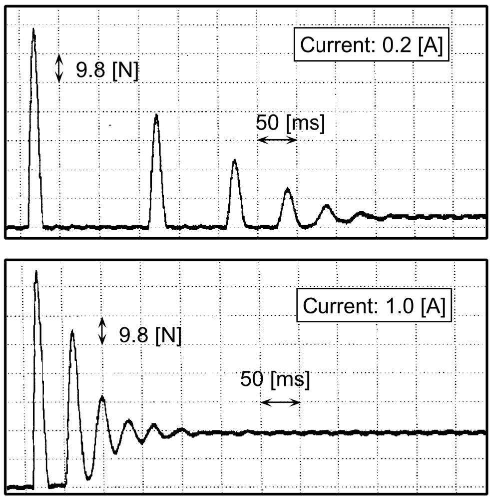


Figure 8. Comparison of impulsive force reduction effect .

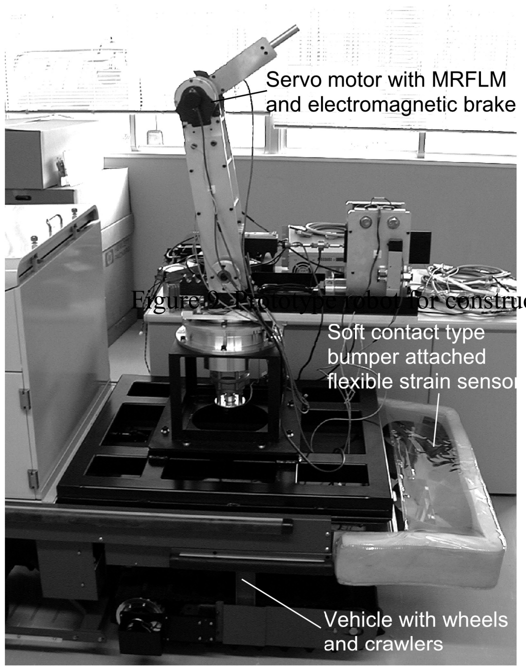


Figure 9. Prototype robot for construction work.

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