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Safety Assessment in Operation of Human-centered Robots – An Information-theoretic Approach

Gi Heung Choi*

Department of Mechanical Systems Engineering, Hansung University, Seoul 136-792, Korea

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Abstract : Operations of human-centered robot, in general, facilitates the creation of new process that may potentially harm the human operators. Design of safety-guaranteed operation of human-centered robots is, therefore, important since it determines the ultimate outcomes of operations involving safety of human operators. This study discusses the application of information-theoretic measures to safety assessment of human-centered robotic operations. Some examples are given.

Key words: Human-centered Robot, Safety Assessment, Discrimination Information, Head Injury

1. Introduction

Safety is considered to be a commonsense approach to removing agents of injury [1]. Safety, as a concept and practice, has shifted to a complex methodology for the reliable control of injury to human beings and damages to property. However, it does lack a theoretical base. As safety is concerned with reducing accidents and controlling or eliminating hazards at the robotic operations, accident prevention is a significant step towards safety improvement.

Recently, there have been increasing interest in emerging field of human centered robot. This field focuses on applications such as medical robotics and service robotics, which require close interaction between robotic manipulation systems and human beings, including direct human-manipulator contact [2]. Robotic manipulator that is to interact with human operators has a single design consideration at a premium - safety [3]. Under no circumstances should the robot manipulator cause harm to people in its surroundings, directly or indirectly, in regular operation or in failure. Robot safety involves several different considerations and depends on many factors, ranging from software dependabil;ity, to possible mechanical failure, to human errors in interfacing with the machine, etc.

Process design, in general, facilitates the creation of new process that may potentially harm the human operators [4]. Design of safety-guaranteed operation of human-centered robots is, therefore, important since it determines the ultimate outcomes of operations involving safety of human operators. Safety in robotic operations is considered to be a measure of relative freedom from accidents. In order to improve the safety performance, control of accident is essential and the effectiveness of control of accidents needs to be estimated before any new robotic operation is put into practice. Safety performance criterion, in this case, needs to be defined a priori.

This study discusses the application of information-theoretic measure to safety assessment of robotic operations. The idea is based on the general principles of design and their applications to quantification of uncertainty in safety involved in the process. An example of Cartesian robotic movement is then given.

2. Information (Entropy and Cross Entropy) Analysis

The concept of entropy was first introduced in statistical thermodynamics by physicist Boltzman to quantify the uncertainty involved in the system [4,5,6,7]. Such uncertainty stems from the randomness of the process.

The entropy of a process with the probability density q is represented as:

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*Corresponding author: gihchoi@hansung.ac.kr

$$E[q] = -\int_C q(x)\log q(x)dx \tag{1}$$

subject to constraints

$$\int_C q(x)dx = 1 \tag{2}$$

The entropy is a measure of the amount of information produced by a random process *x(n)*, or a measure of uncertainty in a random process. The larger value of entropy corresponds to more uncertainty in the process. The discrimination information (or cross entropy) is a generalization of entropy when the *prior* density *p* of *x(n)* is available, and given by:

$$H[q,p] = \int_C q(x)\log\left(\frac{q(x)}{P(x)}\right)dx \tag{3}$$

Eq(3) states that the total amount of information produced by a process *x(n)* equals the sum of the amount of information gained by the *posterior* (current) density *q* and the information already acquired by *p*. The priors must be strictly positive, i.e.,

$$p(x \in C) > 0 \tag{4}$$

For discrete events, $q_i, q_2, q_3, \ldots, q_i$, the average information content of the discrete events (or entropy) is defined as:

$$E[q] = \sum_i E[q_i] = -\sum_i q_i \log q_i \tag{5}$$

subject to constraints

$$\sum_i q_i = 1, \ \sum_i c_i q_i = C \tag{6}$$

It can be proved that the cross entropy functional becomes a function of *2n* variables and

$$H[q,p] = \sum_i q_i \log(q_i/p_i) \tag{7}$$

Interested readers may refer to [7] for more details about entropy and cross entropy analysis.

3. Uncertainty in a Safety Context

In terms of safety involved in the design of manufacturing process, entropy quantifies the complexity of achieving the safety in the process. The more complex a process is, the more information is required to describe and understand the safety features in the process. It is a measure of knowledge required to satisfy a given level of the safety requirement hierarchy and closely related to the probability of achieving safety requirements involved in the process.

Note that the knowledge required to achieve a task in a safe manner depends on the probability of success. For example, if a task can be achieved safely without prior knowledge or additional knowledge about the potential hazards or no hazards are involved in the task, the probability of success in achieving such task without safety problems is "1" and no requisite information is necessary. Probability of success depends on the complexity of task in guaranteeing the safety involved. Therefore, information is related to complexity. Probability of success in achieving tasks increases as complexity of designed processes decreases. Process design must transmit sufficient knowledge so that probability of achieving task (satisfying safety requirements) is as high as possible.

4. Uncertainty in a System Context

Consider in Figure 1 where the performance of the process is quantified in view of the safety. Safety range signifies the tolerance associated with process parameters [6,8]. System range designates the capability of manufacturing system (in terms of tolerance) and the current performance of designed processes. Common range is the overlap between the safety range and the system range. Figure 1 implies how much of safety requirements are satisfied by the current performance of the designed process (system range).

The probability of achieving the particular safety requirement *i* and the information content are then defined, respectively, by:

$$q_i = \left(\frac{System\ Range}{Common\ Range}\right) \tag{8}$$

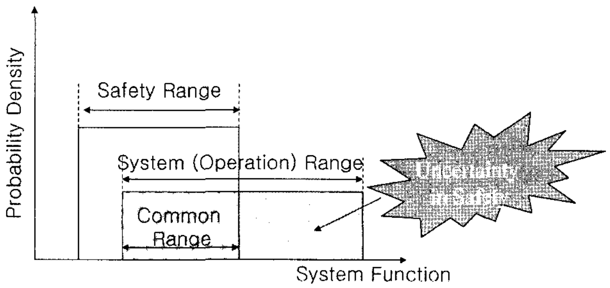

Fig. 1. Probability distribution of a system parameter.

$$E[q_i] = \log\left(\frac{1}{\left(\frac{Common\ Range}{System\ Range}\right)_i}\right) = \log\left(\frac{System\ Range}{Common\ Range}\right)_i \quad (9)$$

Information content is a measure of the probability of success of achieving the specified safety requirements in manufacturing process or a measure of uncertainty in insuring safety in manufacturing process. It is independent of specific nature of process parameters such as work envelop of a robot motion, noise level in work environment, weight of the load and etc. If the safety range does not overlap with the system range (operation range), process design does not reflect the safety requirements. If the safety range covers the entire system range, all the safety requirements are satisfied by the process parameters in the manufacturing processes.

Two ways of reducing uncertainty (information contents) are:

- to reduce the system range so that the process is as simple as possible for safety.
- to increase the common range. This implies that one has to try to satisfy all safety requirements specified by the safety range with process parameters.

5. Examples

5.1 Process Parameters in Robotic Operations

Consider the information associated with the dimensional precision of work envelop in robotic operation. Here, the process parameters are geometric dimensions of work envelop. The work envelop is usually composed of several components depending on the type of robot. Each component independently influences the safety of workers. Cartesian coordinate robot, for example, has vertical stroke, vertical reach, horizontal stroke, horizontal reach and traverse stroke, which define system (operation) range of the process as shown in Figure 2.

For horizontal reach, the safety range is the "safe" horizontal reach that guarantees the safety of workers and is specified by a process designer, from 1.0m to 1.2m in Figure 3. The safety range is usually designated as the "Safe Work Area" on floor. This range varies depending on the types of the robot and the work involved and can be reduced either intentionally or inadvertently by the work range of human operators on floor. The system range is the range of a robot arm to move horizontally and is, say between 0.1m and 1.0m in Figure 3. Then, the "Safety Limit" becomes 1.0m, which implies that if a robot arm reaches beyond the safety limit or the system range is reduced below the safety limit, the uncertainty exists and the safety of workers may not be guaranteed. When the safety range coincides with the system range, no uncertainty (information contents) in ensuring the safety of human operators is assumed.

However, if either human operators break into the safe work area so that the safety range shrinks by 0.2m to between 0.1m and 0.8m as in Figure 4 (case 1) or the horizontal reach of a robot arm is extended by 0.2m to 1.2m beyond the safety limit that is work-specific, as in Figure 5 (case 2), the safety of human operators is

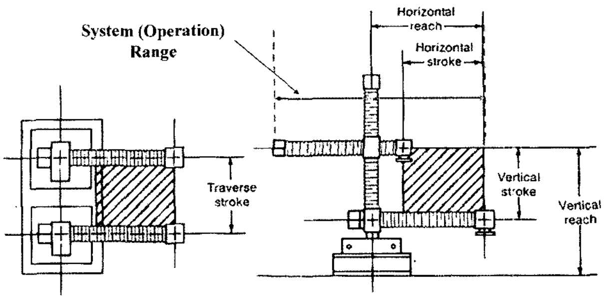

Fig. 2. System (operation) range for horizontal reach of a Cartesian robot.

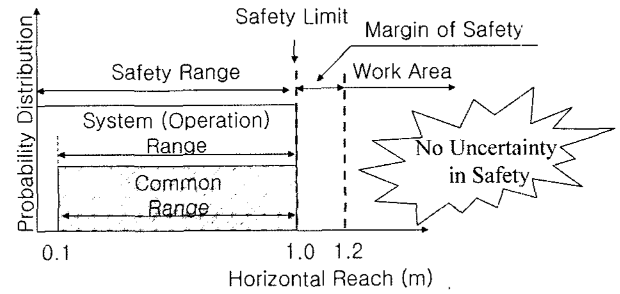

Fig. 3. Probability distribution of horizontal reach that guarantees the safety of workers.

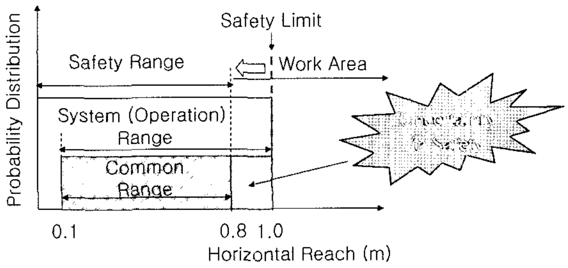
[Case 1] Extend Work Area below SL while keeping SOR (Event p_1)

Fig. 4. Probability distribution of horizontal reach that does not guarantee the safety of workers due to shrinkage of safety range.

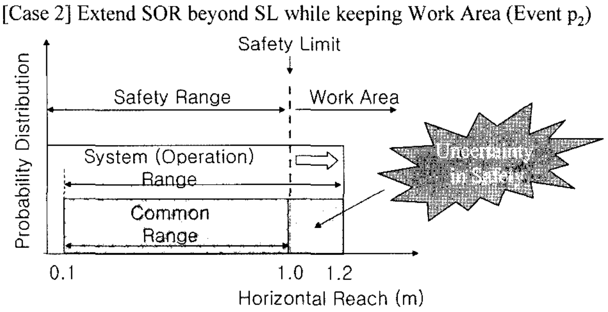

Fig. 5. Probability distribution of horizontal reach that does not guarantee the safety of workers due to extension of system range.

not guaranteed.

The uncertainty in safety in each case is then given by:

$$E[p_1]= \log\left(\frac{System\ Range}{Common\ Range}\right) = \log\left(\frac{1.0-0.1}{0.8-0.1}\right) = 0.109 \tag{10}$$

$$E[p_2]= \log\left(\frac{System\ Range}{Common\ Range}\right) = \log\left(\frac{1.2-0.1}{1.0-0.1}\right) = 0.087 \tag{11}$$

where p_1 and p_2 designate the event of shrinking the safety range by 0.2 m and the event of extending the reach of a robot arm by 0.2m, respectively. The result in Eq(10) and (11) suggest that breaking into the safety limit by human operators causes more uncertainty in terms of safety than extending the reach of a robot arm beyond the safety limit. In general, reducing the common range (by reducing the safety range) causes more uncertainty than extending the system range. Therefore, uncertainty measure must be taken into account in adjusting the safety limit so as to minimize the increase of uncertainty involved in the process. If the safety range shrinks by 0.2m and the system range increases by 0.2m at the same time, the uncertainty in safety is given by:

$$E[q]= \log\left(\frac{System\ Range}{Common\ Range}\right) = \log\left(\frac{1.2-0.1}{0.8-0.1}\right) = 0.196 \tag{12}$$

where q designates the event of both shrinking the safety range by 0.2m and extending the reach of a robot manipulator by 0.2m. Note that the cross entropy quantifies the change in uncertainty in terms of safety as in Figure 6.

If one specifies, for example, the increase of uncertainty using the cross entropy, one can have:

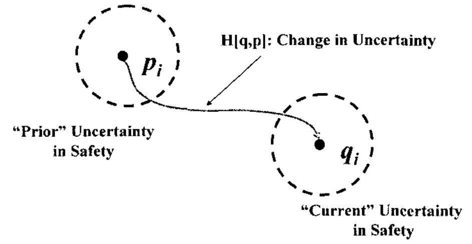

Fig. 6. Concept of discrimination information (cross entropy) quantifying change in uncertainty in terms of safety.

$$H[q,p_1] = \log(q/p_1) = \log\left(\frac{1.2-0.1}{0.8-0.1}\right) - \log\left(\frac{1.0-0.1}{0.8-0.1}\right) = 0.087 \tag{13}$$

$$H[q,p_2] = \log(q/p_2) = \log\left(\frac{1.2-0.1}{0.8-0.1}\right) - \log\left(\frac{1.2-0.1}{1.0-0.1}\right) = 0.109 \tag{14}$$

where $H[q,p_1]$ q specifies the uncertainty increased by extending the reach of a robot arm by 0.2m. Similarly, $H[q,p_2]$ specifies the uncertainty increased by shrinking the safety range by 0.2m. The total safety-related uncertainty of joint events (event p1 and p2) in the process is simply the sum of entropy (cross entropy) associated with each event, provided that each event is probabilistically independent of each other: In this case, one can simply write:

$$I_i = \log\left(\frac{1}{q(p1,p2)}\right) = \log\left(\frac{1}{q(p1)}\right) + \log\left(\frac{1}{q(p2)}\right) = 0.087 + 0.109 = 0.196 \tag{15}$$

Figure 7 depicts the cross entropy calculated for prob-

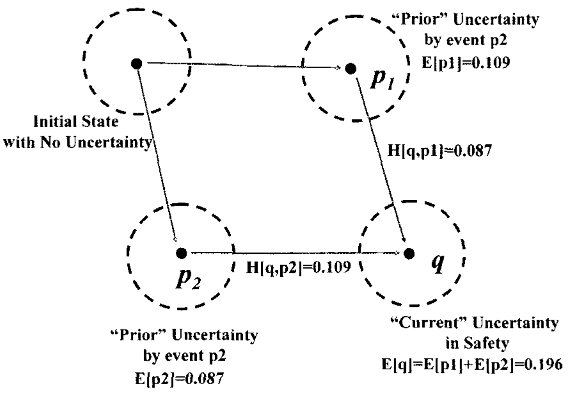

Fig. 7. Cross entropy for independent events p1 and p2.

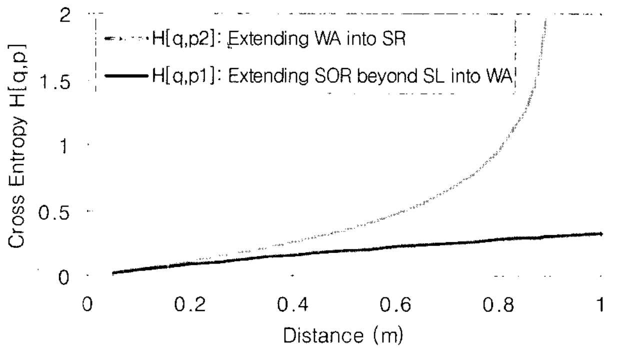

Fig. 8. Cross entropy as a function of distance.

abilistically independent events.

Next, cross entropy was calculated as a function of distance and shown in Figure 8. It is apparent from the figure that extending "Work Area" has more significant effect on the uncertainty in safety than extending the system range.

5.2 Uncertainty in Head Injuries on Human Operators

The most serious hazard present when working in close proximity with robotic manipulator is the potential for large impact load (high impedance), which can result in serious injury or death. To evaluate the potential for serious injury due to impact, an empirical formula developed by the automotive industry to correlate head acceleration to injury severity known as the head injury criteria (HIC) can be used. Figure 9 shows HIC as a function of effective inertia and interface stiffness [2]. Also shown in Figure 9 is the corresponding likelihood of a concussive injury.

The solution to reducing the effective impedance and thus improving safety is to build a lightweight, low inertia manipulator (low impedance/compliant material). However, this is impractical due to amount of material used and system bandwidth. Instead, one can use new actuation approaches. New actuation approaches have been developed to overcome the safety and performance limitations of existing systems. They are SEA (Serial Elastic Actuation), DMM (Distributed Macro-Mini Actuation) and VST (Variable Stiffness Transmission).

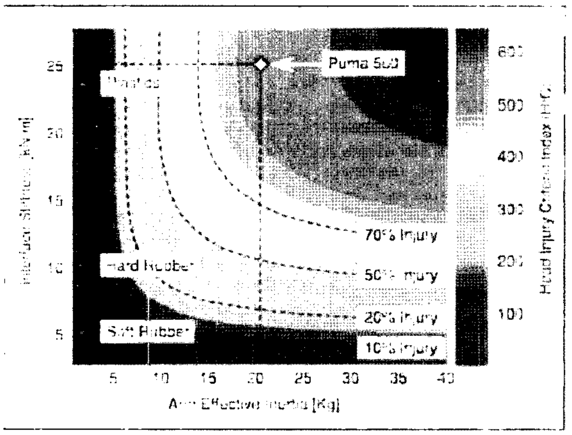

Fig. 9. HIC as a function of effective inertia and interface stiffness

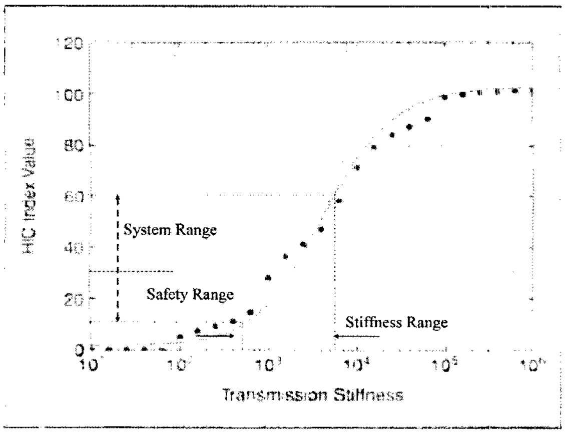

Fig. 10. HIC evaluated for the impact of a manipulator [3]

The positive effect of transmission elasticity on safety is shown in Figure 10, where the HIC of the impact between an elastically actuated manipulator movement at uniform velocity and an operator is reported at varying the transition stiffness. The downside of elastic coupling is the performance degradation. Intuitively, compliant transmission tends to respond slowly to torque inputs on the actuator and to oscillate around the goal position, so that it can be expected that the promptness of an elastically actuated arm is severely reduced if compliance is high enough to be effective on safety accounts.

Consider in Figure 10 where the performance of the robotic manipulator is quantified in view of the head injury coefficient. Given the stiffness range of a robotic manipulator, the corresponding range of HIC values (solid line) can be evaluated from the equation [3]:

$$M_{rot}(K_{transm}) = M_{link} + \frac{K_{transm}}{K_{transm}+\gamma} M_{rot} \tag{16}$$

where

- K_{transm}: transmission stiffness
- M_{link}: effective link inertia of 0.1kg
- M_{rot}: rotor inertia of 1.2kg
- γ: constant

and uniform rotor velocity of 10m/s before impact was assumed. A value of 3000 was assumed for γ.

Safety range signifies the tolerance associated with the HIC. System range designates the capability (in terms of tolerance) and the current performance of robotic manipulator. Common range is the overlap between the safety range and the system range. Figure 10 implies how much of safety requirements are satisfied by the current performance of a robotic manipulator (system range). For example, for the case where the transmission stiffness of robotic manipulator ranges from 4×10^2 to 4.5×10^3 and safety range from 0% to 30 % of HIC value, the uncertainty in safety is calculated to be

$$E[e_2] = \log\left(\frac{System\ Range}{Common\ Range}\right) = \log\left(\frac{60-10}{30-10}\right) = 0.398 \qquad (17)$$

5.3 Total Uncertainty due to Geometric Tolerance and Head Injuries on Human Operators

The total uncertainty in the process is simply the sum of uncertainty associated with both geometric tolerance (e_1) and head injury on workers (e_2), provided that each event is probabilistically independent of each other:

$$\begin{aligned} I_{total} &= \log\left(\frac{1}{q(e_1, e_2)}\right) = \log\left(\frac{1}{q(e_1)}\right) + \log\left(\frac{1}{q(e_2)}\right) \\ &= 0.196 + 0.398 = 0.594 \end{aligned} \qquad (18)$$

The process of robotic operation then must be designed in such a way that the total uncertainty in safety in Eq(18) is minimized.

5. Conclusions

In this study, application of information-theoretic measure such as entropy and cross entropy to safety assessment of human-centered robotic was suggested. The idea is based on the general principles of design, design axioms and their applications. An example of Cartesian robotic movement was given in which the entropy and the cross entropy proved to be effective in determining the ultimate outcomes of operation involving safety of human operators. The process must be designed in such a way that the total uncertainty in safety is minimized.

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