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Techniques for Rapid Visual Communication of Uncertainty in System Safety Analyses

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Abstract

Visual representations (e.g., block diagrams, notional illustrations, schematics, engineering or architectural renderings and animations) of complex, high-consequence systems are efficient means to relay a wealth of subsystem and component information to a wide range of audiences (e.g., regulators, managers, key policy makers). Unfortunately, these rich visualizations (often presented only once) may not include salient and efficient representations of uncertainty estimates in subsystem and component performance reflecting a range of possible operating environments. System safety analyses of complex systems are particularly susceptible to miscommunication of uncertainty ranges due to the myriad of factors that may influence critical failure modes. More than one engineer has encountered the situation in which an impressive visualization of a complex system (or inter-system interactions) is remembered by key decision makers, while spoken caveats, tabular data, detailed footnotes, etc., concerning uncertainty bounds are poorly remembered or forgotten. This paper presents methods of salient and efficient visual presentation of safety analysis uncertainties for complex systems. Specific visual manipulations including object focus, transparency, and color are used to quickly relay uncertainties spanning orders of magnitude.

Introduction

Numerous techniques are available for visually representing complex, high-consequence systems and their subsystems and components. These visual descriptions may be in the form of diagrams, schematics, animations or photorealistic images that are used to describe attributes, performance characteristics, and interaction behavior with other systems. One or many volumes of technical reports are typically generated to contain the many design and analysis details of such systems and multi-system interactions. For complex systems, the large number of subsystems and potential variations in subsystem reliability, operating environments or threats to which they may be exposed may result in a wide range of actual performance over the system lifecycle. This level of complexity is often not amenable to thorough empirical analysis due to resource limitations, hence the need for expert judgment. The set of system performance uncertainties is further compounded when system failure can result in high-consequence events and also when various permutations of malicious intent are conceivable. In conducting a system safety analysis for a complex, high-consequence system it is essential for technical experts to obtain a deep knowledge of the types of failures that can occur as well as understand the many subtleties of uncertainty that can effect system performance in normal, off-normal, and emergency environments. Such analysis is challenging with respect to the "known" characteristics of a system; however, there is also the issue of "known unknowns" which are conceivable failures that remain unanalyzed (e.g., due to resource constraints on experimentation) and the ever-present "unknown unknowns" or "blind spots" in system knowledge (e.g., unanticipated failure mechanisms and/or modes, unanticipated common cause failures). At some point, the results of a safety analysis or risk assessment must be put into a form amenable for review and action by high-level decision makers (e.g., managers, regulators, politicians). While it is incumbent upon management decision makers to understand and knowingly accept some degree of residual risk where appropriate, it is also the responsibility of system safety practitioners to make such risks and related uncertainties understood (ref. 1). In the interest of improving the communication of uncertainty during a safety analysis review, this paper presents specific visual manipulations including object focus, transparency, and color that may be used to quickly relay uncertainties.

Biases Involving Uncertainty

It has been estimated that nearly 80% of the information used by people to understand their relationship to the outside world is obtained visually (ref. 2). Therefore, properly used, the visual modality is rightly assumed to be highly effective for efficiently transmitting important information in a memorable way. A common approach for

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communicating system information and safety analysis output is to display salient graphic depictions of systems accompanied by textual or verbal descriptions of the analysis. The visual depictions that appear to be popular (in the author's experience) among management decision maker audiences are often dominated by the description of the nominal system or by specific instances of system failure and related consequences. Uncertainty information is not often supplied in the same type of visually captivating manner as are well-understood system characteristics and specific analysis cases. These differences in presentation of "system characteristics" and "uncertainties" are very important in light of experimentally observed decision making biases and the anecdotal experiences of system safety analysts who have seen key decision makers remember impressive system visualizations, but forget risk-relevant probabilistic or other uncertainty details. Some of the biases that apply to the description of uncertainty and risk have been termed *normative knowledge* biases and consist of experimentally observed phenomena, e.g., insensitivity to sample size, overestimation of small probabilities, underestimation of large probabilities, etc.; other biases fall into the *availability* and *individual specific* categories (ref. 3). A specific, and well known divergence of probabilistic and uncertainty understandings between safety analysts/engineers and high-level decision makers for a complex, high-consequence system relates to manned spaceflight and the loss of the Space Shuttle Challenger.

Richard P. Feynman's personal observations on perceptions related to the reliability of the space shuttle are insightful (appendix F) in the *Report of the Presidential Commission on the Space Shuttle Challenger Accident*, "It appears that there are enormous differences of opinion as to the probability of a failure with loss of vehicle and of human life. The estimates range from roughly 1 in 100 to 1 in 100,000. The higher figures come from the working engineers, and the very low figures from management. What are the causes and consequences of this lack of agreement? Since 1 part in 100,000 would imply that one could put a Shuttle up each day for 300 years expecting to lose only one, we could properly ask, 'What is the cause of management's fantastic faith in the machinery?'" (ref. 4).[3] It may be inferred that the different levels of hard-earned technical understanding between the engineers and managers (i.e., with respect to failure modes, failure mechanisms, failure likelihoods, various uncertainties, etc.) were partially responsible for these perceptual divergences. However, it is also possible that the means of communicating uncertainties and risks in summary information reports and presentations, over an extended period of time, also contributed to the manager's ability to discount risk. In the specific case of the Challenger accident, concerns by engineers at Morton Thiokol (the manufacturer of the shuttle's solid rocket boosters) were voiced hours before launch and textual summaries of O-ring test data and accompanying engineering analysis were used in discussion with managers. Edward Tufte, a world renowned expert in techniques for visually displaying information, provides a fascinating analysis of the specific items used to communicate with decision makers during these shuttle pre-launch discussions and provides helpful examples of improved information displays that could have been used (ref. 5).

There are many bias processes that can affect the communication of uncertainty information. Some of them are cultural in nature. For example, the language habits of Western culture tend to promote confusion between certainty and belief. People are encouraged to act and speak as though they are certain of things even when they are only fairly certain. The other end of this phenomenon is acting and speaking as if opinions are worthless when they are only perceived as weak (refs. 6, 7). These tendencies may assist with simplifying our interaction with those around us, but they are simultaneously discounting the importance of certainty in our reflection about a topic and can have direct relevance to safety analyses.

In addition to bias processes, the limitation of working memory plays a role in the communication of uncertainty information (especially for relatively brief, infrequent presentations to decision makers with many oversight responsibilities). There is a finite capacity of the consciously controlled memory for the manipulation of disparate ideas or other pieces/chunks of information. Miller (ref. 8) conducted an extensive review of experiments involving memory processes, and he found that in general, people were capable of consciously storing and manipulating 5 to 9 pieces of information in what is now referred to as working memory. Anyone who has studied memory processes will have encountered references to Miller's paper and will probably recall its very memorable title: *The magical number seven plus or minus two: Some limits on our capacity for processing information* (or at least the first 8 words of the title will be recalled). Fairly complex "chunks" of information can be included within those 5–9 memory items if structured techniques are followed. See reference 9 for a good discussion.

[3] Note that the observed failure rate per launch and recovery cycle at the time of the Challenger accident was 1/25 (0.04).

Given that bias processes and other cognitive capacities are at work when safety analysts attempt to present uncertainties related to complex, high-consequence systems to decision makers, it is imperative to seek effective communication methods. It is not the intent of this paper to explore the difficult issues of biases or communication techniques in great detail. However, there appear to be opportunities for improving visual representations used to communicate uncertainty, and representation schemes chosen for brief presentations may best be limited to 5–7 categories or levels.

Visualization Techniques

Many approaches have been used to manipulate graphical images with respect to color, size, transparency, position, angle, texture or edge definition/crispness, etcetera to provide information (ref. 10). Much of the emphasis with these approaches has been on large datasets such as topographical information, meteorological models, and complex computer model output (refs. 5, 9). Specific visual approaches for displaying uncertainty within various data sets have also included color, blurring, the addition of texture or glyphs, and animation effects (refs. 10–13). A typology has also been proposed for the visual display of uncertainties relevant to intelligence analysis, particularly for geospatial information (ref. 14). With respect to continuous tasks, degraded or blurred icons were both found effective for conveying uncertainty regarding the hostile or friendly identity of radar contacts (ref. 15). In the radar contact experiments it was found that among three manipulations (i.e., degraded icons and probabilities, nondegraded icons and probabilities, and degraded icons only), task performance was similar with some advantage with respect to speed and correct identifications when using only degraded icons. Recently, in a series of experiments it has also been shown that numeric (e.g., 0%, 41%, 86%), linguistic (e.g., absolutely impossible, uncertain, better than even), differently colored square icons, and blurred arrow icons were nearly equally effective at communicating probabilistic profitability information as part of hypothetical stock purchases (ref. 16). Stock purchase performance progressively improved as the number of probabilistic categories was increased from 3 to 5 and then to 11. Another ingenious and experimentally proven use of visual images developed for use in reducing uncertainty (especially regarding misses) during inspection activities is the “blinking” method in which an “ideal” image of a product is briefly displayed as overlaying a video image of the product to be inspected (ref. 17). These alternations in images allow for efficient use of the sensitive motion detection capacity of the human visual system. The results mentioned above support the concept of using visual image manipulations to effectively transmit uncertainty information; and they also suggest that a wide range of visual manipulations may be similarly effective. It is further inferred that “blinking” between images of visually enhanced and non-visually enhanced versions of system entities may be especially salient. This paper extends these concepts to image manipulation techniques for use in summary presentations of system safety analysis results.

Scales of Measurement

Many options exist for the presentation of uncertainty information in system safety analysis summaries. One helpful framework for describing possible scales is the nominal, ordinal, interval and ratio scales suggested by Stevens (ref. 18). The nominal scale simply separates properties of entities into different classes or categories (e.g., power supplies, fuzes). The ordinal scale enables an ordering of entities (e.g., greater, less, or equal), but does not indicates the spacing between entities. The output of a paired comparisons approach typically produces an ordinal scale. The interval scale includes both ordering and spacing information, and incorporates the concept of a unit distance (e.g., a Fahrenheit or centigrade temperature scale). The ratio scale is very similar to the interval scale, however it has a natural measurement called zero, whereas the zero point for an interval scale is arbitrarily assigned. An example of the ratio scale is the absolute temperature scale (Kelvin), where the zero point is associated with limiting physical phenomena. Uncertainty scale representations are found at various levels of scale-of-measurement specificity. For example, mishap probability levels may be used such as frequent, probable, occasional, remote or improbable (ref. 19). A three region scheme may be used such as the core damage frequency and large early release frequency bins used as part of the U.S. Nuclear Regulatory Commission’s risk-informed regulatory framework for nuclear power plant oversight (ref. 20). Order of magnitude uncertainty ranges about a nominal value (e.g., ≤ 1, 2, 3, ≥ 4) are another option. Finely grained intervals may also be used (e.g., a log probability scale ranging from 1 to 10E-7). Confidence factors or reliability factors (i.e., k-factors) may also be used to display uncertainty with reference to both performance thresholds (i.e., requirements) and margins (i.e., the degree to which the design is known or asserted to be within or outside of stated requirements) (ref. 21). Levels of dependency may also be an important aspect of uncertainty to be displayed for systems, subsystems, and/or components. For example, estimated levels of dependency between subsystem failures (i.e., from expert judgment or observed data) could be represented by nominal categories, intervals of correlation coefficient values, etc.

Specific Visualization Techniques Investigated

For this paper, several image manipulations were investigated for quickly relaying uncertainty information for system entities as they may be presented in a system safety analysis summary. The first step in this process was to identify the types of image objects to manipulate. The three example image types included: (1) a simplified functional block diagram; (2) a simplified hierarchical block diagram; and (3) near-photorealistic system images. Figure 1 shows the first two image types, which involve notional descriptions of weapon systems. Figure 2 shows images related to a hypothetical vulnerability study. Black, white and dark gray colors were chosen to represent system entities (i.e., text, outlines, and surface shading) to facilitate visual discrimination between the notional system and uncertainty enhancements using color. The second step in this process involved an investigation of image manipulation types and choosing the number of levels (i.e., ≤ 7) of manipulation that would be quickly and easily distinguishable. To facilitate rapid prototyping of image manipulation, two commonly available software packages were used. Microsoft® Office PowerPoint® 2003 was used for transparency and color manipulations and Adobe® ImageReady® CS, version 8.0 was used for object focus/blurring manipulations. Figure 2 (B) shows the six color panels that were generated in PowerPoint® for overlay upon subsystem and components in the hierarchical block diagram. The percentage values shown below the color panels indicate the degree of transparency applied using the “Colors and Lines” submenu within the “Format AutoShape” option in PowerPoint.® Altering the transparency of the color panels was necessary to provide similar “apparent transparency” across a range of colors. Figure 2 (C) displays the six gray tone panels which were modified only using transparency manipulations for overlay upon entities in the functional block diagram. Note that the first element in figures 2 (B) and 2 (C) show an unaltered entity as the reference or lowest level value (i.e., transparency for the overlay panel is set at 100%).

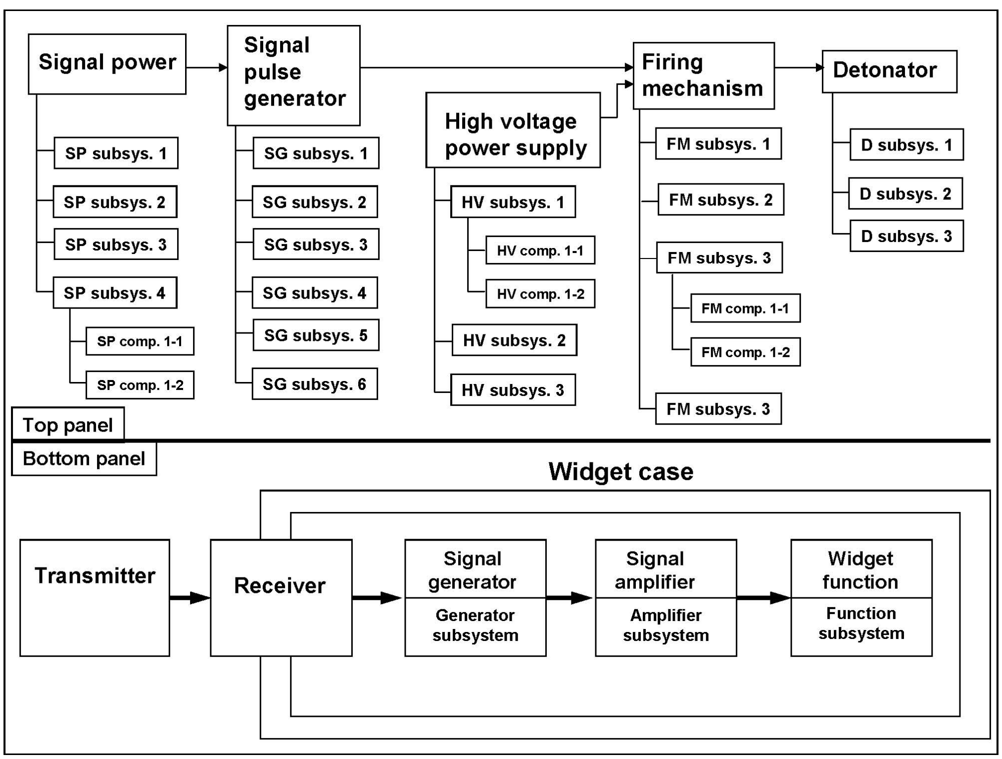

Figure 1 – Block diagrams used to illustrate the visual manipulation concepts. The top panel shows a hierarchical block diagram and the bottom panel shows a functional block diagram showing system boundaries.

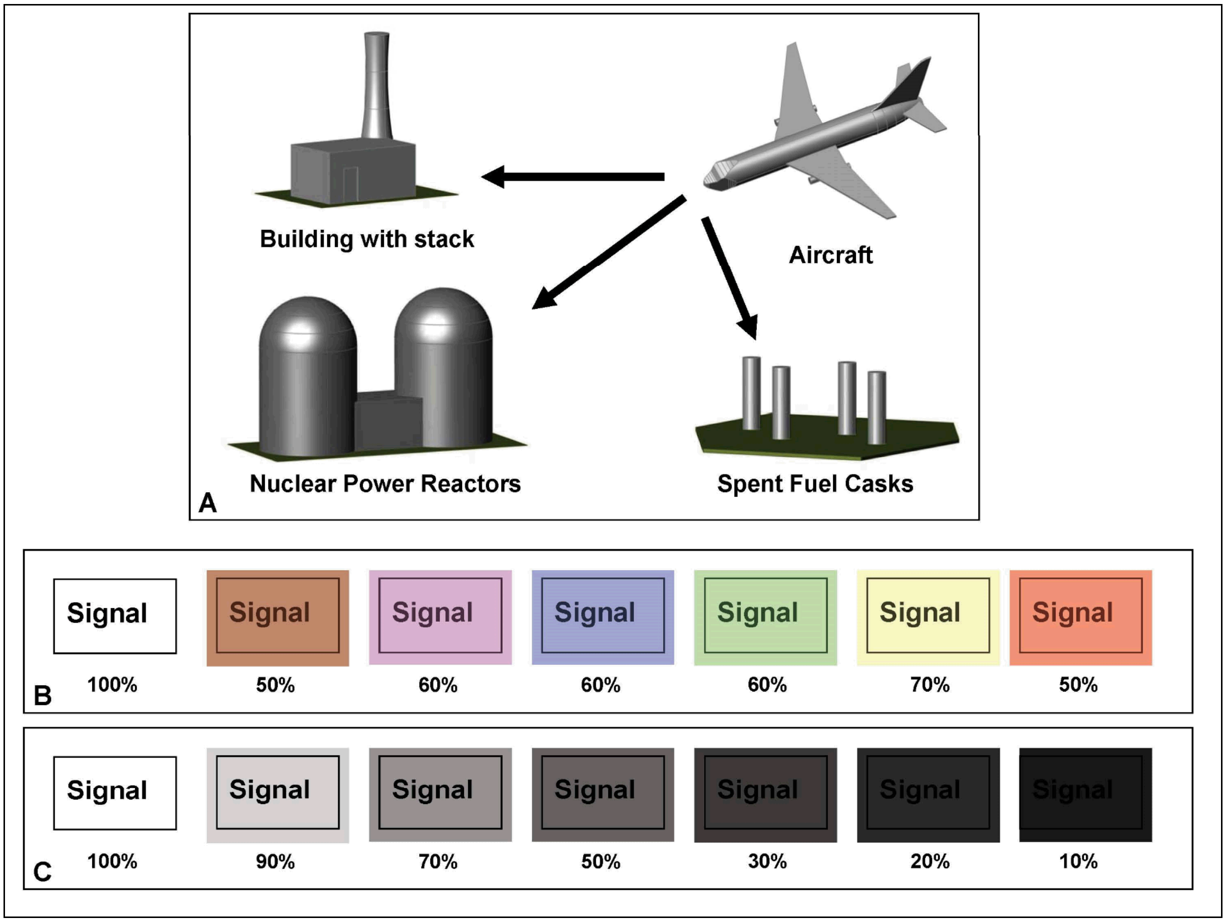

Figure 2 – Images from a hypothetical vulnerability analysis are shown in (A), color manipulations with associated transparency levels are shown in (B), and transparency manipulations with a single gray shade is shown in (C).

An application of the color manipulation approach is shown by contrasting the unenhanced hierarchical block diagram (fig. 3) with the color enhanced version (fig. 4). The color manipulation approach easily allows the use of seven, easily distinguishable visual enhancements; however, given working memory limitations, it may be best to only use five levels when applying the technique in system safety presentations. The image manipulation involving only transparency is shown in figure 5 using the functional block diagram. This technique appeared less amenable to displaying seven different levels and it is recommended that its use be restricted to five or fewer levels.

Two types of object focus/blurring manipulation techniques were explored using the Adobe® ImageReady® software. The first involved a Gaussian blur in which the user specifies the pixel radius for blurring which is then applied to the entire image. Figures 6 (A) and 7 (A) display a five-level scale including four Gaussian blur manipulations (i.e., blur radius of 6, 15, 30, or 100 pixels). The second blurring technique used the radial blur option in the ImageReady® software in which the user specifies a degree of radial spin to be applied about an axis perpendicular to the image plane that passes through the image center. Radial spin factors of 5, 12, 25, and 100 were applied to create four blurring levels, which, including the no distortion condition, results in a five-level scale shown in figures 6 (B) and 7 (B). Several types of images and many specific values of blur radius and radial spin factor were explored before arriving at the four the chosen values (for each blurring technique) which were subjectively deemed to be very easy to distinguish. Figure 8 shows a "before" and "after" visual manipulation example of applying radial spin blur to the hypothetical vulnerability analysis images. Presenting static "before and after" images side-by-side is proposed to be a salient and efficient means for visual presentation of uncertainty. The reader is further encouraged to imagine the potential salience of alternating between the images in figure 8 (A) and 8 (B) using the "blinking" method described earlier during a slide presentation. While PowerPoint presentations are not necessarily the best vehicles for transmitting safety critical information (ref. 22), the author's personal experience with this technique anecdotally supports its use as both salient and efficient.

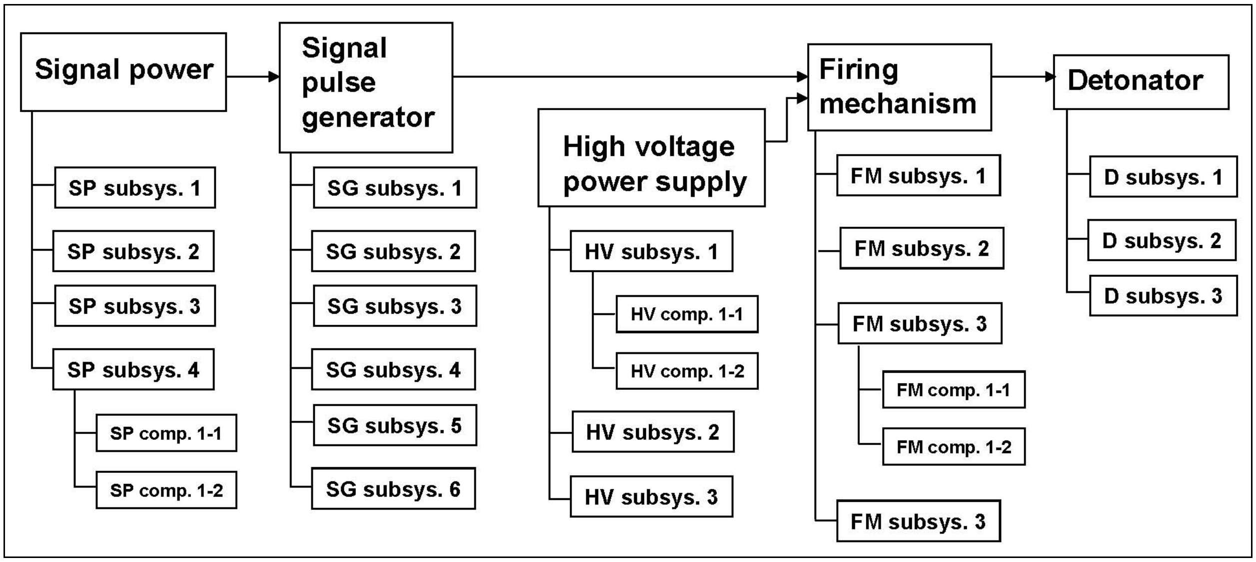

Figure 3 – Hierarchical block diagram without visual manipulation of entities.

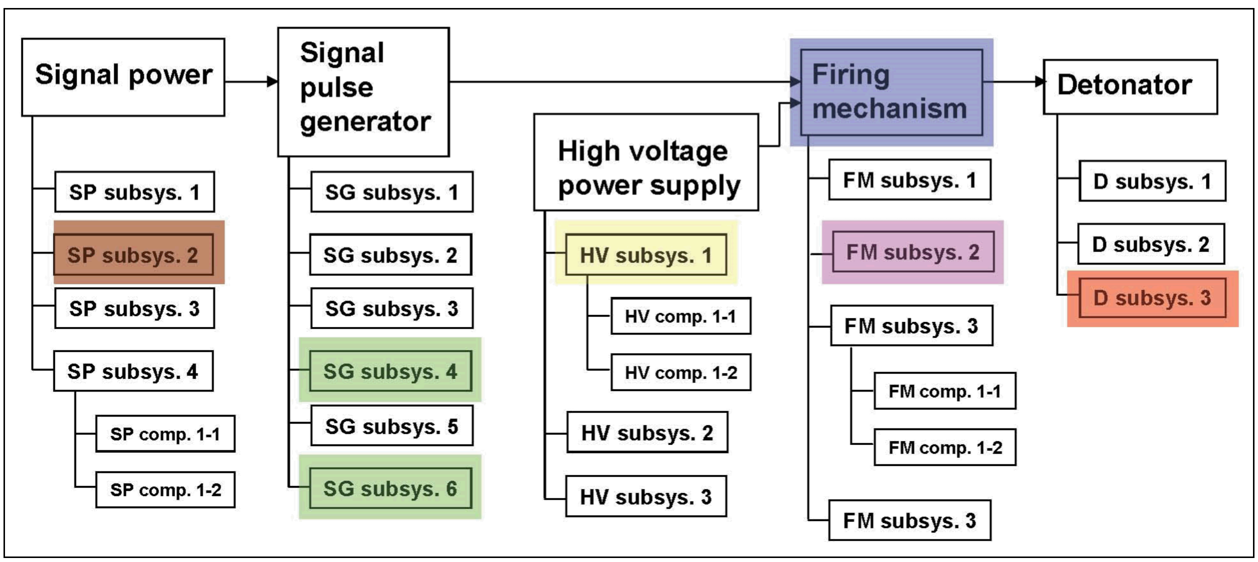

Figure 4 – Hierarchical block diagram with visual manipulation of entities to distinguish up to seven levels of uncertainty information.

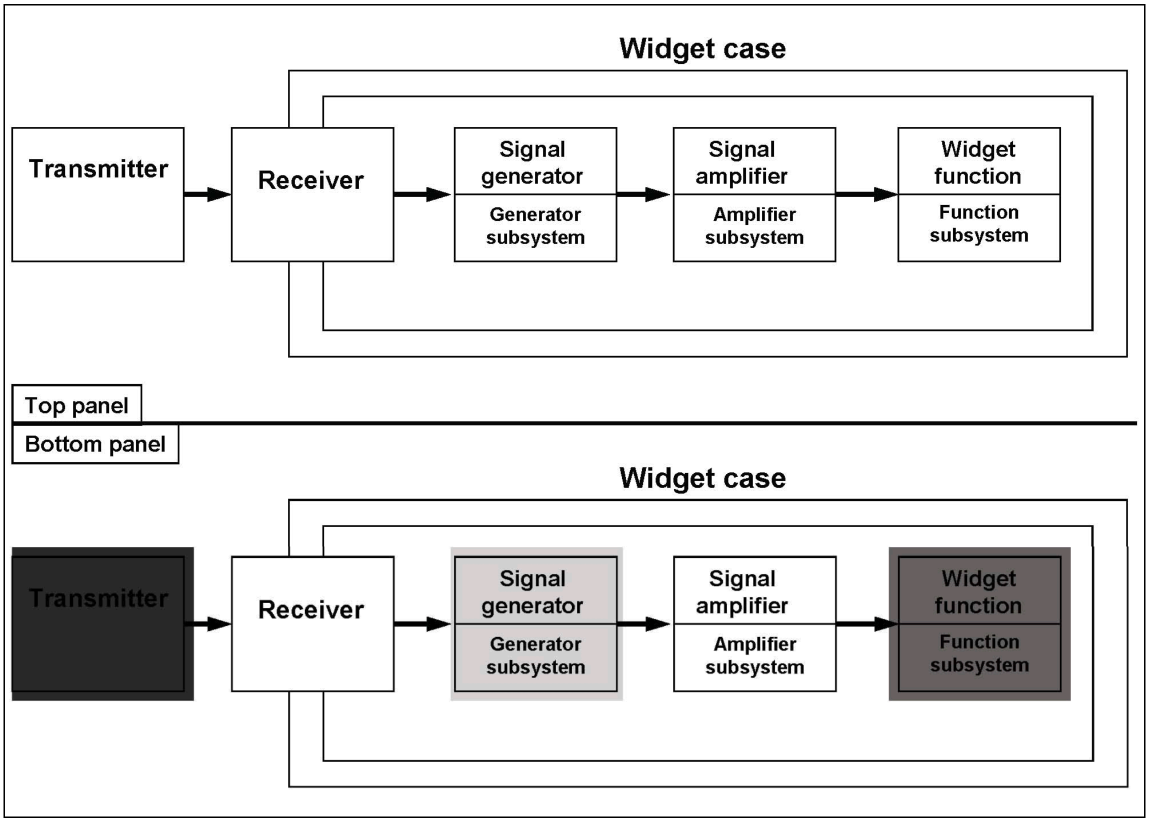

Figure 5 – Functional block diagram for a notional weapon system.

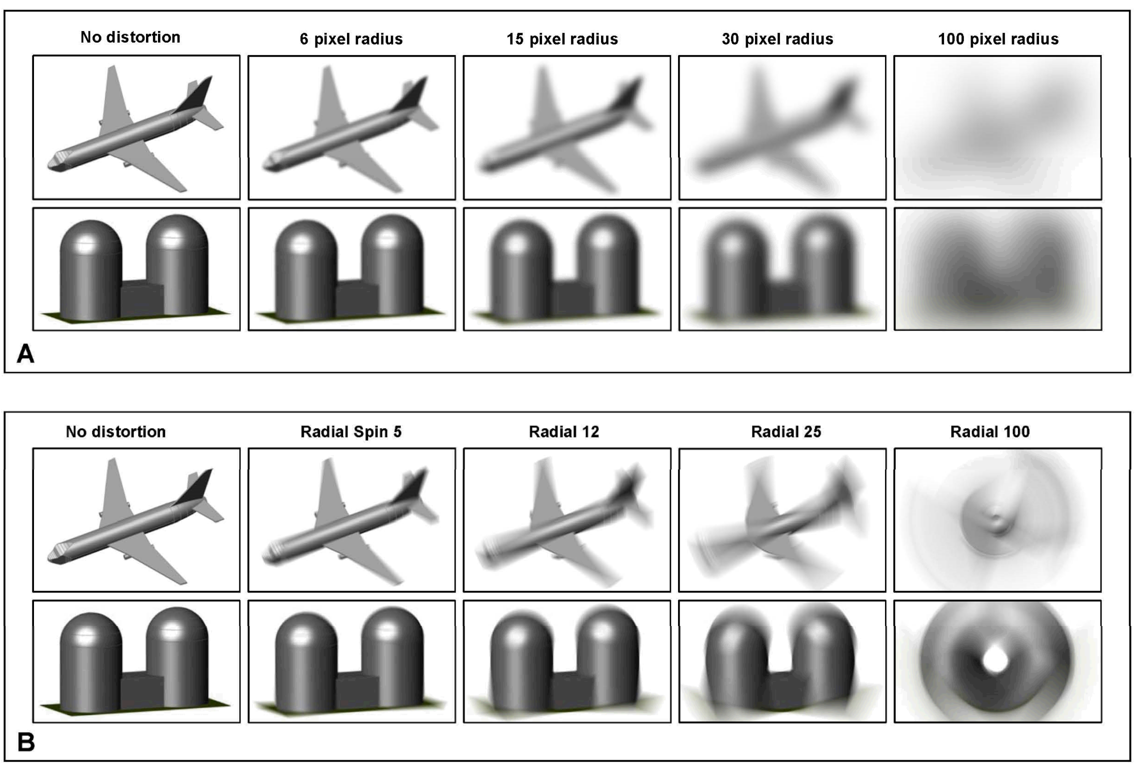

Figure 6 – Gaussian (A) and radial spin (B) blurring for the aircraft and nuclear power reactor images.

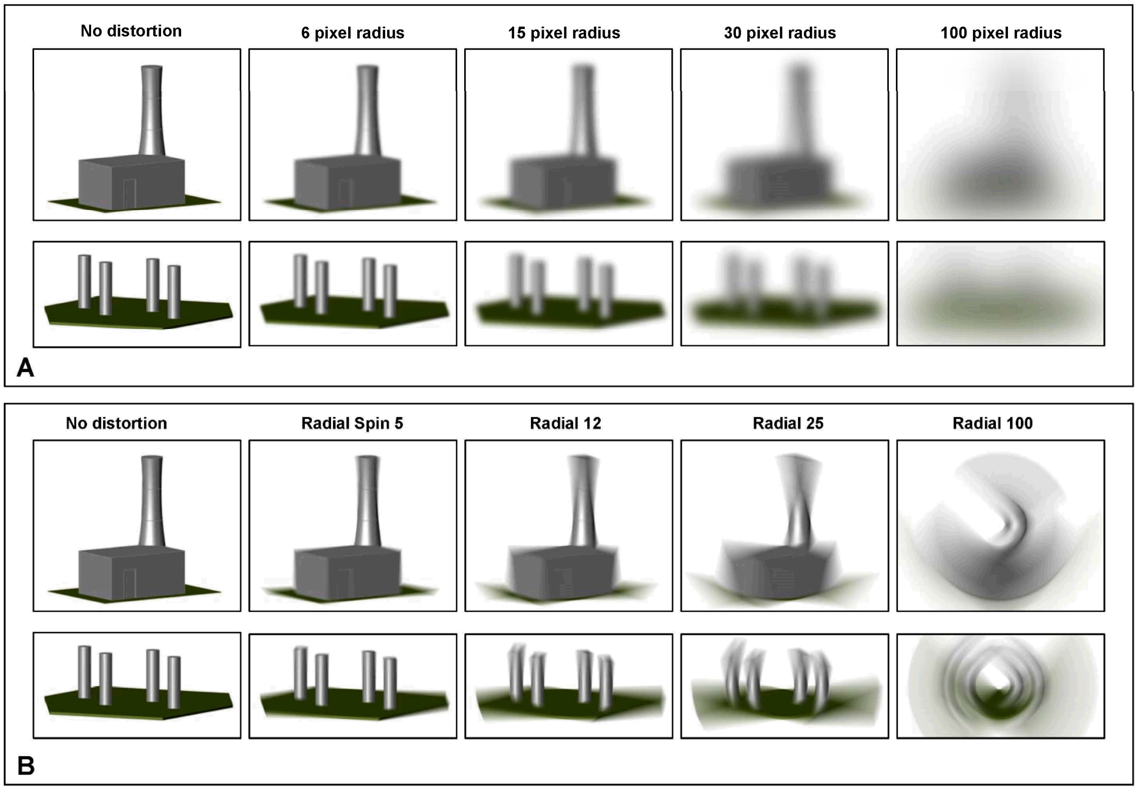

Figure 7 – Gaussian (A) and radial spin (B) blurring for the building with stack and spent fuel cask images.

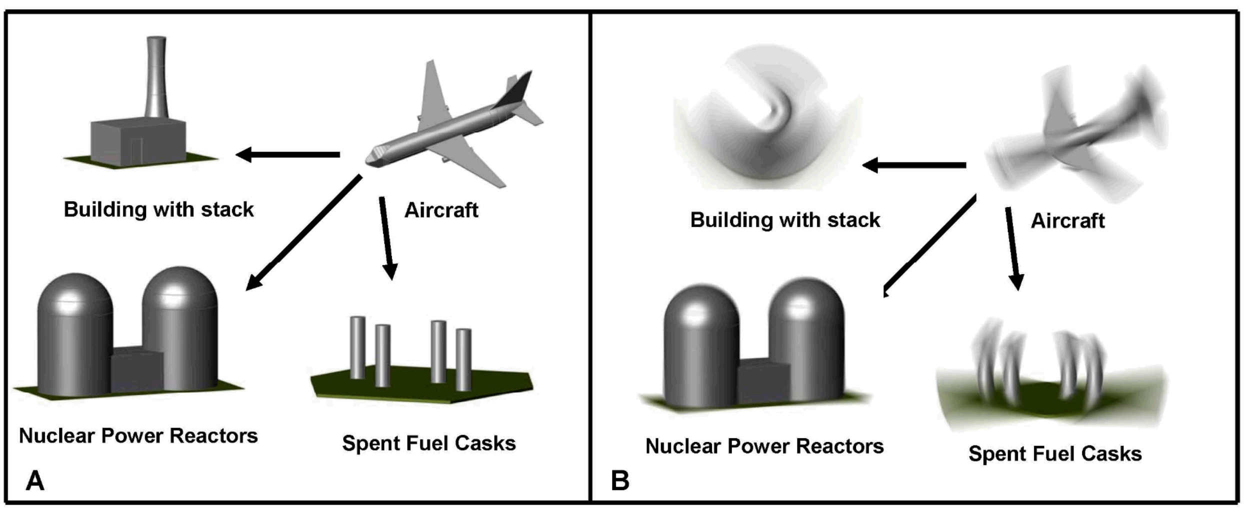

Figure 8 – Before and after example of radial spin blurring

<u>Discussion</u>

During the investigation of these visual manipulation techniques it was noticed that selecting objects or images with relatively similar edge features and aspect ratios (i.e., width divided by height) allowed for more consistent (between object) visual effects when using object focus/blurring techniques. This degree of geometric similarity enhances rapid understanding and internalization of the uncertainty scale by the intended audience of the system safety analysis. Block diagrams have entities with highly consistent forms, thus same-level visual manipulations across multiple entities are readily understood. The use of photorealistic images and other three-dimensional representations, while engaging and attention-grabbing for many audiences must be carefully chosen so that particular levels of visual manipulation (i.e., the uncertainty levels) are readily understood across images. The visual manipulations developed in this paper are proposed to offer salient and efficient means to present safety analysis uncertainties for complex systems. The justification for this claim is based upon a review of visual display approaches, basic human factors insights, related experimental data and the subjective judgment of the author. Ideally, systematic experiments should be conducted to verify that the proposed visual manipulation techniques provide the proposed benefits.

Conclusion

Visual representations of complex, high-consequence systems are efficient means to relay a wealth of subsystem and component information to a wide range of high-level decision makers (e.g., regulators, managers, key policy makers). However, system-related uncertainty estimates often communicated with spoken caveats, tabular data, detailed footnotes, etc. may not be attended to or remembered well by such decision makers due to factors including time limitations and other biases which may encourage a discounting of uncertainty-related risks. System safety analyses of complex systems are particularly vulnerable to such miscommunication of uncertainty ranges due to the myriad of factors/subtleties that may influence critical failure modes. Often, uncertainty information presented along multiple scales of measurement is needed to provide a robust description of relevant uncertainty bounds. This paper briefly discussed biases impacting the communication of safety analysis uncertainties and presented several specific visualization techniques aimed at improving such communication. The specific visual manipulations of object focus, transparency, and color are proposed to be salient and efficient means to quickly relay uncertainty information spanning orders of magnitude.

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