0 Highlights of the proposal: What is *live design*

1. All available information such as:
   (a) safety (numerical responses from structural analysis)
   (b) security (sensor data: monitor observation, fire & smoke level)
   (c) regulatory (building code, legal code, surveillance protocol)

   is aggregated in a single database which is self-updating without human intervention. The difficulties associated with manual input of any new technical data in a conventional CAD are circumvented.

2. Each piece of information is dynamically updated as necessary.

3. New class of data:
   (a) sensor: chemical, biological, nuclear
   (b) monitoring: face recognition, biometric identification
   (c) intelligence: friendly foreign agency, neighborhood awareness

   can be incorporated as each becomes available.

4. A generic variable contains:
   (a) statistical information (e.g., mean, standard deviation, skewness, kurtosis)
   (b) confidence bounds with `interval arithmetic`
   (c) probability distributions from `interval arithmetic` object bounds
   (d) an index to represent subjective threat data from government intelligence reports

   as opposed to a single deterministic value for an object in conventional CAD.

5. Extreme value statistical distributions to detect threats.

6. Automatic Bayesian updating of the database after observing each physical event.

7. Automatic reassessment of threat index from the most up-to-date state variables i.e., future threats are predicted from the most comprehensive present information.

8. XML-application that provides an extensible data format for interchange, deep domain modeling, and content-based searches.

9. A special case of blast loading will be examined.

10. Combination of fire, smoke, and chemical agents will be focused in case studies.

11. Automatic forecasting and subsequent generation of threat alarms with suggested rescue and evacuation plans as animation graphics driven by fast numerics.

<u>DEFINITION:</u> Any design against threats should be an ongoing dynamic process, the design should not end after construction and that the statistical measures of safety-security data should trigger rescue and evacuation intervention. A threat must be a compound (principal) effect (a statistical combination) of all deviations in safety-security.
This paradigm is termed to be <u>live design</u>.

1 Introduction: development of a novel paradigm — *live design*

This scientific project tests the boundaries of what can be done to guarantee security in buildings. It is proposed that uncertainty modeling of the most current information can be used to predict extreme events that will endanger peace and prosperity of civil society.

Terror attacks at home and abroad have made the flow of evacuation/rescue information from facilities to disaster mitigation agencies a top priority in multi-disciplinary research. This proposal looks into possible solutions on the understanding that an investment of time and energy by qualified and dedicated academics and professionals could greatly benefit society by saving human lives and facilities.

1.1 Most up-to-date '`design state`'

The novel *live design* concept addresses the challenge of seamlessly integrating architectural details and subjective (legal) policies with real time numerical (engineering) responses to generate warning statements after processing the complex probabilistic information in the light of Bayesian updating.

Live design will issue constant updates on the operational condition of a facility (e.g., buildings, airports, life-line systems) by performing extreme value statistical analyses of real-time data from controlling, monitoring and surveillance devices.

1.1.1 Self-documenting *live blueprints*

Live design IT tools will convert conventional architectural drawings into evolving *live blueprints* and respond to imminent threats. The *live design* paradigm essentially replaces the existing CAD (computer-aided design) type static environments.

The *live design* environment saves a record of the advice it broadcasts along with descriptions of the conditions that triggered such actions.

A *live design* prototype will provide a versatile conduit to interchange data (related to physical security) between engineers, legal and medical professionals, and civic authorities.

1.1.2 Utilizing available non-IT resources

Funds from this grant will be utilized to creating IT interfaces between building occupants and rescue authorities.

No new computer program for structural analysis under mechanical loading, e.g., wind and earthquake, will be developed. Existing codes and published results are deemed to be adequate.

1.2 University-industry-government cooperation

As the project manager the principal investigator will coordinate the following team activities.
(i) The professional engineers will identify all building design/construction regulatory requirements.
(ii) MIT will run dynamic stress analysis programs.
(iii) MIT will design and fabricate wireless self-powered (e.g., fire and smoke) sensors, whose streaming record will furnish an input to the *live design* prototype.
(iv) CMU will undertake all aspects of the basic IT research based on deep domain models suitable for symbolic representation and manipulation, as well as datamining. The notable aspects are: formal representation of safety and security information and data exchange protocol written in a markup language to facilitate computer searches by content.
(v) Subsequently, the PI will quantify disaster probabilities according to *principal component* statistical computations founded on *fuzzy logic* and *extreme value statistics*. To implement Bayesian updating he will use `interval arithmetic` that represents *bounded variabilities*.
(vi) The legal professionals will guarantee that the aforementioned proposed security enhancements comply with all governmental regulations.
(vii) The MIT *Media Laboratory* will guide the architects in designing intelligent rescue and evacuation signs employing the virtual reality software.
(viii) The PI will organize workshops to interact with civic authorities who will test the prototype.

1.3 International cooperation

The project involves innovative foreign collaborators who have secured their own funds as professors. Advice on fuzzy logic will be sought from Ishikawa and Arakawa, Kagawa University, Japan, who have used this technique to analyze the Kobe earthquake and Tokyo subway sarin cases. Gharbi, Franche-Comtè University, France, will lend his expertise in *lab-on-chip*, which can be used to fabricate new MEMS (micro electrical mechanical systems) to detect chemical and biological agents. Fritzson, Linköping University, Sweden, will supervise the development of a higher level programming environment to convert mathematical equations into C++ codes. In addition, Jonassen and Weierholt, Oslo University College, Norway, will guide the construction of a parallel computing environment and a network of fiber-optic sensors.

2 Core technology development of *live design*

Rescue/evacuation optimization is based on extreme value probabilistic analysis of threats

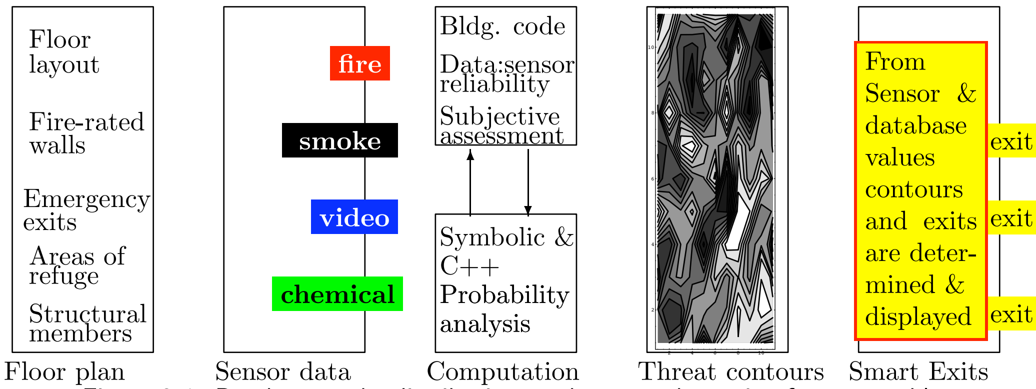


Figure 2-1: Random smoke distribution as threat : schematic of a test problem

Testing: The prototype will display evacuation/rescue paths when a user randomly assigns: (i) building design; (ii) sources of blasts, fires/smoke; (iii) intensity and location of a yet unknown threat. The core IT employs `deep domain modeling` and virtual reality-based graphics.

2.1 Four key concepts

To successfully construct a *live design* prototype the team will undertake the following activities.
Information acquisition: online sensor data, available structural stress analysis data;
Probabilistic calculations: principal component analysis, extreme value statistical analysis;
Action: indicating evacuation signs, broadcasting rescue path, documenting the current state, Bayesian updating of all probabilities;
Security analytics: adjusting safety models, incorporating new engineering and legal policies.

2.2 Overview: *live design* IT-core

Intellectual merit
Conventionally, dynamic responses (e.g., to earthquakes and wind) govern designs in which computational activities end with the completion of construction. Here, an ongoing information processing environment is proposed and a new paradigm of *live design* is formulated. Design specifications, which are formally represented and written (using IT tools) in a content searchable markup language, are maintained and updated according to new observations of system performance, government regulations and policy changes during the entire lifetime of facilities. This new concept of *live design* requires an analysis of the logical structure of the building design documents, and the development of a `DTD` (`document type definition`) that models this structure.

The team will develop a `DTD` and employ *fuzzy logic*, *vide* ref. [71], to quantify the legal and policy (subjective) components. Subsequently, Bayesian updating will be implemented, *vide* ref. [40], to incorporate lessons from the past predictions.

The team proposes to develop content-oriented models for civil engineering design and construction, including associated policy and legal requirements. To this end the team will design and implement *Live Design ML* (`LDML`), an XML-application that formalizes the requisite markup formats. A key requirement here is a transition to entirely machine understandable formats, as opposed to the current standard practice of only human readable documents produced by `AutoCAD`, ref. [45]. These novel formats allow a deep modeling of the domain of discourse and provide strong support for the development of tools such as intelligent search engines and symbolic/numeric computing environments.

Broader impact
The `LDML` format will be sufficiently flexible to accommodate descriptions of specific structures as well as general requirements. A highly successful example of this approach in the domain of pure mathematics is the `OpenMath` specification, *vide* ref. [56]. It is a common belief that `XML` applications are in the process of becoming a widely accepted standard for the storage and interchange of information, *vide* the emerging concept of a semantic web, ref. [65]. This makes the proposed undertaking not just feasible but necessary.

3 Goals, milestones and performance assessment

3.1 Phases and goals

The following project components:

1. computer science development:
   design formalism: XML applications
2. civil mechanical system research:
   interaction with *design formalism*

will be completed in three phases (Ph-I, II and III) at the end of the second, third and fourth years. All development will be completed by the end of the fourth year. The fifth year will be devoted to documentation, workshops, preparation of dissertations/reports and an ITR large proposal.

The IT goals will comprise:
a. a deep domain model
b. sensor interfaces to databases
c. a real-time computing interface

3.2 Milestones

The participating units will cross nine milestones whose labels are indicated below in parentheses.

1. **CU and MIT**
   - Ph-I: Statistically correlated structural responses as bounded variables with `interval arithmetic` (1)
   - Ph-II: Bayesian updating from sensor measurements (2)
   - Ph-III: Extreme value statistics of combined data from building and sensors (3)
2. **CMU**
   - Ph-I: Develop security dictionary (4)
   - Ph-II: Input/output environment (5)
   - Ph-III: Database applications in `C++` (6)
3. **OKG- Engineers, lawyers and architects**
   - Ph-I: Organizing building design codes, legal and policy documents (7)
   - Ph-II: Examination of arbitrary blasts on arbitrary building models (8)
   - Ph-III: Design of rescue/exit paths (9)

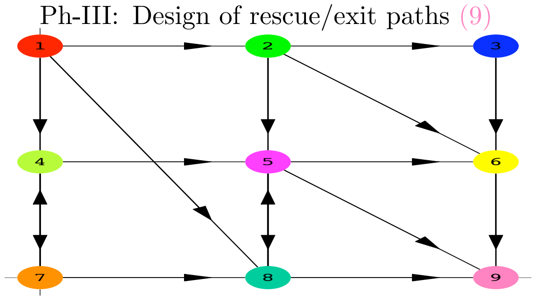


Figure 3.1: Paths connecting milestones

3.3 Timeline: performance metrics

Phase-wide demonstration and documentation of rapid prototyping will serve as yardsticks.

- Ph-I: Statistical safety assessment after blasts with simulated time history
- Ph-II: Updating databases from sensor and policy information
- Ph-III: Demonstration of *smart signs*

3.4 Expected deliverables

The *live design* prototype: A completely documented environment to execute statistical methods and subsequent database operations on a common IT platform will address the following issues.

1. <u>Civil engineering aspects:</u>
   a. Examples for users, including but not limited to, the stress distributions as queried from the *live design* databases;

   b. Prototype to provide guidelines for tension and compression members, curved members in three-dimensions, slab thickness depending on whether the object is (i) a ramp in a garage or (ii) an evacuation collapsible exit ladder;

   c. Examples to examine all legal and regulatory restrictions in building structures — whether exterior or interior evacuation facilities.
2. <u>Terror simulation:</u>
   a. Safety-security input: blast effects, fire and smoke propagation, sensor system responses;

   b. Statistical modules: correlation matrices with bounded variables; Bayesian updating scheme on vectors and matrices; identification based on extreme values;
3. <u>Computer science software aspects:</u>
   a. `LDML`, i.e., the *live design* markup language, augmenting available `XML` variants;

   b. Calculation efficiency: Modules to estimate the computation time between receiving signals from planted instrumentation and generating warning text messages as three-dimensional graphics with sound;

   c. Design formalism: `LDML` applications; computer algebra modules; C++ executables;
   Benchmark: validating quick response to simulated hypothetical threat scenarios to broadcast threat and render warning messages via graphics akin to virtual reality.

4 Project organization

After the tragedy of September 11, 2001 the principal investigator set up an active communication with Professor J. J. Connor, MIT, to propose a new way of investigating security concerns. This resulted in an NSF-ITR proposal in November 2001.

The current proposal accommodates the criticism of the former one and focuses on presenting a composite picture rather than explaining different components of *live design* in a disjointed fashion.

4.1 Background

The complex problem of *security of civil infrastructure* and intelligent operation during disasters cannot be solved by any single conventional discipline.

4.1.1 Multidisciplinary cooperation: Civil, mechanical, computer science

Advances in sensor technology (civil/mechanical engineering) have made it compatible with an up-to-the-second database that may encompass all conceivable parameters. This concept of deep domain modeling has been an IT/CS research area.

Probabilistic notions and fuzzy logic, *vide* ref. [3], allows qualitative regulatory constraints coexist with quantitative engineering data. Engineering mechanics models for instantaneous Bayesian updating (related to extreme value statistical estimates of threats) keep all events current, and ready to be activated by the streaming sensor data.

IT/CS provides common platforms for exchange of information between building occupants and civic authorities. The NSF showed its foresight in the ITR-RFP, where a highly intertwined research endeavor such as *live design* is encouraged as a multidisciplinary mission to enhance physical security.

4.1.2 Multi-university courseware: CU, MIT, CMU

The principal investigator has been associated with Co-PI Connor, MIT, since the mid-seventies. They have shared common interests in engineering mechanics and advanced computations.

The PI has also been interacting with Co-PI Sutner, CMU, on the topic of computer algebra and has team-taught a number of tutorials with him since 1994, *vide* refs. [61] and [53], for all levels.

In July 2003, Connor, Sutner and Dasgupta will conduct tutorials across the engineering disciplines at the Imperial College, London, UK, on `MathML` and web-based computation, *vide* ref. [38].

4.2 History of the team's research

During the last eighteen months, the PI has achieved considerable success in developing computer algebra programs to implement extreme value statistical computations with `interval arithmetic`, *vide* §6.3, page 8.

At MIT, wireless sensor technology has materialized in a wide class of problems, *vide* §6.4, page 9 and §8.8.1, page 14.

Interactions between practical engineers, blast loading analysts, attorneys specializing in product liability issues, and architects designing building systems have substantially increased team's knowledge since the last NSF-ITR proposal of 2001.

4.2.1 Interest from Government agencies

Two proposals on physical security were sent to DARPA and two in response to Board Agency Announcements. The requirements were very specialized and geared towards more industrial problems, e.g., blast resistant vehicle constructions. Another difficulty therein was the allocated time of eighteen to twenty four months, which was inadequate to develop the core technology, *vide* §2 in page 3.

4.3 Rationale for a midsize proposal

The team has completed the volume of work which is comparable to the output of a typical ITR small grant, *vide* §6 in pages 7 – 9.

Since 1999, CU funded faculty research has effected the synergy of safety `databases` and digital representation of infrastructure systems.

After the tragedy of September 11, security concerns overshadowed stress-based safety considerations. The inherent flexibility of *live design* allows conventional structural monitoring data, code-based safety indices, and security sensing/surveillance readings to be accommodated alongside legal/policy *qualitative constraints*.

To implement the proposed security paradigm for any civil infrastructure (e.g., energy conduits and transportation systems), an ITR large proposal will be needed. This can only be initiated after the core technology is validated.

A system approach will elaborate the distributed computing needs of a deep domain model. The sensor technology and its reliable functioning should be guaranteed. Extreme value and Bayesian statistical modules should be validated.

In the coming five years the team feels that goal of building a *live design* prototype will be attainable.

5 Tasks to achieve the goal

The team proposes the following tasks for the most efficient conduct of the project.

5.1 Four specific tasks

T-I: Database initialization with simulated engineering and legal requirements.

T-II: Distributed computing to (i) process digital sensor data and (ii) expedite warning systems.

T-III: Probabilistic calculations for security events with *finite bounds*, *vide* refs. [18] and [27].

T-IV: Code development for distributed computing of computer algebra and object oriented programs.

5.1.1 Sample demonstration and delivery

The three models to be studied are: a small privately owned building, a large government office building, and a secured building for homeland security agencies. The legal guidelines for monitoring, surveillance and structural design for safety/security, *vide* refs. [9] and [55], are very different, *vide* refs. [14] and [26], for each of the three cases.

The *live blueprint* will first examine design compliance of a model to prompt essential corrective and desirable enhancement measures. Signs that lay dormant during normal conditions will broadcast audio-visual security instructions on the premises and at the command post. The crucial points to be emphasized are:

1. three-dimension animation of rescue/evacuation trajectories and sound annotated warnings;
2. record keeping of what took place over time and what action was taken by *live design*;
3. cases of failure of computers and the effects of manual intervention by trained personnel.

5.2 IT related activities

All illustrative examples will share the following common items of development.

1. Formalizing design with `LDML`:
   A markup language associated with civil engineering design and construction will contain all local codes and associated legal requirements to construct office buildings. The professional engineers from OKG will extract all regulations written in English for trained civil engineers and suggest the markup tags. CMU will design the `LDML` to accept the semantic assertions.

   The professional engineers, architects and lawyers will report on additional safety/security needs. Their concerns will be incorporated in a database by CMU.

2. Applications to interface databases:
   `LDML` protocol facilitates content searching and data interchange. Optimized object oriented codes will be written for efficient execution, and easy extension and maintenance.

   The *live design* environment will run applications for database query and numerical simulations. `LDML` will be suitable for data exchange activities across all applications, e.g., Maya written in a proprietary language, ref. [12]. Generation of a full electronic version of a *live blueprint* will be the first test of the prototype.

3. Language and protocol:
   Databases, query programs and all `LDML` data exchange tools will be fully documented.

4. Formalizing design regulations:
   The IT modules will run side by side with structural stress codes, e.g., refs. [39] and [7], after the following stages are completed:

   a. extraction of relevant sections of the building (engineering and legal policy) codes into a *live design* database;
   b. setting up a collection of *live design* markup language meta-tags;
   c. housing a *live design regulation database* (engineering/legal) specifications;
   d. applying this knowledge-base.

   Specification of completed designs will be written in `LDML`. It is then possible to test whether a given design meets the regulatory requirements.

5. Querying a *live design* database:
   Applications will be developed to optimize information via `LDML`. Special purpose routines will communicate with sign animation modules so that the queried answers are displayed in three-dimensions with sound messages.

   The path by which a fire might propagate to a stairway or a closet with chemicals will be quickly predicted with perturbation schemes, refs. [6] and [62]. Cellular automata, *vide* refs. [67] and [80], will yield intuitive predictions of the composite effect when two neighboring units catch fire.

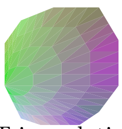
6 Team's preparation

The background work meets the demand equivalent to completing an ITR small grant on physical security. Individual and cooperative research, which will constitute the foundation of the proposed ITR midsize grant on *live design*, are summarized below.

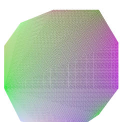
6.1 Principal investigator

The PI's research on probabilistic modeling, computer algebra, and finite/boundary element interpolants will be used in building a *live design* prototype. The highlights are summarized below.

6.1.1 Digital communication of graphics: smooth interpolation



Triangulation



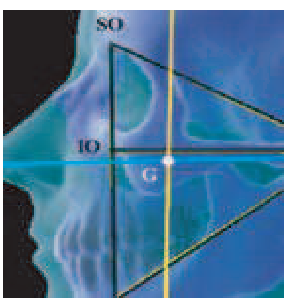
Convex element

An essential task of this proposal is to communicate rescue/evacuation messages 'as fast as possible' to the *smart sign* displays.

A floor plan is stored as a collection of convex polygons in the *live blue print*. Color interpolation on each segment requires only smooth shape functions [28]. The results of rational polynomial interpolants are essential since (higher order) conventional finite elements invariably yield negative interior values for color intensity that are inapplicable.

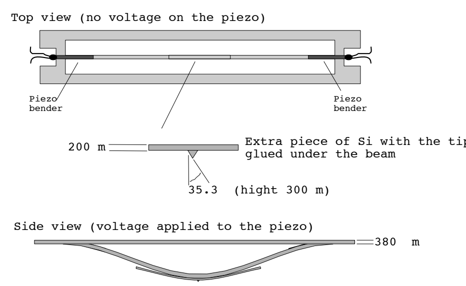
Boundary element approximations [7] were investigated for rapid rendering. In monitoring disaster images or controlling remote evacuation operations, animation algorithms can be codified and then compiled for a web browser to efficiently display the time series data in color.

6.1.2 Cooperation with medical and optics researchers



Generated by Jacques Treil

Interaction of smoke and temperature on RF-coded MEMS require nano-scale models, *vide* ref. [16]. Using high accuracy elements, *vide* ref. [76], stress values for concave probes (in the left figure) can be streamed out using nodal information, which constitutes the most compact sensor dataset.



The Treil Maxillo-facial model (the left figure),*vide* ref. [58], which is based on the biological functional constructs, *vide* ref. [52], can be utilized to recognize human faces, refs. [13] and [74]. The principal component analysis, ref. [48], on the model, which includes geometrical randomness, has been carried out by the PI, *vide* ref. [24].

6.2 Co-PI: Klaus Sutner, CMU

Sutner is the PI of a CMU project, funded by an NSF-ITR grant, for designing and implementing a system that will store, organize, index and make searchable academic course content, and preserve that content reliably over long periods of time.

A central component of the system is an XML-based course model that supports both content and presentation markups. A primary goal of the project is to deal with highly technical course content encountered in mathematics and the sciences. Mathematical expressions, for example, must be presented in an executable format, so that an integral can be sent to a computer algebra system for evaluation. Likewise, assertions and proofs have to be presented in a manner that enables the use of proof checkers.

On a larger scale, the conceptual structure of a document is captured in terms of a dependency graph that makes it possible for the user to navigate the document in a content-dependent fashion.

Integrated computational environments that combine symbolic and numeric computation, visualization, and structured archiving of data will be deployed in *live design*.

Sutner has implemented `interval arithmetic` in computer algebra. He utilizes symbolic manipulations, *vide* ref. [79], in his `Automata` system, *vide* refs. [69] and [68].

6.2.1 `LDML` development

Sutner and the PI have formulated the following questions to set the path of this research.

1. What semantic models and markup formats are required to provide the functionality essential for a *live design*? What is the appropriate notion of a content dictionary in this context?

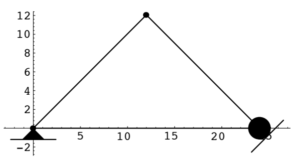
2. What computational support is necessary to fully exploit the semantic content of the data? e.g., for mathematical content one will require the ability to perform both numeric and symbolic computation.

3. How can the team support real-time computation for the parts of the model that require immediate response? How can one incorporate large amounts of real-time data into the model?

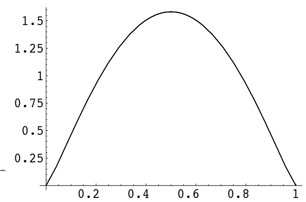
4. How can a deep domain model be used to validate design ideas in accordance with both engineering and legal requirements?

Arakawa, refs. [3] and [4], and the principal investigator recognized the difficulties of quantifying design variables when the legal and policy rules are prescribed in the linguistic form. In their ongoing projects, researchers from Kagawa University, Japan, are using ordering by existing data to extend the rules. However, in most cases, the number of rules exploded in datamining as the scheme of *border line linearity* was attempted. Prediction of land collapse from rain data met with partial success.

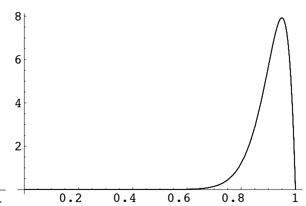
6.3 PI's work with graduate students — courses and research: `Interval arithmetic` and bounded stochastic variations



Truss model



Bounded variation



$\beta-$distribution

<u>Theoretical bases for uncertainties</u>

For a location x_i a sensor $s_i^j, j = 1 \ldots n_i$ indicates a time dependent reading interval $(v_i^j(t), V_i^j(t))$, t: time. Let the (probabilistic) reliability index for s_i^j be $\wp_i^j(t)$. According to the engineering knowledge of the sensor types the (building) design requirement is consulted to assign a danger index $z_i^j(t)$ and correlations to neighboring sensors. The intrinsic `interval arithmetic` in $(v_i^j(t), V_i^j(t))$ populates the banded correlation matrix $[\mathcal{C}(t)]$, *vide* ref. [34] which correlates s_i^j and s_α^β, with intervals within $(-1, 1)$. The highly diagonal domination feature of $[\mathcal{C}(t)]$, is suitable for Cholesky factorization, *vide* refs. [57] and [31], leading to principal component analyses, *vide* ref. [41].

<u>Extreme value statistics</u>

The spatial plot of the eigenvectors indicates one *peril path*. The relative values of eigenvectors provide the initial data for disaster propagation (e.g., spread of fire). From the stored thermo-mechanical responses a temporal calculation yields the evolution of a disaster (e.g., spread of fire in a passage or stairwell). Its extreme value statistical considerations, ref. [43], guide evacuation/rescue strategies.

<u>Determination of $\wp_i^j(t)$</u>

The conventional unbounded Gaussian assumption is replaced by bounded $\beta-$distributions. Previously observed lower and upper cut-off values, and means and standard deviations yield $\wp_i^j(t)$.

<u>Rationale behind non-Gaussian distributions</u>

Conventional probability analysis is performed primarily with Gaussian distributions. For spatial events, probability with bounded variables is more realistic, and also temporal events necessarily occur in a semi-infinite domain $(0 \rightarrow \infty)$. Consequently, β and γ distributions have been studied along with extreme value distributions ref. [33] using computer algebra to yield covariance matrices.

Interval arithmetic accounts for the bounded behavior of responses in terms of the minimum and maximum possible values. Most of the available programs yielded very large intervals (unrealistic values outside (-1,1)) for (scaled) correlation coefficients, and Cholesky factorization further deteriorated the bounds. This was circumvented by the principal investigator in a major development by providing new rules for `interval arithmetic`. Structural analysis for the truss model shown above was carried out with the crown height is given between .9 and 1.01 feet. The resulting tensions, due to a 1 Kip downward force at the crown, became:

```
Interval[-21.8836, 15.621],
Interval[-856.996, -568.572],
Interval[-805.034, -617.438].
```

Note: `Interval[x, y]` indicates that the value lies between x and y.

Series and parallel truss structure can model more abstract n-dimensional systems. The correlation matrix, due to cross connected probabilities, should yield eigenvalues with a positive lower bound. This has already been achieved for small systems, ref. [72]. For large systems the projects will develop similar algorithms and generate fast C++ codes.

Probability intervals are related to the β distributions. A wide interval has a lower probability of occurring than a narrower one. Computer algebraic operations (with interval arithmetic) have been augmented to calculate the first and higher order perturbations automatically in order to address small departures in probability indices from those already prepackaged. ref. [24].

6.4 MIT: Sensor and systems

6.4.1 Micro electronic monitoring system

MEMS sensors can be cheaply produced and easily installed. Structural dynamics experiments, refs. [19] and [47], routinely employ sensors. MIT graduate students have demonstrated a number of innovative applications, e.g., thermal effects, during their Fall 2002 course examinations.

6.4.2 Large-scale distributed computing

MIT has developed distributed computing systems which support large-scale science and engineering applications and internet infrastructure transactions, *vide* refs. [81] and [17]. The product has been distributed to the Department of Energy National Laboratories and Universities. Distributed computing for visualization and rendering have been completed. Software development to assist the migration of proprietary analysis databases to a client visualization platform was performed in conjunction with Sandia Laboratories and B.P. Research and development. Design and construction of a low cost prototype for scalable distributed memory parallel computers has been performed. Basic research has been completed and a micro-scale flow modeling environment has been developed which integrates lattice Boltzmann techniques with complex geometric domains from reconstructed confocal microscopy data.

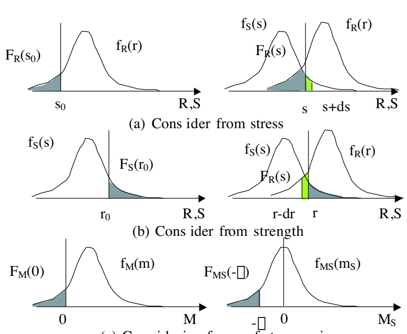
6.4.3 A system for monitoring traffic

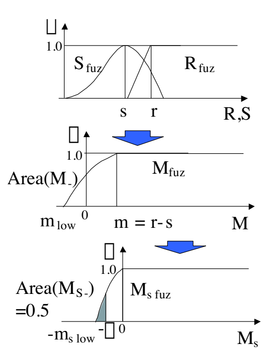
A traffic demand modeling system, DynaMIT, has been under development for the past four years. It is a real-time simulation-based system for traffic prediction that accepts road surveillance information and generates a summary required for traffic management. It is an integrated system which incorporates behavior models that predict driver relations based on assessments about the state of road networks, which is vital for evacuation and rescue. DynaMIT is a distributed object oriented software system that is scalable for large and small networks.

In order to implement information mediation, as required for traffic prediction, an information management architecture was developed. Computer aided design and finite element analysis is combined with geographical information systems, an urban data manager and a decision-support system. The data from these systems is appropriately integrated and stored in an array of databases in a variety of exchange file formats (e.g., `STEP`, `VRML`).

6.5 Collaborators with Kagawa University on fuzzy logic

Associated collaborators have unique practical experience with securing facilities from deadly public threats, communication through visualization, and reliability and innovative instrumentation monitoring. The inadequacy of conventional safety factors in design became apparent after the Kobe earthquake. The lessons from failures motivated the fuzzy logic implementation.





Fuzzy logic (steps shown in figures to the left) was employed to relate design variables and observed behavior in robust design calculations. While it is possible to make reliability estimates to the order of 99%, *vide* refs. [8] and [35], the accuracies of these predictions depend on the underlying statistical distributions. Fuzzy logic models are devoid of such limitations. In highly coupled systems (e.g., large finite element models) fuzzy logic-based estimates prove superior to available Monte Carlo simulations.

7 Interdisciplinary research results from NSF supports

7.1 Convex Polygonal Finite Macroelements: Closed-form kinematics and exact quadrature — NSF Award number: CMS-98-20353

Amount: $ 130,000; duration: September 1999 to August 2002.

7.1.1 Summary of results

The title of the project describes two principal aspects of 'high precision finite element formulation.'

The summaries follow as research (**R**) items:

R-I (*Closed-Form Kinematics*) ref. [23];

R-II (*Exact Quadrature*) ref. [22].

R-I: For any arbitrary convex polygon, the displacement based finite element shape functions presented in ref. [23] guarantee the exact linear interpolation. Wachspress established the projective geometric basis in the early seventies, *vide* ref. [76]. An alternative to Wachspress' denominator, that is based on external intersection points, has been developed to accelerate computation. An algebraic proof for the proposed algorithm has been constructed. One application relates to an eye model with one hundred and twenty sides. Its growth interpolants are generated as rational polynomials. The general computer algebra code is included in ref. [23].

R-II: The principal obstacle to the employment of Wachspress convex polygonal finite elements was that there could not be any Gaussian quadrature-like integration scheme subsequent to isoparametric-like formulation. A technique based on the Green's function in ref. [22] furnished a numerically feasible method within the framework of a computer algebra formulation. Almost all functions encountered in engineering analysis can be integrated within arbitrary elements, i.e., convex and concave polygons of arbitrary numbers of sides using the code included in ref. [22].

C++ codes for the computer algebra programs were completed by a graduate student.

7.1.2 Fundamental contribution: Intellectual merit

Beyond Courant's triangulation, displacement-based finite element formulation was severely restricted to isoparametric quadrilaterals as reported in standard text books and incorporated in popular commercial computer programs. Here, shape functions have been generated for polygons for any number of sides. The NSF-sponsored project was instrumental in bridging the intellectual gap between the abstract mathematical formulation and useful computer formulation.

MS projects:
Currently available computer algebra programs were indispensable in translating the mathematical concepts into operational codes. C++ object-oriented programs will be written during this proposed research.

Educational impact:
(i) The resulting formulations and computer codes can be incorporated into graduate-level curricula of engineering and computational mechanics.
(ii) Future results of applications to analyze historical monuments will be included in the undergraduate core curriculum of CU in two years.
(iii) Graduate student presentations in three international conferences, refs. [49], [50] and [51], and participation in two additional technical sessions (in Denmark on system reliability and Austria on advance computation, in 1999) can be cited.

Research impact:

(i) Boundary element formulation:
The ability to develop polygonal finite elements of an arbitrary number of sides blurs the distinction between the finite and boundary elements.

(ii) Random fields for constitutive and geometrical stochasticity:
The ability to capturing secondary effects of material and boundary geometrical randomness has been extensively verified in two papers refs. [24] and [21].

(iii) Bioengineering applications:
Cooperative research with morphologists from UCLA and a team from Toulouse, France, hinged on the delivery of the high precision elements addressed in the research.

A paper, ref. [25], which deals with the craniofacial growth and shape changes after medical procedures, appeared as a feature article in a computer algebra journal.

(iv) New kinds of applications:

Granular materials:
The partial contact phenomenon, which is a characteristic of granular materials, *vide* ref. [20], as evidenced in silo problems, can best be captured

by element contacts on parts of boundary pieces. Investigation on elements with side nodes naturally evolved so as to determine the limitation of the convex polygons.

Masonry structures: historical monuments: The PI won a prestigious award through CU's 'Academic Quality Fund' to work with professors of computer science, architecture and art history on historical monuments and engineering preservation.

Aging effects and initial construction defects of historical buildings, e.g., Beauvais Cathedral in France, are being studied, *vide* ref. [54].

Security threats, which can cause deterioration and possible collapse of such large buildings of cultural importance, are now of concern.

Resulting publications:

Eight journal publications and six conference papers have arisen out of the NSF research. In addition, a report, ref. [46], contains C++ codes.

7.2 Partial Travel Support NSF Number: CMS-01-20437

Amount: $14,760; duration: June 2001 to December 2003

ICTACEM 2001 (*Int. Conf. on Theoretical Applied Computational and Experimental Mechanics*), held in December 2001 at the Indian Institute of Technology, Kharagpur, India . Partial travel support for one professor and one graduate student was provided. The proceedings were published in two CDs.

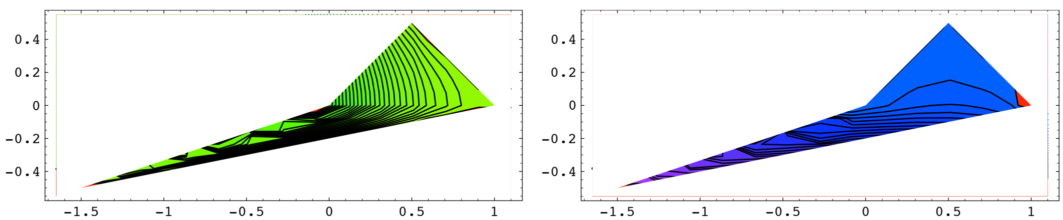
7.3 Concave Finite Element Shape Functions NSF Award 0202232

Amount: $275,104; duration: June 2002 to September 2004

Two months of research during the summer of 2002 is summarized here.

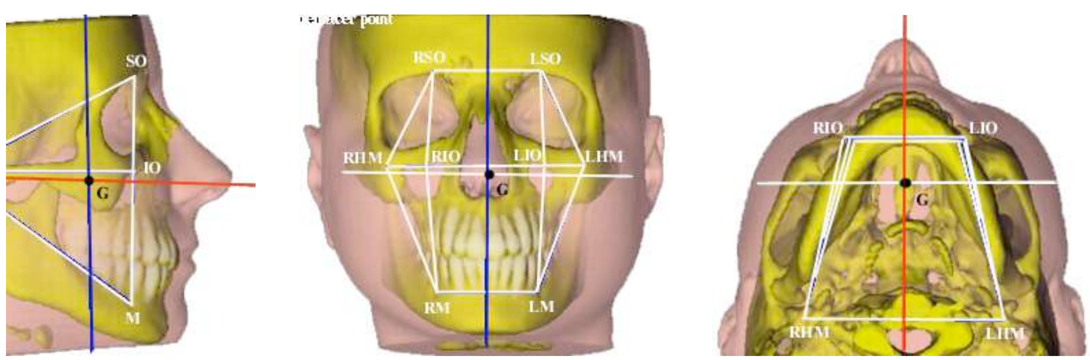
Intellectual merit: singular interpolants

It was possible to construct interpolants with $\mathcal{C}^1$ continuity for concave domains as rational polynomials.



Concave elements: contour plots for two interpolants (red zone of error is being investigated)

Broader impact: a clinical application



A B C

Generation of user selected views from radiological data: graphics by CIRAD

Anatomical landmarks are the universally identifiable references that are routinely extracted from radiological images [10]. Concave elements (with nodal landmarks) analyze the morphometric balance [73] of functional components, ref. [52], of human faces.

Mechanical strain-like tensors compare maxillofacial differences, *vide* refs. [1] and [32]. These changes are suitable for face identification.

Graphic and IT-based semantically rich documents for face analysis have been prepared by CIRAD, Paris, France, *vide* ref. [11].

8 Intellectual merit

The discipline of civil engineering, the earliest branch of technical education at universities, has continuously changed its focus to respond to contemporary social needs. The notable integration (in the thirties) of solid/fluid mechanics as its intellectual basis culminated in the successful aerospace programs (of the sixties). The primary motivation for designing early high-speed scientific computers and software has largely been attributed to the ever growing demands of finite element and fluid dynamics numerical calculations pertaining to civil and mechanical engineering, *vide* refs. [42] and [70].

8.1 Specific changes

The recent emergence of bioengineering in CU arose out of a strong cooperative program with health science researchers, *vide* ref. [66]. Nationwide, the field of environmental engineering emerged from civil engineering with life science as its new element.

Unfortunately, the above peacetime efforts, which exhibit grand success in probabilistic safety analysis, refs. [2] and [5], are not adequate when security becomes the primary concern. In the dawn of this new millennium, with the help of the IT tools e.g., preparation of highly *markedup* computer readable documents, *datamining*, probabilistic analysis of streaming sensor readings is anticipated to open up yet another new field: the *physical security of intelligent civil infrastructure*. Ushering traditional engineering into the current IT arena so that evacuation/rescue actions can be executed within the shortest time window is the principal intellectual merit of this proposal.

8.1.1 History of progress in curriculum

At each stage, current aspects of basic science and technology have been brought together to develop needed teaching and research materials. The principal intellectual challenge of this research is the proposed fusion of apparently divergent fields to solve a concrete problem, viz., physical security of civil infrastructure. Internationally reputable teaching and research universities are expected to address this issue since no part of the world is immune from threat. This demand has motivated the team to organize all available tools of computing, policy making, statistical predictions, engineering stress analysis, and sensor fabrication under the common umbrella of IT. To our knowledge, no other group has undertaken such an exciting task.

8.1.2 Impact on engineering curricula

The stagnation in enrollment in civil and mechanical engineering classes has prompted university policy makers to label these as matured areas where little change is envisioned in research and teaching. The stereotypical impression of civil and mechanical design is that it does not evolve once the item is built. With the proposed *live design* paradigm the team challenges this view. The team believes that classical engineering in decades to come will focus on security issues, which will assume priority over stress-related safety and cost-related constructions — areas that are indeed fully matured by now.

The faculty members and professional associates strongly feel that the proposed research on security will revitalize interest in the disciplines of basic engineering since the basic research on advanced IT tools is already available. Encouraging education and training with a particular focus on the physical security of buildings is at the forefront of the specific intellectual merit that the team brings to this NSF-ITR solicitation.

8.2 Lessons from completed work

Here are some examples emphasizing typical aspects of engineering mechanics in the light of the synergy of different disciplines.

8.2.1 Instrumentation: MEMS

The MEMS demonstration at MIT brought to light design concerns currently mitigated with the lab-on-chip concepts at Université de Franche-Comté, France. During this research, sensor efficiency and reliability will be examined under the combined effects of fire and smoke. The potential impact of mounting the lab-on-chip devices on skin for clinical diagnosis of victims has initiated a new cooperation between the health science and engineering departments of CU.

8.2.2 Analytical and numerical methods

Very high level languages are desirable where the formulations can be input in mathematical notation, and computer algebra codes can be generated automatically. Advances in software engineering, *vide* ref. [29], support this optimistic attitude. The principal investigator modeled blast loading on foundations using such a language. Another noteworthy on-going cooperative application relates to the energy absorption analysis of semiconductor photonic crystals, ref. [60]. The governing modified Schrödinger equation is being solved numerically, ref. [36], following a computer algebra formulation, ref. [30], meeting complex configuration design requirements.

8.2.3 Theoretical development

Advances in material research from the constitutive property viewpoint of continuum mechanics will aid the development of composites which generate electrical energy under viscoplastic deformation refs. [16] and [37]. These materials are the basic elements of self-powered sensors. The intellectual merit in combining atomistic models, nanotechnology in thermo-viscoplasticity is noteworthy. Photonic devices, such as switches, often make use of absorption in semiconductor material.

8.2.4 Interactive projects

Early 2001, the principal investigator explored with scientists from Canada and Norway the possibility of using photonic crystals to make all-optical switches for fiber-optic telecommunications. Now there are numerous research teams and companies around the world working on these new revolutionary structures with the focus on controlled manufacturing of photonic crystals (PCs). However, few efforts deal with sensors and amplifiers. Nanotechnological analysis, *vide* ref. [15], is envisioned to predict the stochastic behavior of these objects. The present project provides an opportunity to combine these diverse developments to take advantage of the IT tools appropriate for *live design* environments.

8.3 A *live design* environment — open-ended and self-updating

Take for example the planned rescue of authorized personnel. Here, as elsewhere, new information can continuously be incorporated into the strategic action, thus permitting a higher degree of individual knowledge on security and safety to be be taken into account. For example, essential information from available WTC communication audiotapes will be included in the *live design* data base to avoid repetition of past mistakes.

The aforementioned ability to incorporate evolving information is rare in conventional designs.

8.4 Areas of PhD dissertations

1. CU : Reliability analysis of civil mechanical systems with bounded statistical variables;
   Extreme value statistics with `interval arithmetic` and Bayesian updating;
   Quantification of professional policy with heuristics and fuzzy logic.

2. MIT: Synthesis of stress calculations and RF coded self-powered sensor data— a composite fire/ smoke and blast loading;
   Parallel computing for virtual reality based intelligent signs

3. CMU: Deep domain models for civil infrastructure

8.5 Courses

A number of existing courses in engineering schools address the science behind the proposed core technology. Here are some examples of how those theoretical developments can be linked to design a practical *live design* IT environment. Since the Computer Science related courses are evolving at their usual fast pace only courses in CU and MIT are enumerated below. The required computer science work provides a sound background that when incorporated in graduate and undergraduate project work can enhance cross-fertilization.

8.5.1 Undergraduate

The freshman civil engineering class can be provided with contemporary sensors monitoring technology. Measured records can be used as inputs in structural analysis classes. Post- construction tasks will be emphasized in the understanding of building codes. Probabilistic modeling with the aid of computer-aided graphics will substantiate engineering policy understanding.

8.5.2 Graduate

Sensing and monitoring of physical infrastructures
Symbolic computational mechanics (`interval arithmetic`)
Nonlinear mechanics (materials for sensors)
Stochastic computations (principal components and Bayesian updating)
Design of buildings, bridges and tunnels
Real time large scale computation

8.6 Research

Doctoral level
Computational engineering mechanics
Online monitoring of decision systems
Postdoctoral level – foreign scholars
1. Large scale correlation matrix
2. Higher order perturbation
3. Principal components, `interval arithmetic`
4. Infrastructure management
5. Stochasticity with bounded variables
6. Symbolic computation in stochastic mechanics

<u>Role of visiting scholars</u>

Distinguished visiting researchers will teach tutorial and seminar courses at national and international conferences. Professors Wachspress and Weierholt, refs. [77] and [78], who are currently visiting CU, will teach graduate/undergraduate computing laboratory courses. Experience indicates such courses to be efficient means of communicating current research findings to the student body.

<u>Facilities, instrumentation and networks</u>

While completing the background tasks, the senior participants have made considerable advances in their respective research infrastructures. The present budget for permanent equipment reflects the need for further enhancement of IT related instrumentation.

<u>Extension courses</u>

In addition to the aforementioned state-of-the-art research, an important educational component will be to introduce the concepts of intelligent infrastructure security to future PhD students, engineering professionals and civic authorities. Summer courses and workshops will provide such opportunities.

8.7 Aiding the handicapped

Dean Vreeland's work for the blind and visually impaired students and adults, *vide* ref. [75], and Prof. Gharbi's instrumentation, *vide* ref. [59], for optical visualization in museums will be used to design *smart signs*.

8.8 Undergraduate and MS students

In the interest of economy, undergraduate research assistants (seniors of civil and mechanical engineering) will carry out numerical simulation and document case studies. Their work in ongoing projects, especially in computer graphics, *vide* refs. [63] and [64], in maintaining websites with research records and technical papers has been extremely helpful. The research team envisions partially supporting four undergraduate students, each under the supervision of CU, MIT, CMU and OKG.

The MS students will undertake computer graphics projects, *vide* refs. [44] and [63], as a part of their class work, and will help to organize conference publications and research reports. Many such students will continue in the subsequent NSF-ITR large project on infrastructure security. Their assistance will also be of value to this complex research endeavor.

8.8.1 Sample MIT masters projects

The crucial steps in developing self-powered wireless sensors were demonstrated in November 2002.

<u>1. Energy harvesting:</u>

Piezoelectric strain sensors were incorporated in a load cell, which was intended for placement within a bridge deck slab. The voltage produced by the strain was stored using a capacitance device and provided the EMF for wireless transmission of other sensors.

<u>2. Wireless sensor network:</u>

A set integrated acceleration sensors designed and distributed by the Sensor and Actuator Center, University of California, Berkeley, were used to monitor the motion of a building located adjacent to a construction site during pile driving activities. The sensor consisted of a MEMS based two-directional accelerometer, an eight bit programmable microprocessor, and a RF (radio frequency) transmitter/receiver. The microprocessor allowed incorporation of a filter processing program to remove drift from the accelerator data, as well as packaging the data and controlling the transmission rate. The unique feature of the sensor was its processing ability at the source, which minimized the amount of data to be exchanged so allowed wireless transmission.

<u>3. Battery powered sensors:</u>

A set of sensors was aligned sequentially to propagate acceleration data to a laptop computer capable of wireless communication with a web-accessible sensor. This demonstrated a wireless sensor networks for real-time data acquisition.

Synthesis of the above experiments will advance the self-powered wireless sensor technology.

8.8.2 CU student members of the team

During the last two years, undergraduate, masters and doctoral students have played an effective role in preparing this research proposal. Their CVs are included as supplementary documents.

9 Broader impacts

9.1 Benefits to society

The timeliness of this research cannot be overemphasized. Today, security is of paramount importance to every occupant of a building.

The following diverse examples hinge on *live design*'s ability to generate qualitative (non-technical) results out of complex mathematical quantification of mechanics and econometrics. The items point out the shortcomings of the conventional technology and emphasize the need for intelligent management of civil infrastructures by employing IT tools.

1. The fine-tuned (in space and time) voice annotated three-dimensional rendering of spatial distribution of threats (as opposed to permanent 'Exit' indicators above doors) will broadcast the most efficient evacuation/rescue routes and notify dangerous paths to be avoided. These smart signs will reduce panic, confusion and stampede.

2. Rescue workers will be better trained through practice with computer animated threats (like simulated flights). Their handheld wireless devices will communicate *live* with the base station.

3. The availability of *live design*'s record history, which depict victims' surroundings (e.g., smoke intensity), will provide a more detailed picture of disasters to all concerned parties.

4. The testimonials will improve and expedite treatment planning for injuries and trauma. They will also aid legal professionals to less ambiguously pursue product and management liability cases.

5. *Live design* evidence (like the aircraft *blackboxes*) will aid forensic investigators by playing back sequences of total or partial collapse of buildings.

6. Building owners will have a deeper understanding of safety/security. A *live design* environment will suggest improvements to reduce insurance costs.

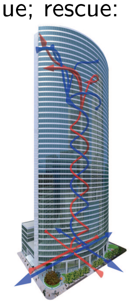
7. While retrofitting, professional engineers will have a record of site deficiencies. Varying reliability of communication devices can be incorporated during the prototype demonstration.

8. Improved public awareness will immensely assist homeland security measures.

9. The research team will organize regular workshops to bring together engineers, computer scientists, professionals and homeland security representatives who will communicate the progress of the *live design* prototype to the public at large.

The overwhelming need for program development will be met by junior participants (at the technician level), who will acquire IT training and work experience from their participation in the workshops.

evacuation: blue; rescue: red



A demonstration problem

Each year, three graduate students (one each from CU, MIT and CMU) will attend national meetings and will promote seminars in student chapters of professional societies. At each university undergraduate students will be financially supported to set up demonstrations for high schools.

9.2 Commercial potential

University-industry cooperative programs and university research enterprises have already expressed interest in commercializing security software.

The MEMS patenting activities of MIT and the patent possibilities of *live design* in CU are worth mentioning.

9.3 A typical sample test case

The lack of a clear UN evacuation and rescue program after the November 12, 2001 American Airline crash will be analyzed.

The policy issues in formulating evacuation/rescue strategies of foreign and international bodies will be discussed and webcast during special seminars organized with the CU schools of Law, Journalism and International/Public Affairs.

The New York Times has expressed interest in regularly covering the proposed CU workshops.

These forums will contribute valuable information towards preparing the follow up ITR large proposal that will consider scenarios related to the closure of bridges and tunnels.

9.4 Research dissemination

1. Delivery of software

Software releases will contain: source and executable codes, detailed technical documentation, user manuals with examples and lists of archived publication references. All research material will be posted on the internet for unrestricted distribution.

2. Dissertations, reports and journal papers

It is anticipated that this development oriented research will produce about fifty journal and conference papers. These publications and details of an estimated ten PhD dissertations will be published as university reports for unlimited distribution.

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