Robot systems reliability and safety: a review

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Abstract *This paper presents a review of published literature on robot reliability and safety. The literature is classified into three main categories: robot safety; robot reliability; and miscellaneous. Robot safety is further categorized into six classifications: general; accidents; human-factors; safety standards; safety methods; and safety systems/technologies. The period covered by the review is from 1973 to 2001.*

Practical implications

This paper will be useful to practitioners working in the field of robot safety and reliability, because it provides a comprehensive review of literature published on various aspects of robot reliability and safety. There are two basic ways in which the paper can be useful to people involved with robot safety and reliability:

(1) to gain a bird's eye view of progress made in robot safety and reliability; and

(2) to conduct further research in the area of robot reliability and safety.

Hopefully, this will result in an effective application of proposed safety and reliability concepts, thus better reliability and safety of robot systems in the field.

1. Introduction

Webster's Dictionary defines a robot as a mechanism guided by automatic controls. The word "robot" first entered the English language in 1923 when Czech playwright Karel Capeck's play, *Rossum's Universal Robots* (RUR), was translated and introduced to the English speaking world, the Czech word for "worker" (Jablonowski and Posey, 1985). In 1954, George Devol (Zeldman, 1984) designed and applied for a patent for a programmable device for what is generally considered to be the first industrial robot. Two years later, in 1956 Joseph Engelberger realized the potential of inventor George Devol's programmable machinery concept, and together they built and installed the first industrial robot in 1961 for die casting. From then on industrial robots proved to be a practical possibility and the development of industrial robots has been steadily advancing ever since. In recent years, the application of robots in the industrial sector has increased at an impressive rate. The development of advanced sensor systems, improvements in the intelligence area, and robot mobility have helped to introduce new areas for robot

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application, including nuclear power generation, construction, fire fighting, underwater exploration, outer space exploration, and medicine.

For the first decade, after its birth, robot population increased at 20 per cent (Schreiber, 1983) annually and by 1983 world robot population was estimated at 30,000 (Robotic Institute of America, 1983). According to the International Federation of Robotics, the worldwide industrial robot population was 350,000 in 1987 (Solem, 1987), 590,000 in 1994, 760,000 in 2000, and forecasted 890,000 industrial robots by the end of 2003 (United Nations, 2000). Figures 1 and 2 present the robots' population growth and a breakdown of the worldwide robot population for 2000, respectively.

Although in the early years of robotics, applications were concentrated in the automotive industry, recently, however, the technology has been diversified and vastly utilized in other sectors of industry as well. A future potential market will undoubtedly be the general consumer where robots may well become another household item. This makes the safety factor even more crucial, since service robots have to work among human beings. This means robots have to be much more reliable and safe, so as not to injure humans should a malfunction occur. In any case, the exponential increase in robot utilization underlines the fact that robots are here to stay. Not surprisingly, Polakoff (1985) expressed his passion for robots and wrote: "Man's marriage to robotics: a 'for better or worse' union".

This review is conducted by categorizing published literature on robot reliability and safety into different classifications. The collected publications listed include conference proceedings, technical reports, journals, and books from 1973 to 2001. Table I presents the classification of references listed at the end of the paper.

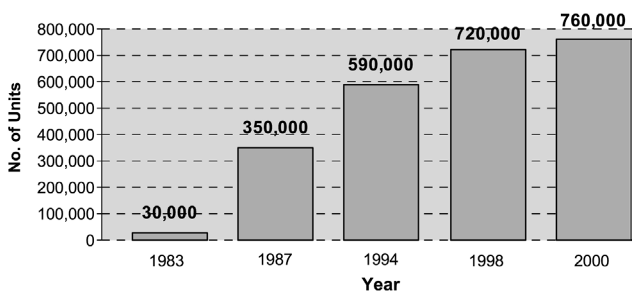

Figure 1. Population growth of industrial robots

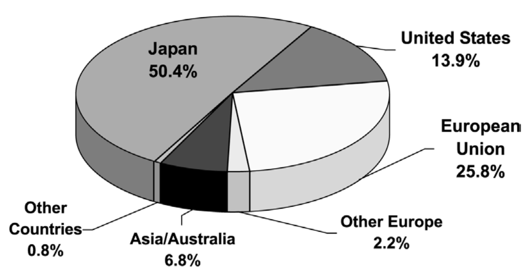

Figure 2. Worldwide population breakdowns of industrial robots in 2000

Categories	References
Robot reliability	3, 10, 29, 35, 38, 45, 52, 59, 68, 79, 80, 83, 84, 85, 86, 87, 89, 92, 94, 100, 105, 108, 116, 118, 120, 129, 130, 133, 134, 135, 136, 137, 156, 157, 174, 176, 183, 200, 218, 230, 231, 232, 247, 248, 249, 250, 255, 259, 260, 264, 283, 286, 290, 291, 296, 305, 310, 318, 321, 330, 332, 361, 381, 384, 398, 409, 422, 423, 427, 437, 442, 463, 465, 481, 488, 491, 492, 499, 508, 511, 512, 513, 515
Robot safety	
General	12, 13, 19, 27, 36, 42, 43, 47, 55, 66, 69, 101, 111, 131, 140, 145, 147, 151, 164, 168, 178, 181, 184, 186, 194, 195, 211, 212, 246, 297, 298, 301, 308, 320, 322, 326, 329, 335, 345, 346, 354, 359, 377, 378, 385, 391, 394, 397, 400, 404, 405, 411, 426, 434, 444, 445, 446, 456, 466, 476, 478, 482, 485, 507, 517, 518, 522
Human factors	17, 32, 48, 49, 50, 58, 102, 107, 112, 113, 114, 139, 142, 154, 166, 185, 188, 189, 190, 192, 193, 198, 201, 202, 208, 209, 214, 233, 238, 242, 243, 261, 273, 285, 299, 300, 323, 336, 337, 338, 352, 353, 356, 357, 358, 360, 364, 365, 366, 368, 369, 370, 371, 380, 392, 399, 410, 429, 431, 436, 459, 494, 500, 501, 502, 503, 504, 505, 514
Accidents	5, 62, 67, 71, 75, 76, 77, 78, 95, 96, 97, 146, 149, 173, 220, 221, 223, 227, 239, 240, 241, 258, 267, 307, 312, 339, 343, 347, 367, 375, 408, 412, 417, 418, 432, 438, 448, 449, 452, 453, 455, 472, 473, 479
Safety systems	1, 6, 8, 14, 20, 21, 22, 23, 24, 25, 26, 30, 37, 51, 60, 61, 64, 65, 81, 90, 99, 104, 119, 122, 127, 128, 138, 159, 160, 161, 162, 172, 175, 199, 203, 234, 237, 251, 253, 254, 257, 263, 287, 288, 289, 292, 302, 303, 313, 314, 325, 331, 333, 334, 340, 341, 342, 374, 386, 387, 388, 395, 396, 421, 424, 439, 441, 458, 464, 469, 471, 483, 493, 497, 506, 509, 519
Safety method	2, 4, 7, 9, 18, 28, 34, 39, 40, 46, 56, 70, 73, 82, 88, 103, 110, 141, 152, 155, 163, 165, 167, 170, 191, 207, 213, 228, 229, 235, 244, 265, 266, 268, 271, 275, 278, 281, 282, 311, 319, 324, 327, 328, 344, 362, 389, 390, 393, 402, 413, 414, 415, 416, 419, 420, 425, 430, 433, 435, 447, 454, 457, 460, 462, 480, 486, 489, 490, 520, 521, 523
Safety standards	15, 41, 44, 53, 54, 74, 91, 109, 124, 126, 143, 148, 150, 153, 158, 169, 182, 196, 204, 210, 215, 222, 224, 225, 226, 236, 262, 269, 270, 272, 276, 277, 279, 293, 295, 304, 316, 363, 372, 373, 376, 379, 382, 383, 401, 403, 407, 428, 450, 474, 498, 516
Miscellaneous	11, 16, 31, 33, 57, 63, 71, 93, 98, 106, 115, 117, 121, 123, 125, 132, 144, 171, 177, 179, 180, 187, 197, 205, 206, 216, 217, 219, 245, 252, 256, 274, 280, 284, 294, 306, 309, 315, 317, 348, 349, 350, 351, 355, 406, 440, 443, 451, 461, 467, 468, 470, 475, 477, 484, 487, 495, 496, 510

Note: Reference names are shown in the Appendix

Table I. Classification of publications on robot reliability and safety

1.1 Classification of literature

The publications on the subject have been grouped into three main classifications: robot reliability; robot safety; and miscellaneous. Table II presents sources of journal and conference proceeding papers. The robot reliability classification includes publications that discuss methods, evaluation,

Journal
Advanced Robotics
American Machinist
Chemical and Petroleum Engineering
Computer World
Computing and Control Engineering
Human Factors
IEEE Transactions on Automatic Control
IEEE Transactions on Industrial Applications
IEEE Transactions on Reliability
IEEE Transactions on Software Engineering
Industrierobotor
Institute of Industrial Engineers (IIE) Transactions
International Journal of Human Factors in Manufacturing
International Journal of Robotics Research
International Journal of System Science
Journal of Intelligent Manufacturing
Journal of Occupational Accidents
Journal of Quality in Maintenance Engineering
Journal of Robotics and Mechatronics
JSME Bulletin
JSME International Journal
Katakana/Robot (Japanese)
Machine Tool Research
Microelectronics and Reliability
National Safety News
Nuclear Engineering International
Plant Engineering
Plant Maintenance
Professional Safety
Reliability Engineering & System Safety
Robot News International
Robotica
Robotics
Robotics Ace
Robotics and Autonomous Systems
Robotics and Computer-integrated Manufacturing
Robotics Engineering
Robotics Today
Robotics World
Safety and Health
Soviet Engineering Research

Conference proceedings
Proceedings of Spie – The International Society for Optical Engineering
Proceedings of the 1987 ASME Design Automation Conference
Proceedings of the 1990 International Industrial Engineering Conference
Proceedings of the 1st Robotic Europe Conference
Proceedings of the 2nd Conference on Industrial Robot Technology
Proceedings of the 31st and 37th Annual Meeting of the Human Factors Society
Proceedings of the 37th Annual Meeting of the Human Factors Society
Proceedings of the 3rd Canadian CAD/CAM and Robotics Conference
Proceedings of the 4th National Reliability Conference
Proceedings of the 4th, 6th, and 7th British Robot Association Annual Conferences
Proceedings of the 8th International System Safety Conference
Proceedings of the Annual International Industrial Ergonomics and Safety Conference
Proceedings of the ANS 7th Topical Meeting on Robotics and Remote Systems
Proceedings of the ASCE Speciality Conference
Proceedings of the ASME International Conference on Nuclear Engineering
Proceedings of the Conference on Remote System Technology
Proceedings of the IEEE Annual Reliability and Maintainability Symposium
Proceedings of the IEEE International Conference on Intelligent Engineering Systems
Proceedings of the IEEE International Conference on Intelligent Robots and Systems
Proceedings of the IEEE International Conference on Robotics and Automation
Proceedings of the IEEE International Conference on Systems, Man and Cybernetics
Proceedings of the IEEE International Workshop 1997: Robot and Human Communication
Proceedings of the IEEE Southeast Annual Conference
Proceedings of the International Conference on Robotics and Factories of the Future
Proceedings of the International Seminar on Safety in Advanced Manufacturing
Proceedings of the 17th Annual Electronics and Aerospace Conference
Proceedings of the RI/SME AUTOMACH Conference
Proceedings of the Robot 8 Conference
Proceedings of the Robot 9 Conference
Proceedings of the Robot Safety Conference
Proceedings of the Robot VI Conference of the Society of Manufacturing Engineers
Proceedings of the Robotic Industries Association's Robot Safety Seminar
Proceedings of the Workshop on Object Oriented Real Time Dependable Systems (WORDS)

Table II. The sources of most of the journal and conference proceedings papers and modeling techniques to assess overall robot system reliability. The robot safety category contains publications that emphasize various aspects of robot safety. In turn, these publications are classified under many categories: general safety; safeguarding techniques and methods; robot accidents; robot safety standards; safety systems/technologies; and human factors. The miscellaneous category covers published literature that discusses relevant topics dealing with both robot reliability and robot safety directly or indirectly. Both robot reliability and robot safety classifications are described below in detail.

2. Robot reliability

Despite the existence of a vast amount of literature on robotics research, there has been only limited effort on robot system reliability. Most works pay more attention to repeatability and accuracy (Brady *et al.*, 1996). Figure 3 illustrates the increased attention toward robot system reliability in recent years.

Engelberger (1974) compared the reliability of a numerically controlled (NC) machine and of an industrial robot, and concluded that since NC machines carry more than 90 per cent up-time, an up-time of 97 per cent should be expected from robots to satisfy their users. In the following year Thomopoulos (1975) presented a probabilistic method related to the design analysis of certain classes of industrial robots and, in general, of machines subjected to numerous combinations of stress, including cyclic loadings. A year later Engelberger (1976) assessed the reliability of the Unimate-2000 robot. The robot was examined in modules which consisted of components for which failure rate data were available from a database. The mean time to failure (MTTF) was estimated to be about 500 hours. Jones and Dawson (1983), on the basis of collected data, emphasized the fact that robot installation does give some concern about variable reliability and potential for injury and harm. Khodabandehloo *et al.* (1984a) presented an assessment of robot reliability by applying failure mode and effect analysis (FMEA), event-tree analysis (ETA) and fault-tree analysis (FTA), and Critchlow (1985) discussed robots' expected useful life and other parameters. He suggested that well-designed robots are to be expected to have a useful life of at least 40,000 working hours, MTTF of at least 400 hours, and a MTTR of no more than eight hours. Four years later,

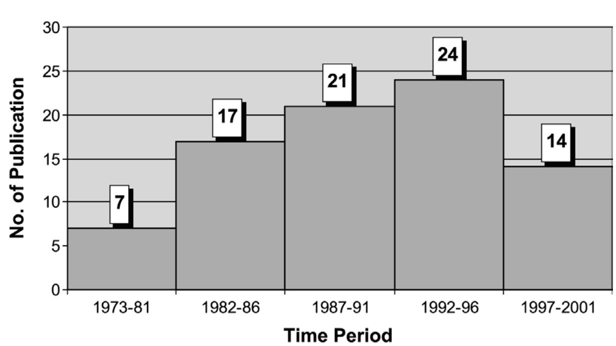

Figure 3.
Profile of publication on robot reliability

Jin *et al.* (1989) measured probabilistic behavior and performed reliability analysis of a multi-robot system by applying Petri net and Markov renewal process theory. Dashui *et al.* (1990) presented a reliability model and proposed a design approach for robotics assembly operation that could estimate the assembly reliability over a robot work-space. Wewerink (1991) considered a model approach to describe complex manned robotic systems. The objective of the model was to answer questions related to reliability and efficiency, design alternatives, function allocation, automation, etc. In the same year Dhillon (1991), in a book entitled *Robot Reliability and Safety* covered many important aspects concerning robotics. The main objective of the book was to be wide in scope, in particular with respect to reliability. Khodabandehloo (1992) stated that the safe and reliable performance of robot systems depends on many factors, including the integrity of the robot's hardware and software, the way it communicates with sensory and other production equipment, the reliable function of the safety features and the way the robot device interacts with its environment. Schneider *et al.* (1994) performed a case study and showed that the framework for the reliability performance index is a useful empirical tool during the selection and design of a configuration of robotic modules of varying reliability and precision. Maier *et al.* (1995) described the derivation of a reliability and safety analysis methodology, and its application in a case study of a handling device (i.e. robot) for the blankets that constitute the fusion reactor Torus. Dhillon and Yang (1996) presented availability analysis of a system composed of a robot and its associated safety system. Supplementary variable and Markov techniques were employed to obtain expressions for state probability, Laplace transform of the state probabilities, and steady-state system availability. The following year, Dhillon and Fashandi (1997) presented an overview of various safety and reliability assessment techniques in robotics. Also, Monteverde and Tosunoglu (1997) developed a measure for fault tolerance capacity of the robot systems by using kinematic redundancy and dual actuation on robot manipulators. Lynne (1998) presented a fully distributed, behavior-based software architechture, named "Alliance", which facilitates the fault tolerance cooperative control of multiple mobile robots. The following year, Monteverde and Tosunoglu (1999) further addressed the fault tolerance measure development and application for serial and parallel robotic structures, where fault tolerance has been promised with higher reliability and safety. A novel modelling of redundancy system in multiple mobile robots developed by Michaelson and Jiang (2000), exhibited the research interests in mobile robots operating in groups to have a considerable degree of fault-tolerance. Also, Dhillon and Aleem (2000) conducted a survey of Canadian robot users concerning robot reliability and safety, and produced a report that provides some constructive conclusions in this field.

The robot system's success based on maintenance was described by Pollard (1980), Ottinger (1983), Cop (1983), Munson (1985), Anon (1987a), Wells (1992), Schneider (1993) and Crowder *et al.* (2000).

3. Robot safety

The earliest statement regarding robotics safety may be credited to the famous science fiction writer Isaac Asimov. He may not have been a recognized authority in the field of robotics safety, but at the age of 21, in 1942, he wrote the three laws of robotics which are still lofty design standards (Asimov and Fredkel, 1985):

(1) A robot must not harm a human being, nor through inaction allow one to come to harm.

(2) A robot must always obey human beings, unless that is in conflict with the first law.

(3) A robot must protect itself from harm, unless that is in conflict with the first or second law.

Historically, one of the fundamental reasons for using robots in industrial applications was to remove human operators from potentially hazardous work environments. The hazards in the workplace included heat, noise, fumes, radiation, toxic atmosphere, physical dangers and other health hazards. Since the passing of Occupational Safety and Health Act (OSHA) (Hamilton and Hancock, 1986) in 1971, worker safety has become a significant factor in promoting the substitution of robots for human labor in dangerous work environments. Although robots may liberate humans from hazardous working conditions, they also bring about safety concerns. The Machine Tool Trade Association (1982) guidelines stated that a working robot can be a potential hazard to personnel under certain circumstances. Nevertheless, robot safety was in the front line of robotics technology during the 1980s. In fact, the bulk of literature had been published (i.e. 287 articles) between 1982-1988, with a record number of 60 articles in 1985 alone. The probability of serious robot accident occurrence and legal actions has forced manufacturers and users to a quick adoption of safety devices and regulations. The need for system safety was highlighted by a $10-million lawsuit awarded to the family of a worker killed by an industrial robot in 1983 (*Computerworld*, 1983). A breakdown of publications on robot safety for various categories is given in Figure 4. Each category is described below.

General safety. Park (1978), to achieve overall robot safety, made various suggestions:

- redundancy;
- fail-safe design of hazard detectors;
- protection against software failures;
- protection against hardware failures;
- intrusion monitoring;
- use of dead-man switches and panic buttons;
- workplace design considerations;

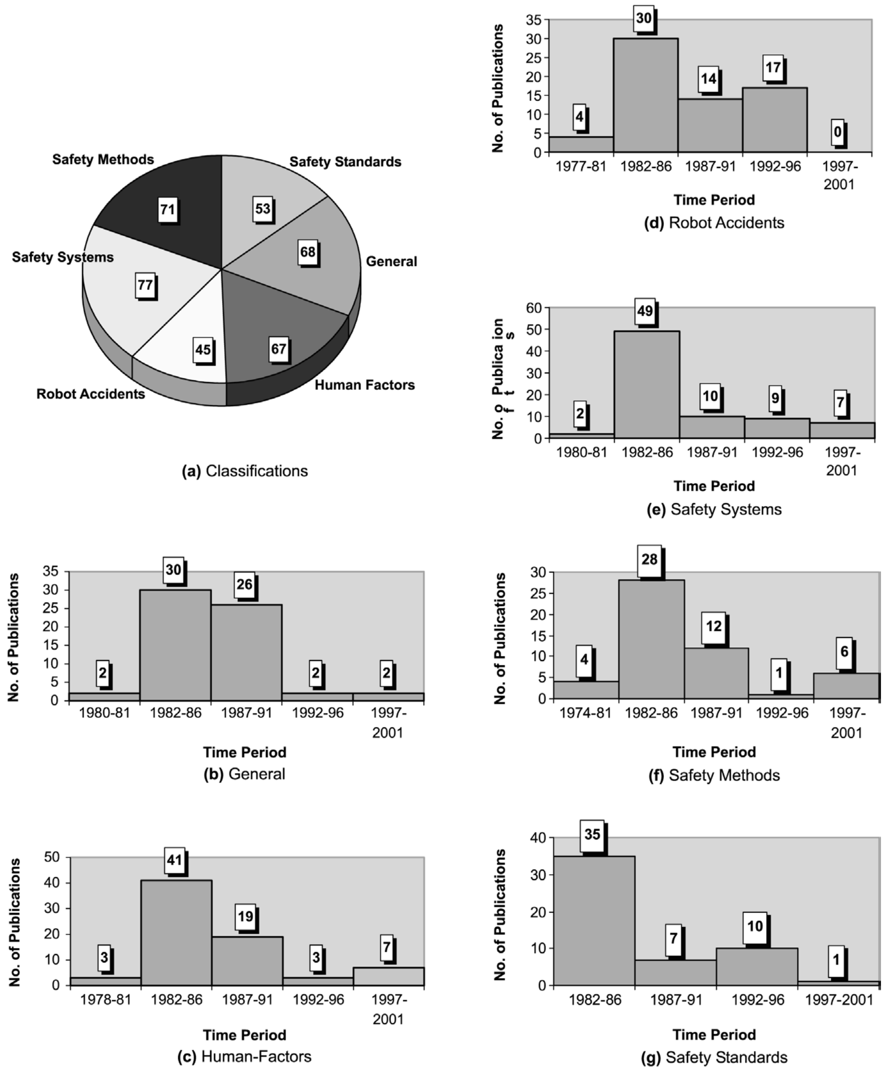

Figure 4.
Profile of publications on robot safety

- restricting arm motion; and
- operator training.

Engelberger (1980) reviewed ambient factors influencing decisions to use robots or presenting environmental requirements. Such factors included:

- ambient temperature;
- shock and vibration;
- electrical noise and interference;
- liquid sprays;

- gases; and
- harmful particles.

Hasegawa and Sugimoto (1982) stated that the safety problem of industrial robots is mainly composed of two elements: one is promoting industrial safety by utilizing industrial robots and the other avoiding unhappy accidents caused by robots themselves. Ghosh *et al.* (1984) reviewed relevant data on accidents involving robots and discussed actions that could be taken to increase the intrinsic safety of robots. In the same year, Noro (1984) connected education and safety in relationship between man and robot. Similar studies on training coupled to safety were presented by Trouteaud (1981), Finnerty (1985) and Balancio (1987). Ziskovsky (1985a,b) suggested that robot safety should start before the robot is introduced into the work environment. He pointed out three steps in establishing any robot system application: planning; installation and start up; and continuing operation. In the same year, Linger *et al.* (1985) proposed the concept of a “production adopted” safety system, i.e. a safety system based on high knowledge about the process. A safety system for automated production to maintain the highest level of safety with the lowest loss of production was proposed by Kilmer (1985). Jones and Dawson (1986) established strategies for ensuring safety with industrial robot systems while Deivanayagam (1986) addressed the possible safety measures for controlling hazards unique to robotic work systems. Ramachandran and Vajpayee (1987) investigated robot safety and presented an analysis of the sources of accidents, and the accident-prone operational phases of robotics installations. Similar studies on safety consideration for robotics installation were presented (Barrett *et al.*, 1981; Bellino, 1985a; Ghosh, 1984; Leipold, 1983a,b; Vautrin, 1985; Wakita *et al.*, 1998). As successful operation of any robotics system, the maintenance of robots, especially of the preventive type, is essential; two of the typical sources of accidents during maintenance are control errors and mechanical failures. In 1987 and 1988, Etherton proposed safe maintenance guidelines for robotics workstations (Etherton, 1987a,b, 1988; Etherton *et al.*, 1988). Jiang and Otto (1990) reviewed several robot safety techniques, and presented a procedure analysis for the planning, installation, and operation stages of adding a robot to the workplace. The analysis covered safety measures that could be taken, risk of not taking them, causes of the risks, and corrective or preventive measures. Fox (1999) took a general look at robotic safety and concluded that robotic safety is everyone’s responsibility, including plant managers, buyers, integrators, maintenance people, operators, and robot manufacturers.

Human factors. Human factors in robotics is the study of principles concerning human behavior and characteristics for efficient design evaluation, operation and maintenance of robots (Karwowski, 1991). Ghosh and Lemay (1985) discussed man-machine interactions during robot maintenance and methods to improve safety. Parsons (1987) explained how the applied science known as “human factors” can help prevent accidents in which robots may harm workers, damage equipment, or themselves. Karwowski *et al.* (1988a, b) discovered the average approach distance of 20.9cm for those who had seen the accident, compared to 15.3cm for those who did not. Rahimi and Karwowski (1990) reviewed critical issues in the human-robot interaction area, and proposed a research framework to study human aspects of robotics system design, while Beauchamp and Stobbe (1990) evaluated factors that could effect human performance in the event of an unexpected robot motion. Sun and Sneckenberger (1992) introduced conceptual safety guidelines for the design of a human-robot symbiotic system to achieve reasonable allocation of function and optimum match between the human and the robot, to reduce the possibility of human error, and to enhance system safety and reliability. Yamada (1997) and Yamada *et al.* (1997) introduced a human-oriented design approach for human-robot coexistence by adopting human pain tolerance limit and its application. In the same year, Kuroda (1997) reviewed the influence of ethnic culture on human robot cooperation. Yamada *et al.* (1999) reviewed, with fault tree analysis (FTA), human safety issues for a human/robot coexistence system, developed fail-safe analog circuits and mechanical safeguarding measures, and demonstrated that human/robot intention mismatch leads to an emergency stop. Also Yamamoto *et al.* (1999) examined the avoiding motion of robots for humans by considering human emotions, Lim and Tanie (2000) presented significant research on human safety mechanisms of human-friendly robots, which paid much attention to the technologies of human robot symbiosis and proposed a human-friendly robot with passive viscoelastic trunk and passively movable base.

Accidents. Almost all reports involving industrial robot accidents specify an actual or potential risk to those involved in programming, and specifically teaching (Carlsson, 1974; Japanese Industrial Safety and Health Association, 1983; Jiang and Gainer, 1987; Millar, 1984; Nicolaisen, 1985; Sugimoto and Houshi, 1986). Jiang and Gainer (1987) define the robot accidents as:

> Contact between the person and a robot either directly or indirectly, leading to a record of the accident.

Sugimoto (1977), in one of the earliest publications on robot accidents, showed that the greatest risk of accident occurs during programming, and maintenance. Also, he pointed out that only 10 per cent of the accidents occurred during normal operation. On the basis of an investigation by Carlsson *et al.* (1980) carried out in Swedish industry, out of 13 accidents examined, the prime hazard was either operator error or the entrance of a worker into the envelope of the robot during its operation in the automatic mode. The result of another robot survey conducted by the Japanese Ministry of Labor in 1982 pointed out 11 cases of accidents and 37 of near-accidents. Furthermore, eight of the 11 accidents (73 per cent) were due to unexpected start-moving. It was also reported that more than a third of the accidents occurred because of operator error and nearly two-thirds were due to robot problems (Sugimoto, 1982a,b). Ziskovsky (1983a) identified the common cause of fatal accidents involving industrial robots, i.e. the lack of proper respect for what the robot is and the accompanying appreciation for its capabilities and limitations. In the same year, Percival (1983a) studied accident reports from various countries and provided a summary of sources of hazards that may lead to an accident. A similar study was conducted by Parsons (1985). Collins (1984, 1986) pointed out the importance of space requirements for designing a robotics work station to avoid pinch points, while Ryan (1986) presented a review of research efforts in determining the quantification of accident causation based on a human behavior model. Also, in the same year, to express hazard in the field of robot safety, Sugimoto and Houshi (1986) formulated the following relationship:

$$\text{Hazard} = [(\text{Error Frequency})] \times [(\text{Percent Shift to Hazard Rate})$$

$$\times(\text{Severity of Injury})] = (\text{Reliability})] \times [(\text{Safety})].$$

Safety systems. Rahimi (1984), on the basis of earlier robot accident reports, classified major factors contributing to robot accidents and concluded that system safety analysis is an appropriate approach to analyze safety of semi-automated and automated robot systems. In the same year, in two separate articles, an automatic robot safety shutdown system was proposed by Anon (1984a) and Ziskovsky (1984a, b). Kilmer *et al.* (1985) considered a Watch Dog Safety Computer that could be used to monitor robot movements in the workstation to detect operations and to stop the robot before collision or damage. Millard (1986) discussed results of the research at the Center for Manufacturing Productivity (CMP) at Rensselaer Polytechnic Institute (RPI) to develop an intelligent sensory system that will monitor the working envelope of a robot. Ward (1988) reviewed the robot safeguarding problem and presented an overview of programmable electronic based control systems. Motamed and Schmitt (1993) discussed the development of "intelligent" safety systems using computer vision, while Hischfeld *et al.* (1993) studied survey responses from 19 out of 55 industrial robot users of over 580 robots. Findings indicated that only 20 per cent of robots were found to be completely enclosed, while 60 per cent had a limited barrier or no barrier. Furthermore, safety measures such as light curtains and floor mats were found to be the most widely used safety devices at 67 per cent and 59 per cent, respectively. In addition, industrial robot users demonstrated poor adherence to the Occupational Safety and Health Administration (OSHA) requirements and to the American National Standards Institute/Robot Industries Association (ANSI/RIA) standards. Abdallah *et al.* (1994) proposed a real time system that is able to detect an intruder in a dangerous area, even when there are disturbing illumination changes in the considered shop-floor. Stentz and Hebert (1995) developed a complete system that integrates local and global navigation. The local system uses a scanning laser range finder to detect obstacles and recommends steering commands to ensure robot safety. These obstacles are passed to the global system which stores them in a map of the environment. Crane *et al.* (1996) successfully implemented tele-proprioception techniques for determining robot position and orientation in known environments with a single camera. Pegman and Reed (1997) pointed out that more complex electromechanical systems with competent control systems could be beneficial to safety of remote operations when the operator interface is well designed. In the same year, Dhillon and Yang (1997) presented mathematical analysis of a redundant robot configuration with built-in safety system. The following year Aghazadeh *et al.* (1998) presented a simple and effective hazard analysis system for a robotic work cell. Dhillon and Fashandi (1999) presented reliability and availability analysis of a robot with duplicate safety units. The following year Karlsson *et al.* (2000) introduced a dynamic safety system based on sensor fusion that can be implemented in an industrial robot system. Beerthuizen and Kruidhof (2001) presented system and software safety analysis for the European Robotic Arm (ERA), to be used in manned space operation on the International Space Station.

Safety methods. Lee (1985) described safety precautions for robot users including risk analysis, safety consideration, and proper methods of safeguarding. He also presented safety measuring methods and devices. Weck and Schoenbohm (1987) presented a mechanism that allows improvement of the existing safety precautions in all fields of robot technology. Rahimi and Xiadong (1991) presented a generic software safety verification and encoding for safety-critical actions of robots. Buckingham (1993a, b) considered examples of robotic devices applied to different surgical tasks that illustrate the issue of intrinsically safe design and passive and active systems. Akeel *et al.* (1994) addressed the factors that influence robotic safeguarding with respect to the identification of potential hazards and the various controlling mechanisms instituted to prevent them. Suita *et al.* (1995) proposed a concept and a design method of covering a robot with a visco-elastic material to achieve both impact force attenuation and contact sensitivity, and keeping it within the human pain tolerance limit. Montgomery and Lauderbaugh (1996) developed a space robot hazard identification checklist through the identification of sources of possible hazards, assessment of associated risks, and determination of necessary safeguards. Also, Atcitty and Robinson (1996) demonstrated the use of failure modes and effects analysis (FMEA) approach for the safety assessment of a robotic system developed at Sandia National Laboratories. Ikuta and Nokata (1999) developed a general safety evaluation method for human-care robots.

Safety standards. Ordinance amending parts of the industrial safety and health regulations were officially announced in 1983 (Kotake, 1989). Thus, the action to be taken by employers for the prevention of industrial accidents caused by industrial robots was established. Motosko (1986) reviewed the literature on robot-related hazards and discussed when and how they occur, as well as precautions and safeguards that may prevent industrial incidents and accidents involving robots. Domning *et al.* (1992) identified safety issues as well as the general safety requirements necessary for the safe operation of the automated test bed (ATB) to handle the processing of special nuclear materials (SNM). In 1993, the Robotic Industries Association (RIA), in association with the American National Standards Institute (ANSI), established stringent safety guidelines for robot manufacturers and users (Seim and Beutler, 1993). Pegman (1994) outlined the activities of the National Advanced Robotics Research Centre (NARRC) in the promotion of safety and standards for advanced robots. Standards and user guidelines for robot safety were also recommended and discussed extensively by Park (1978), Potter (1983), Ziskovsky (1985a, b), Clem (1986), and Fryman (2000).

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(continued)

Table AI.

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504 Yamashita, T. (1987a)	517 Ziskovsky, J.P. (1983b)
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506 Yeh, P. *et al.* (1988)	519 Ziskovsky, J.P. (1984b)
507 Yokomizo, Y. (1987)	520 Ziskovsky, J.P. (1984c)
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Table AI.