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Assessment of Safety Performances in Operation of Human-centered Robots Using Geometric Tolerance and Head Injuries Criteria

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Abstract : Operation 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 geometric tolerance and head injury criteria to safety assessment of human-centered robotic operations. Examples show that extending “Work Area” has more significant effect on the uncertainty in safety than extending the system range in the presence of velocity control.

Keywords: human-centered robot, safety assessment, discrimination information, geometric tolerance, head injury criteria

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 dependability, 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.

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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:

$$E[q] = \sum_i E[q_i] = -\sum_i q_i \log q_i \tag{1}$$

subject to constraints

$$\sum_i q_i = 1, \sum_i c_i q_i = C \tag{2}$$

The discrimination information (or cross entropy) is a generalization of entropy when the *prior* density *pi* is available, and given by:

$$H[q,p] = \sum_i q_i \log(q_i/p_i) \tag{3}$$

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

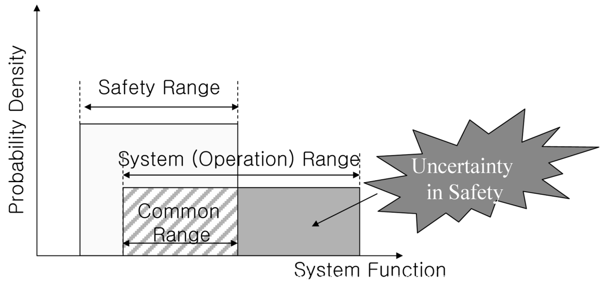

Fig. 1. Probability distribution of a system parameter.

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:

$$q_i = \left(\frac{System\ \ Range}{Common\ \ Range}\right)_i \tag{4}$$

$$E[q_i] = \log\left[\frac{1}{\dfrac{Common\ Range}{System\ \ Range}}\right] = \log\left(\frac{System\ \ Range}{Common\ \ Range}\right)_i \tag{5}$$

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 0.1 m and 1.0 m in Figure 3. Then, the “Safety Limit” becomes 1.0 m, 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 0.1 m and 0.8 m as in Figure 4 (case 1) or the horizontal reach of a robot arm is extended by 0.2 m to 1.2 m beyond the safety limit that is work-specific, as in Figure 5 (case 2), the safety of human operators is not guaranteed.

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

$$E_1[p_1] = \log\left(\frac{System\ \ Range}{Common\ Range}\right) = \log\left(\frac{1.0-0.1}{0.8-0.1}\right) = 0.109 \tag{6}$$

$$E_1[p_2] = \log\left(\frac{System\ \ Range}{Common\ Range}\right) = \log\left(\frac{1.2-0.1}{1.0-0.1}\right) = 0.087 \tag{7}$$

where p_1 and p_2 designate the event of shrinking the

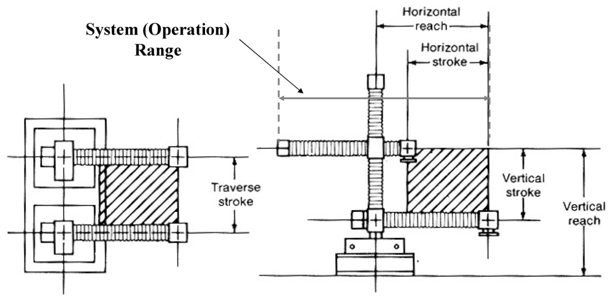

Fig. 2. System (operation) range for horizontal reach of a Cartesian robot.

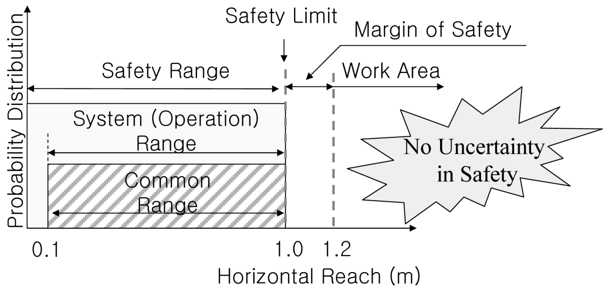

Fig. 3. Probability distribution of horizontal reach that guarantees the safety of workers.

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

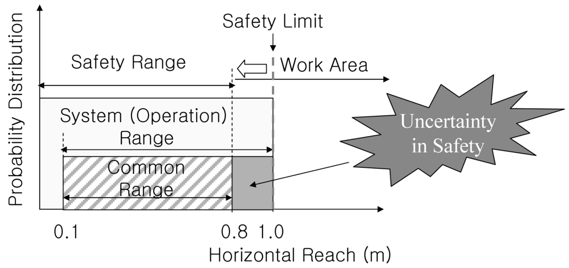

Fig. 4. Probability distribution of horizontal reach that does not guarantee the safety of workers due to shrinkage of safety range.

[Case 2] Extend SOR beyond SL while keeping Work Area (Event p_2)

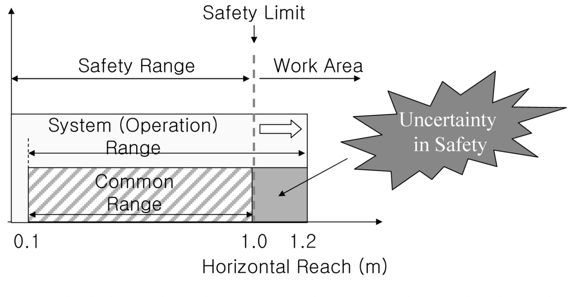

Fig. 5. Probability distribution of horizontal reach that does not guarantee the safety of workers due to extension of system range.

safety range by 0.2 m and the event of extending the reach of a robot arm by 0.2 m, 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 0.2 m and the system range increases by 0.2 m at the same time, the uncertainty in safety is given by:

$$E_1[q] = \log\left(\frac{System\ Range}{Common\ Range}\right) = \log\left(\frac{1.2-0.1}{0.8-0.1}\right) = 0.196 \tag{8}$$

where q designates the event of both shrinking the safety range by 0.2 m and extending the reach of a robot manipulator by 0.2 m.

Note that the cross entropy quantifies the change in uncertainty in terms of safety as in Figure 6.

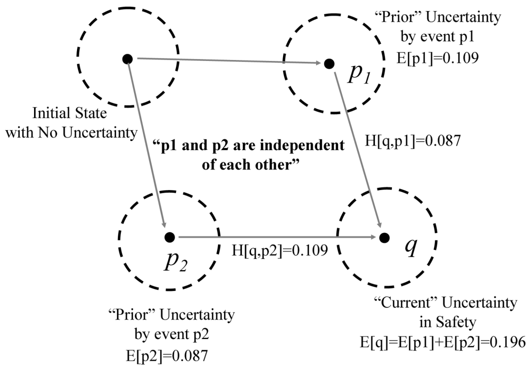

Fig. 6 Concept of discrimination information (cross entropy) quantifying change in uncertainty in terms of safety

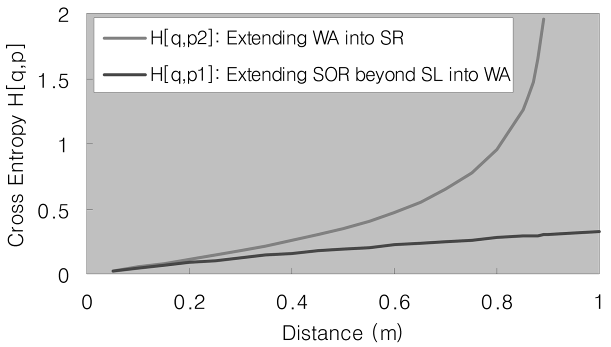

Figure 7. Cross entropies H[q, p1] and H[q, p2] as functions of distance.

For example, 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.

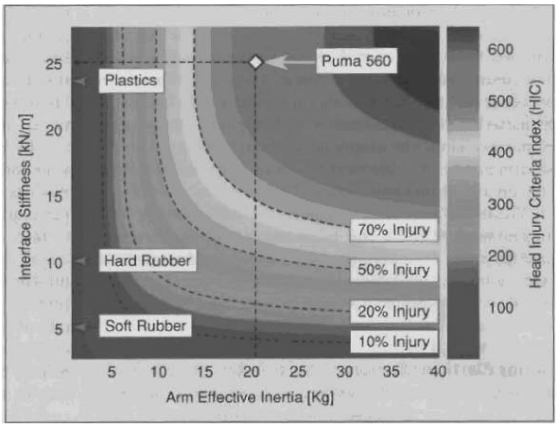

Fig. 8. HIC as a function of effective inertia and interface stiffness [2]

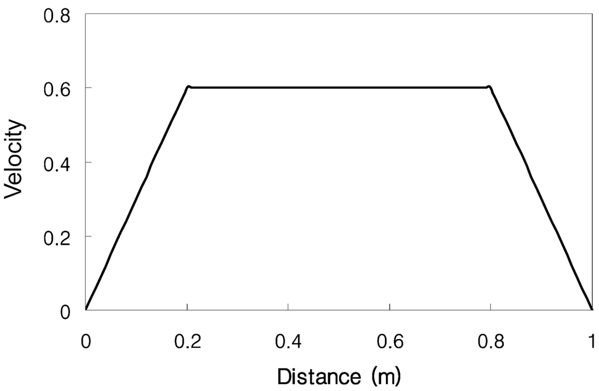

Fig. 9. Velocity as a function of normalized distance traveled by a single joint.

Versace [4] defined HIC to be:

$$HIC = T\left[\frac{1}{T}\int_0^T a(\tau)d\tau\right]^{2.5} \tag{9}$$

where T is conventionally the final time of impact. As the choice of this time is difficult, it is recommended to consider the worst case HIC at varying T, which corresponds to taking T equal to the time at which the head reaches its maximum velocity *v(T)*. An HIC value of 1,000 or greater is typically associated with extremely severe head injury; a value of 100 can be considered suitable to normal operation of a machine physically interfacing with humans. In general, an acceptable HIC of 100 would imply a velocity upper limit $v_{safe}=2\ mm/sec$. A generalization of the HIC to collisions with other parts of the body can be considered whereby the 2.5 coefficient is replaced by other empirically determined values α and assuming the operator is standing still before the impact, one can write

$$HIC = T^{1-\alpha}v(T) \tag{10}$$

where *v* is a constant and v is the velocity. In general, evaluation of the above severity indices is numeric, based on either experimental or simulation data. However, it is instructive to compute the HIC for the basic case of a single rigid joint moving at a uniform velocity *v(T)* before impact as shown Figure 9. In general, in order to reach to farther area without sacrificing the performance rotor arm needs to increase its velocity, which in turn results in a higher value of HIC.

If a HIC value of 10 is assumed to be suitable to normal operation for the absolute safety of humans interfacing with machines, the corresponding uncertainty would be calculated as:

$$E_2 = \log\left(\frac{System\ Range}{Common\ Range}\right) = \log\left(\frac{HIC}{10-0}\right) \tag{11}$$

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:

$$E_{total} = \log\left(\frac{1}{q(e_1,e_2)}\right) = \log\left(\frac{1}{q(e_1)}\right) + \log\left(\frac{1}{q(e_2)}\right) = E_1 + E_2 \tag{12}$$

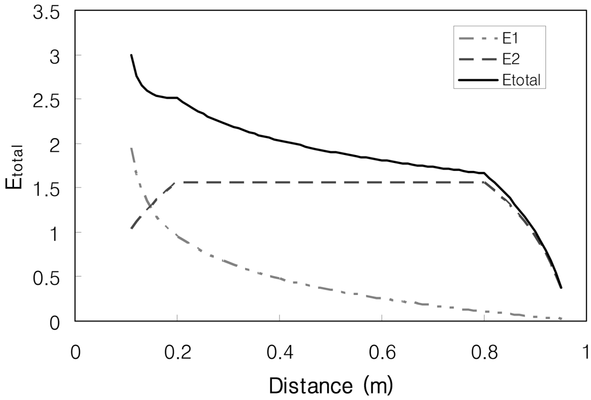

Fig. 10. E_{total} calculated as a function of distance traveled by a single joint. Data in Figure 7 α=2 and and T=10^{-3} in Eq(10) were used for simulation.

Total entropy E_{total} as a function of distance traveled by a single joint is shown in Figure 10. In the figure, α=2 and T=10^{-3} in Eq(10) and the data in Figure 7 were used. The process of robotic operation then must be designed in such a way that the total uncertainty in safety in Eq(12) is minimized.

Again, extending "Work Area" has more significant effect on the uncertainty in safety than extending the system range even when the velocity profile in Figure 9 was taken into account.

5. Conclusions

In this study, application of geometric tolerance and head injury criteria 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.

Acknowledgement

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