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Consideration on safety for emerging technology – Case studies of seven service robots

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ABSTRACT

Despite the fact that several manufacturers of service robots launched their innovations into the market, worldwide guidelines or regulations concerning the safety aspects of service robots are not yet available. However the general principles and methodologies of safety of machinery (e.g., ISO/IEC Guide 51, partly ISO14121, ISO12100) could be implemented to a certain degree. The safety of seven service robots as an emerging technology was verified by safety professionals of "NPO – the Safety Engineering Laboratory" a Non Profit Organization. NPO verified the "Critical Hazards" for each service robot mentioned by the respective manufacturers. For those cases, both the "As Low As Reasonably Practicable" principle and the "Reasonable Alternative Design" standard were applied for judging if the risk associated with the Critical Hazards were tolerable or not and if state of the art measures for reducing the risk were applied adequately. These experiences will help to establish guidelines for the safety of service robots as an emerging technology in the future.

1. Introduction

As an emerging technology, service robots will bring innumerable benefits in the future and will deeply and dramatically change our social culture, while they are by nature dangerous with respect to close human–robot-interaction. Nowadays several service robots have been commercialized without having safety regulations in place. If one of those robots would cause a serious accident with a human, all service robots would be categorized as a kind of unreasonably dangerous products bearing generic risks. This may result in destroying the emerging industry sector of service robots. Therefore, the safety issues are one of the crucial points for the success in their commercialization.

Industrial robot systems, as established for mass production in the automotive industry, are custom-made programmed for their specific task by highly educated robotics engineers to proceed with a predetermined operation with high durability, speed and precision. The adequate safety was basically achieved by protecting through a complete separation of humans from the robot's workspace (principle of separation) and stopping the dangerous movement through safety interlocking devices (principle of stopping).

Recently, the assistant robot systems which were designed for close human-robot-interaction are launching into the market (Oberer et al., 2006). The new international standard for robot systems ISO 10218-1 (2006) includes this situation and provides regulations for the robot–human-cooperation. In this case the humans are in the active workspace of a robot for operating it or handling of work pieces. They can be protected by the internal safety control, while the area surrounding both robot cells and operators are guarded statically against the entry of unauthorized people. Although the industrial assistant robots are released from the strict enclosing with guards, they usually have heavy masses and high velocities, which require an extra guarantee for a minimum hazard of the involved human at any time in the process. This leads to the installation of comprehensively developed safety control systems usually involving high costs.

The service robots are usually smaller in size with lower kinetic energy. They are also more movable with more advanced autonomy than the assistant robots in industry. Their applications are not restricted to mass production in large-sized enterprises, but are dispersed over a wide range of customers (from small-to-medium sized enterprises in industry to non-educated individuals in the commercial market). Therefore, the commercialization for such emerging technology requires a much lower pricing strategy. In order to do so, the right balance between cost/benefit and keeping the risks involved as small as possible needs to be found.

Since the worldwide safety standards comprising safety aspects specific to service robots are currently not available, it is considered that their safety certification should be conducted making ref-

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erence to wider-ranging standards and regulations based on both the ex ante perspectives mainly developed in Europe and the ex post acts developed in USA. Here the former conception demands the reduction of risks arising from the use of products, processes or services in a deductive way by the iterative process of risk assessment and risk reduction. The relevant fundamental concepts are condensed into the guideline ISO/IEC Guide 50 (1999) together with the basic safety standards, ISO 14121 (1999) and ISO 12100-1,-2 (2003).

The ex post conception of products liability litigation and prevention advocates the discipline of law and economics taking into account the balance between cost and benefit (cost-benefit analysis) or the risk-utility-test (United States, 1947; Henderson et al., 2004).

The Safety Engineering Laboratory, a Non Profit Organization, (hereafter denoted by NPO), which was founded by safety professionals in 2002 in Tokyo, has started certification work, to judge the validity of safety measures taken by the manufactures of service robots in Japan. NPO proposes a judgment test procedure for certifying the safety of service robots as follows:

(1) Risk assessment and risk reduction by inherently safe design according to ISO/IEC Guide 51 and the basic standards for safety of machinery, which implicitly obey the well tried safety principles.
(2) Risk judgment test according to the ALARP (As Low As Reasonably Practicable) principle, or risk-utility test. The latter test is originally formulated by Judge Learned Hand for the strict liability context in USA (United States, 1947; Henderson et al., 2004; Owen et al., 2004), and now brushed up to the ALARP principle, which is introduced into international standard (ISO 61508,1,5, 1999).
(3) Identification of the deterministic and significant hazards as Critical Hazards (CHs), when risks are reduced to a tolerable level in the ALARP region, but still remains as residual one.
(4) Test of validity of the risk reduction measures for CHs according to the Reasonable Alternative Design (RAD) standard in the tort litigation (Henderson et al., 2004; Owen et al., 2004). It is presumed that the fulfillment of both the generally acknowledged state of the art and the good engineering practices principles can be judged by the application of RAD standards into such an emerging technology as service robots.

In this paper, Section 2 describes the safety principles used for AICHI-EXPO in 2005, Section 3 the method of certification by NPO. Section 4 explains the case studies of seven different service robots; Sections 5 and 6 contain discussion and conclusions, respectively.

2. Safety principle for service robot

The first occasion to carry out the certification of service robot by NPO was at AICHI EXPO 2005 in Japan, where approximately 100 various kinds of service robots in developing phases were demonstrated during the EXPO from June to September 2005.

Conventional industrial robots for factory automation are protected by guards, where the entrances are interlocked using, e.g., safety switches to enable the robot movements to shutdown when opening the entrance doors and keep zero-energy-state to protect the operators. This well-tried "principle of separating" or "principle of stopping" for industrial machines cannot be applied to all service robots, because the specific function of a service robot is the close human–robot-interaction, basically "people living together with service robots". Therefore a new concept of safety, such as "principle of co-existence" needs to be established for service robots.

To achieve the safety of exhibited service robots at AICHI EXPO, a research committee on safety guideline for robots had been established and an adequate safety guideline had been set up. Here the well-tried international standards on safety, e.g., ISO/IEC Guide 51 guideline for the inclusion of safety aspect in standards (ISO 10218-1, 2006), inherent safety principle of ISO12100-the general principle of safety of machinery (ISO/IEC Guide 50, 1999), the methodology of ISO14121 – the principle of risk assessment (ISO 14121, 1999) were adopted as a concept to ensure the safety of service robots for the EXPO. Particularly the inherent safety design on the base of ISO/IEC Guide 51 and also the safety management including documentation and communication were found essential and each of exhibitors took care of residual risks at each of exhibiting booth.

No accident caused by the exhibited service robots had been reported during the period of AICHI EXPO. The basic procedures, well-practiced for AICHI-EXPO, have been and will be adopted for the safety certification of various kinds of service robot in Japan.

3. Method of certification by NPO

In 2005 NPO was requested for the first time to carry out a certification work on the service robot "wakamaru" as reported by the international conference on Safety of Automated Systems, SIAS 2005 (American Law Institute, 1998) in Chicago. Hereafter the concept of the certification work taken by NPO is described.

As mentioned above, the service robot is by nature required to co-exist with people, including children and old people in private houses or in public spaces. The situation is therefore different from that of industrial robots, which are used in limited spaces like a manufacturing plant and operated by skilled workers. However, the experience at the AICHI EXPO has taught that the well-tried general principle of safety of machinery can also be implemented for service robots to a certain extent.

3.1. Requirements

The documentation requirement for the certification work by NPO follows that of Technical Construction File for CE-Marking System in EU (Kabe et al., 2005). The contents are intended use, technical specification, outline drawing, electrical block diagram, choice of materials used, risk assessment sheets, carried out test records, e.g., Electromagnetic Compatibility tests (Directive 2006/42/EC,), safety measures during the lifetime, operation manual, and so on.

3.2. Certification criteria – judgment of CH

NPO considered that the application of a usual proper certification work according to ISO/IEC Guide 65 or the obligation of test reports by notified testing laboratories according to ISO/IEC 17025 is a too heavy burden to technical regulations for such an emerging industry as service robots.

The test procedure has been itemized from 1 to 4 in the introduction of this paper, and the schematic representation of the iterative test procedure for the corresponding certification is shown in Fig. 1. Here the detailed illustration is given as follows.

3.2.1. Risk assessment

Some suggestions were made by NPO to the certification applicants beforehand.

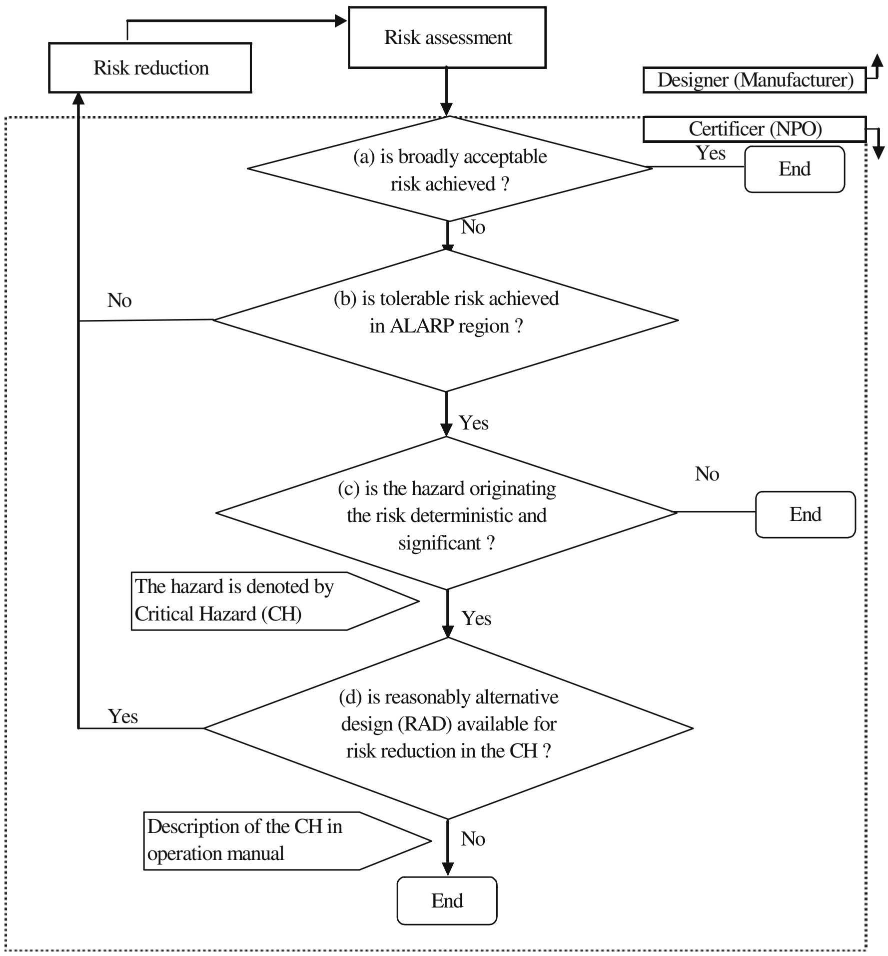

Fig. 1. Iterative process to certify the validity of risk assessment and risk reduction.

(a) Implement the well tried principle of safety for machinery, i.e. application of safety design and practice risk assessment.
(b) Primarily take inherently safe design measures, e.g., carry out impact test and consider the ergonomic factors and safety distances.
(c) Not always demand the solution of safety related signals or software, e.g., according to functional safety IEC 61508 ISO 61508,1,5 (1999) or safety-related parts of control systems ISO 13849 ISO 1384-1,2 (2006). Consider an trade-off between cost of the installation of safety-related control systems and their benefit.
(d) Carefully assess the risk of robot in contact or collision with people and take adequate measures to reduce the residual risk to a minimum.
(e) Make life-time assessment, including maintenance and safety checks during all the phases of lifecycle of a service robot.

NPO certified the conformity of the risk assessment and risk reduction measures with the well-tried principle of safety.

3.2.2. Risk judgment test

NPO judged whether the adequate risk reduction of hazards, which are deterministically identified by designers, has been achieved according to ISO 12100-1,-2 (2003) and/or ISO 1384-1,2 (2006) taking into consideration the trade off between risk and benefit, namely whether the corresponding residual risk is tolerable in the society or not. NPO adopted hereby the thought of law and economics and refers the following two principles.

3.2.2.1. Hand formula. This is the most celebrated formulation of the risk–benefit test in the context of torts, including products liability law in USA trials and formulated in 1947 by Hand (United States, 1947) as:

$$B > R \tag{1}$$

where R is the expected risk avoidance as expressed by $P \times L$, P is the probability that injury would result from the conduct of defendant (manufacturer), L is the loss of the injury, B is the burden or cost of prevention to avoid the risk of loss (United States, 1947; Henderson et al., 2004). Eq. (1) shows that if the cost of adopting of a particular safety prevention (B) is higher than the risk or the safety gains expected to result there from ($P \times L$), the manufacturer's failure to adopt the prevention does not imply its negligence. Or by substituting "defect" for "negligence", a product is not defective if the costs of a particular safety prevention measure exceed the resulting safety benefits, including any diminished usefulness or diminished safety (Owen et al., 2004). Most courts have formulated the risk-utility test in broader terms, whereby the product's risks R are weighed against its benefits or utility U. The formula reads that if

$$U > R, \tag{2}$$

the manufacturer avoids the liability for the injury.

3.2.2.2. ALARP-principle. ALARP-principle is based on the experiences in American nuclear power plants or the process industry and then proposed from Health and Safety Executive (HSE) in UK as a principle defined in the annex of the standard on functional safety ISO 61508,1,5 (1999). Furthermore this principle is adopted in the standard on the risk management of medical devices, ISO 14971 (2002). Medical devices are generally used in direct contact with human being and their "intended use" has a certain similarity to that of service robots. The typical example is the service robots for medical care. NPO thus referred to this standard.

ALARP-principle indicates that all risks are to be reduced as low as reasonably practicable. To judge the tolerability of achieved residual risks, Rr, they are categorized into four risk classes (I, II, III, IV) as follows (ISO 61508,1,5, 1999).

I. Intolerable region:

$$\mathrm{Rr} > \neg\mathrm{Rt}, \quad (3)$$

where ¬Rt is the lower limit of intolerable risk. The risk is so great that it must be refused and the design should be abandoned.

II. Upper ALARP region:

$$\neg\mathrm{Rt} > \mathrm{Rr} > \mathrm{Rt}, \quad (4)$$

where Rt is the level of tolerable risk, which is determined by considering the balance between risk and benefit (utility) as formulated in Eq. (2). The residual risk in this region is not desirable and only tolerable if further risk reduction is impracticable or if its cost is largely disproportionate to the improvement gained.

III. Lower ALARP region:

$$\mathrm{Rt} > \mathrm{Rr} > \mathrm{Ra}, \quad (5)$$

where Ra is the broadly acceptable level. The residual risk in this region is tolerable if the cost of risk reduction would exceed the improvement gained as formulated in Eq. (1).

IV. Broadly acceptable region:

$$\mathrm{Ra} > \mathrm{Rr}. \quad (6)$$

In this region risk is reduced to a sufficiently low level and risk control needs not be further pursued.

3.2.3. Critical-Hazard

The ALARP principle is applied when a risk falls between the two extremes (i.e., $\neg\mathrm{Rt} > \mathrm{Rr} > \mathrm{Ra}$). The risk is only taken if a benefit is desired. The resulting risk may not be reduced to a sufficient low level and therefore the possibility of an accident remains. Particularly the risks in upper ALARP region have a higher possibility. Then the manufacturer must leave the implementation of the human-related procedures to the userwith conveying all information provided by the designer/supplier. Taking into account such a situation, NPO defines the hazards relevant to the residual risks in the ALARP region as Critical Hazards, when they are deterministic and significant.

The identification of CHs is especially necessary for the safety certification for service robots, because this industry is now in development and the application procedures of the well-tried safety principles are not yet established for the design of service robots. The shape, function and working area are different among service robots and therefore CHs should be defined and judged for each individual robot. The CHs identified are a typical indication for potential threats associated with each robot.

3.2.4. Reasonable alternative design standard

Since the formulation by Hand in 1947, the judgment criterion of risk-utility balancing test for torts has improved and the restatement (third) issued from the American Law Institute in 1998 (Owen et al., 2004) adopted a reasonable test for judging the defectiveness of product designs. The defects are categorized into three areas, manufacturing defects, design defects and warning defects. The strict liability for design defects was abandoned and the RAD standard was adopted. The statement provides: A product is defective in design if its foreseeable risks could have been avoided by a reasonable alternative design and the omission of the alternative design renders the product not reasonably safe (Owen et al., 2004).

The notion of "state of the art" is an undeveloped concept whose meaning in products liability law is still evolving. It means quite different things to different people. To some, the phrase refers to the customary practice in the industry, and to others, it reflects technology at the cutting edge of scientific knowledge. Thus, state-of-the-art evidence is relevant to, but not necessarily dispositive of risk-utility analysis (Henderson et al., 2004). In consequence, NPO considers that the RAD standard is more acceptable than state-of-the-art evidence for the judgment criterion of risk-utility test or ALARP test.

In Germany, where the ex ante conception of safety is prevailing, the RAD standard is nowadays also commonly accepted (Cichos et al., 2005). NPO adopted the standard as a key defense against both civil and criminal litigation for the presumed accident caused by service robots. This will outweigh state-of-the-art evidence and ensure the utility of the emerging industry to provide benefits for the society.

3.3. Certification procedure

The certification procedure of a service robot by NPO is as follows:

(1) The applicant submits the required documents on the safety measures to NPO.
(2) NPO sets up a safety committee, consisting of 10 safety professionals as a third party, and selects the member of the judging subcommittee, consisting of several safety professionals.
(3) The subcommittee carries out an assessment of the documentation on the conformity considering the safety principles and the judgment of CHs in order to release the product to the market. Finally it tests the validity of the risk reduction measures for CHs according to RAD standard. Afterwards the service robot is practically operated in the presence of the subcommittee members to check the performance of the safety measures.
(4) Based on the examination report of the subcommittee, the safety committee of NPO makes the final decision and issues a judgment report to confirm the certification (Begutachtung in German).

4. Case studies

Table 1 lists the specification of seven service robots (Nos. 1– 7), which are being in the certification procedure at NPO. Most of the robots are in the development stage and some of the relevant specifications listed in Table 1 are not finally fixed yet. Those robots can be categorized into three categories depending on their working area as follows. The typical CHs associated with the robots of categories A and B are indicated in the lower part of Table 1. Fig. 1 exhibits the view of No. 1, 2, 3, 5, and 7 robots.

Category A: Communication type robots (Nos. 1 and 2). They are serving in public spaces and enable communication with people in real-time situations. The normal consumers including infants, the elderly and handicapped people touch directly the robots. Since the weight of the robots ranges from 50 to 90 kg and the height attains up to 1300 mm, the relevant CH is the collision or crash with humans. For example, the robot may lose its stability by being

Table 1
Specification of seven robots applied for the certification of NPO.

No.	Applicant	Tasks	Robo-name	Approx-size (mm)	Weight (kg)	Feature	Category	Use area
1	Fujitsu	Communication	Enon	540 × 1300 × 560	50	Communication type with arms	A	Public space
2	ALSOK	Guarding+guiding	Reborg-Q	700 × 1300 × 650	90	AGV-type	A	Public space
3	Fuji Heavy Industry	Building cleaning	Robohiter	850 × 1158 × 720	135	AGV-type	B	Building
4	Tsumura	Medical transport	–	Not defined yet	–	AGV-type	B	Factory
5	Matsushita	Medical transport	–	730 × 1310 × 600	120	AGV-type	B	Factory
6	Asante	Detect harmf.insec	–	260 × 108 × 210	4.4	Rescue-type	C	Private house
7	Daiwa House	Detect harmf.insec	–	400 × 250 × 270	–	Rescue-type	C	Private house

Notice: The approximate size is indicated by Depth(D) × Height(H) × Width(W).
List of service robots under certification by NPO (2007).
Typical Critical Hazards(CH):
Category A:
A child jumps to the robot, falls down and hits some part of the body.
The robot falls down from stairs and hits somebody.
Category B:
A robot drives over the limb of somebody, who is lying on the floor by accident.
Unforeseeable risk will be created through remodeling by user.
Pour water on the robot body
Robot falls down by tipping.
Category C: Unreasonable misuse will be done.

hugged by a child. Then it may tip over and fall down to the ground, sandwiching the child between the robot and ground.

For such a colliding or crashing risk, some manufacturers try to verify the data with dummy impact tests. These tests are common in the worldwide automotive industry and evaluates the risks by the Head Injury Index (HIC) (Oberer et al., 2006; Kabe et al., 2005; Festschrift and Lorenz, 1991) value. Nos. 1-1–4 of Photo 1 demonstrates the aspects of the impact crash test with a calibrated child dummy. The HIC-value for the case that the running robot collides with the dummy becomes less than 10. This value is so small that we can judge the corresponding risk as acceptable. It also satisfies Eq. (6). However, for the worst case of the robot tipping over and falling down with a hugging child, the HIC-value becomes 1400. Medical studies reveal that the life threatening head injuries are probable to occur when HIC exceeds 500.

For the automotive society the HIC is provided with a limit of 700 or 1000 (depending on the maximum impact time of interval) (Oberer et al., 2006). Thus, NPO judges that the hazard relevant to the risk of HIC 1400 is CH, and that the risk is not desirable ranging in the upper ALARP region specified by Eq. (4). In consequence, NPO recommends that the manufacturer should provide the user with the information for the limits of the working area to avoid the risk of falling at certain places like stair cases.

Category B: AGV (Automatic Guided Vehicle) – type robots (Nos. 3–5). The feature and the performance such as the movement via elevator are similar to those for factory AGV, though the latter usually run on rails based on the well-tried principle of stopping. Cat-

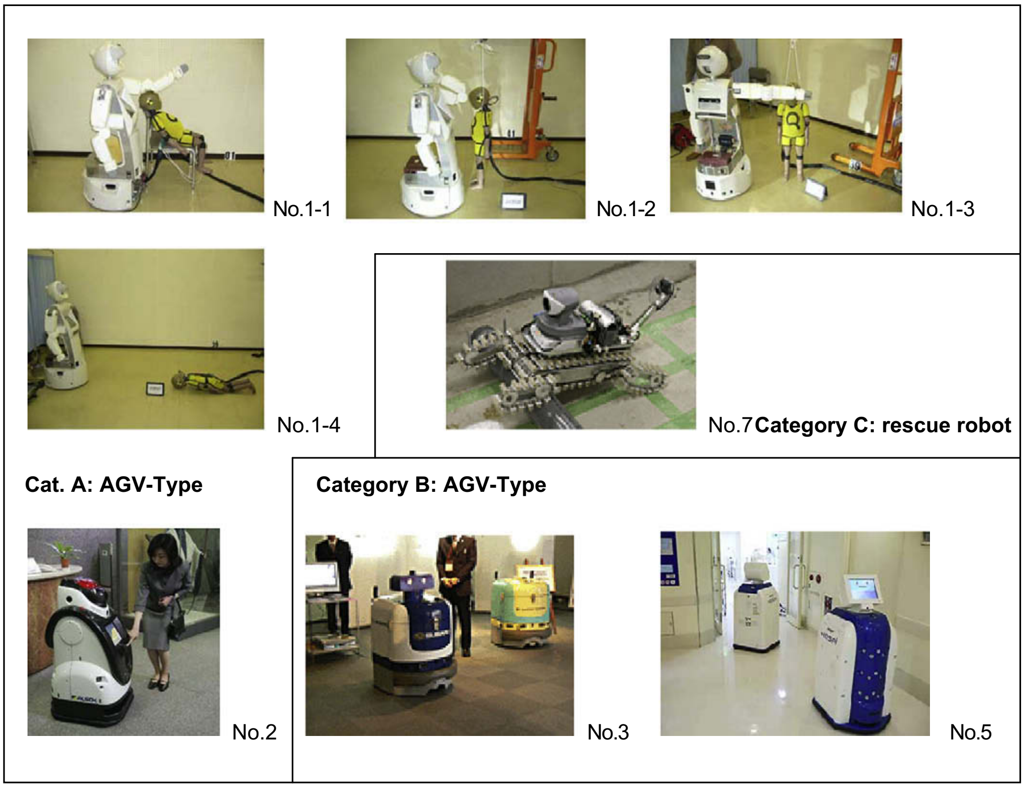

Photo 1. Service robots and dummy test.

egory B robots work in an office building, hospital or factory without any special guard. However, the working area is more limited than that of Category A robots. The working area and the working time are limited and usually only a limited number of people having received special training beforehand to access and operate them. The size and weight of B robots are much smaller than those of factory AGV, while the weight is a factor of 1.5 higher than that of category A robots, though the size is comparable.

Because of higher mass of B robots, the impact value (HIC) is considerably higher than that of A robots, and the risk of collision with people is higher. Furthermore, B robots originate CH of driving over the limb of a person, who is lying on the floor by accident. Therfore they are equipped with a bumper with safety circuits for emergency stop when meeting with some obstacles.

Category C: Rescue type robots (Nos. 6 and 7)

They are developed for the extermination of termites and can crawl into narrow spaces underneath the floor or the rear of the ceiling in a private house. They are driving on wheels or a caterpillar. Both their height and weight are considerably smaller than those of A robots and the working area is separated from people. Thus any CHs are not considerable.

5. Discussions

Since the most significant hazards of the service robots is generated by tipping over or falling on humans, the inherently safe design taking into account the impact values were in principle adopted to reduce the risks. But on the other hand, the electric signals to control all the robots functions were non-safety related signals. The exception was the fail-safe bumper-sensor for category B robot. According to this the safety control via CPU conforming with the standard of the functional safety technology (IEC61508) was not untilized for the robots certified at this time. This is because the extra cost required for complying with IEC61508 would dominate the production cost in the developing phase and lose significantly the balance provided by Hand formula in Eq. (1). In this study, it is considered that the hazards which could be introduced by the insufficient conformity to the functional safety were mostly avoided by limiting the use of robots or taking protective measures by the user. For example, in the case of robot A, NPO recommended that the manufacturer should provide the user with the information for limiting the working area such as high places with a high risk of falling down. However, it is noted that the limitation of working area decreases somehow the utilization of service robots. Hence, the consideration on functional safety would be desirable for robots in order to establish their full utilization. In the future this will be achieved by the adequate reduction in the production cost of robots when matured into the mass-production stage and by the development of a new standard for functional safety controlling the close-human-robot cooperation.

The judgment of the NPO is a trial to a future system of global certification according to the international rules, for instance, one-stop-testing according to the directive 06/42/EC in EU concerning the procedures for conformity assessment (Directive 2006/42/EC,).

For the proper judgment on the validity of safety design of service robots, international rules and testing methods should be created to enable third party testing and certification. A considerable number of experts and professionals as certification body personnel need to be urgently educated especially in Japan.

Most accidents by service robots may be avoided by safety design according to the well-tried safety principle of machinery on the basis of the conventional international standards, but the remedy system of adequate insurance for various kinds of service robot should be constructed in future to obtain social acceptance as an emerging industry. In another words, the successful commercialization of service robots depends both on safety design as a priori prevention and insurance as compensation.

A critical Technical Assessment (TA) will be required for the new technology of service robots, so that such an intelligent and autonomous robot shall not be misused, e.g., for terrorism or war against the intention of original manufacturers. Safety life time could be defined in this concern.

6. Conclusion

The manufacturing of service robots is a new technology and is in an emerging status worldwide. Therefore it is at the moment difficult to establish a general guideline for the safety of service robots as a whole, because the size, shape and function are very different among them. NPO has started the certification work on seven service robots as a professional engineering judgment based on the general safety principle of machinery.

The NPO assesses the residual risk and determines the Critical Hazards as significant and deterministic hazards in ALARP region. For judging the risk reduction of the CH, NPO adopts the Reasonable Alternative Design standard. Therefore this judgment has been effective to secure the validity of technical risk assessment of the design to achieve reduced risk on the one hand and on the other to ensure to provide legal argument as a third party for eventual law suits in case of an accident. It is finally emphasized that the RAD criterion is beneficial to defense a design as a substitute for state-of-the-art evidence.

Hopefully this experiment executed by NPO could globally start the development of a system guideline or a regulatory system for such an emerging technology as service robots.

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