Automated Inspection Planning through CAD Modeling for Steel Bridge Painting Construction

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ABSTRACT

To reduce inspection cost, random-sampling is currently the most popular method to check the quality of steel bridge painting construction. The "randomness" of sampling is the key assumption of the statistical random sampling theory. Only when inspection spots are "randomly" selected, is the decision-making based on the collected data meaningful. Therefore, no mater using human-inspectors, robot-inspectors or remote-sensing, the question -- "where to take measurement" need to be answered. The research proposed a CAD modeling to assist in generating a stratified sampling scheme and random inspection spots. A surface element with four vertexes is introduced as a basic unit to represent steel structures. The geometry operation to trim stratified sampling scheme is defined. Then, the algorithms to produce random inspection spots are derived. This paper starts with interesting finding of "un-equal" quality happened in the recent painted steel bridges to point out the need of a CAD system for generating stratified sampling scheme and random inspection spots. For years, robotics have been helping the inspection work in certain construction areas. A potential extension of this research is the combination of CAD-sampling plan and inspection robots or remote-sensing. In the future, the CAD-produced random sampling plan could guide robot-inspectors to handle a camera and a probe to test quality of steel bridge painting where it is dangerous for human inspectors to access.

1. INTRODUCTION

In the research sponsored by USA Department of Transportation (HPR-2029-089-27 and C-36-20H) [1, 2], the study confirmed that less efforts have been made to maintain the painting quality on the middle span areas of a steel bridge[3]. The major reason of the "un-equal" quality is that many inspectors check the painting quality only on easily accessible areas where they can check the bridge by directly standing on the abutments. However, the "random sampling" is the key assumption of the statistical sampling theory(4, 5). Only when inspection spots are "randomly" selected, is the decision-making based on the collected data meaningful(6). As a result, a CAD system is proposed to stratify the products into lots, and to randomly generate inspection spots. No mater using human-inspectors, robot-inspectors or remote-sensing, the question -- "where to take measurement" could be answered.

2. REPRESENTATION OF SURFACE ELEMENTS

The 3-D wire frame and surface representation are adopted in modeling the steel bridge elements. Although the solid modeling provides a more complete geometric and topological information, several problems keep this research away from using the solid modeling (7). Other researchers have shown that wire frame models can still be a powerful approach to process the geometric data (8).

The proposed CAD system is to assist in generating a stratified sampling scheme and random inspection spots. A surface element with four vertexes on the same plane is introduced as a basic unit to represent bridge structures. Every piece of steel bridge surface is represented by the defined surface element.

Several CAD applications use triangle surface elements to represent their objects(9,10). However, the surface elements of four vertexes are used in this research because of the following reasons:

1) Most of the steel structure components consist of quadrangle shapes. Therefore, the four-vertex surface element can efficiently represent bridge steel structures.
2) To represent most construction products, the quadrangle is more efficient than the triangle shape. As an example, the surface in Figure 1 needs two quadrangle elements; or four triangle elements, to represent the surface pattern.

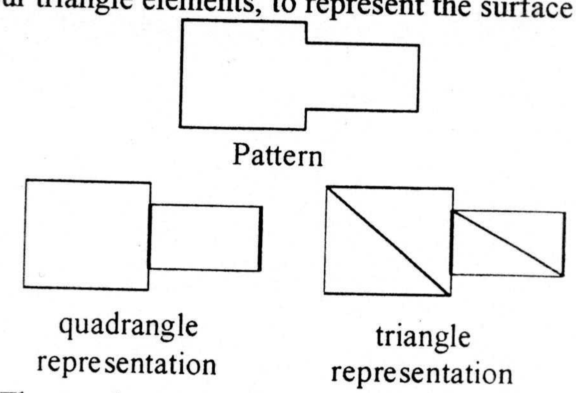


Figure 1: The quadrangle is more efficient than the triangle shape

3) The quadrangle element accommodates the triangle element. In certain designs, a triangle element is indispensable. To directly represent the triangle shapes with the quadrangle is not a must. A modified quadrangle with the third and the fourth vertexes overlaid is capable of mimicking a triangle element. This modification makes the quadrangle element suitable for representing a triangle shape.

3. PARAMETRIC MODELING

Conventional design drawings of the wire-frame model are just a bunch of lines in 2D or 3D space. However, there is no information on the surface, nor on the inside or outside of the object. The wire-frame model is ambiguous, and the lines are difficult to portray real objects. To solve this problem, the elements of modeling need to be further organized.

The proposed system needs to automatically attach surface information to the wire-frame model. To do so, parametric surface modeling is used as a tool to force the origination of the geometry data. For instance, an interface for parametric modeling for I-shape beams can be created to facilitate the users' input. The users only have to answer the questions of depth, width, thickness, and length of the beams; then the parametric mechanism will automatically take care of the generation of beam models in 3D space. Through this approach, the stored geometric information is enough for the process of area querying, cutting, interference checking, and so forth.

4. OPERATION OF SURFACE

In order to generate stratified sampling schemes and create random sampling spots, surface elements need to be processed and transformed into other surface elements. The following sections describe two basic operations of the quadrangle surface element: 1) area query, and 2) stratification.

QUERY OF AREA

The area of each surface element is obtained by calculating the two triangles forming the quadrangle surface element (Figure 2). Because the surface element is not necessarily rectangular (it is an quadrangle), the areas cannot simply be obtained by multiplying the length and width of the surface element. Figure 2 shows one typical surface element. Also, when the four-convex element is used to mimic a triangle shape, the third and forth vertexes are overlaid. The area of one of the two triangles will become zero, and the proposed approach in calculating the area is still valid.

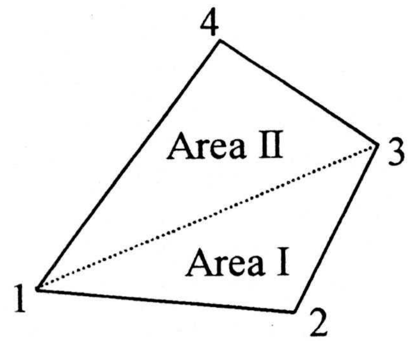
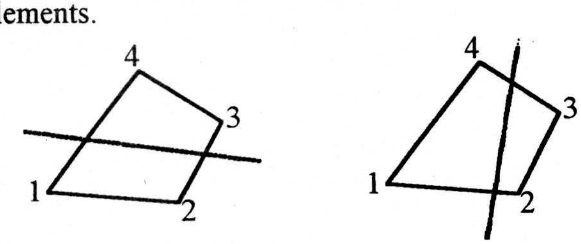


Figure 2: Two triangles forming the surface elements

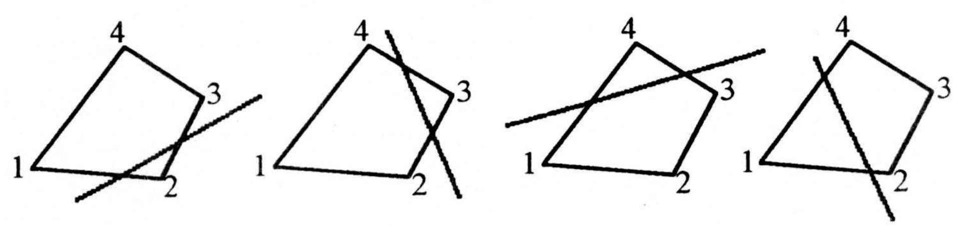
STRATIFICATION

In the developed parametric modeling, each surface element usually spans over the entire axis of the steel structure. To generate stratified sampling lots, the surface elements need to be cut into many smaller subsurfaces. Two cutting conditions, shown in Figure 3, are used to describe by which surface elements are divided into subsurfaces.

For type 1 cutting, the cutting lines cross the surface element and interfere with the non-adjacent edges. For this condition, the surface element will be simply divided into two sub-elements.



Type 1 Cutting



Type 2 Cutting

Figure 3: Two types of Cutting

Type 2 cutting is the other condition: the cutting line crosses the adjacent edges. This condition is more complex. In nature, the surface elements are divided into two elements: one is a triangle, and the other is a pentagon. However, the basic surface element is defined by four vertexes. The pentagon needs to be further divided into two surfaces: one is a triangle; the other is a quadrangle. Figure 4 shows the process of type 2 cutting.

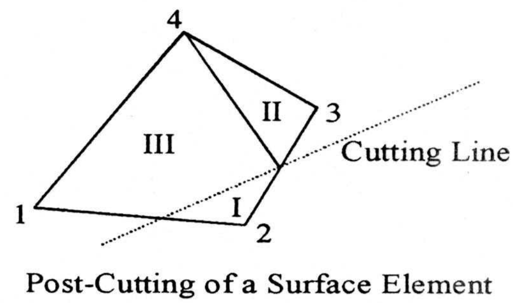


Figure 4: Post-Cutting for Type-II Cutting

5. ALGORITHM FOR RANDOM INSPECTION SPOTS

The "randomness" of sampling is the core assumption in the random sampling theory. Random sampling means that inspection spots should be randomly selected, and each area has an equal chance of been inspected.

Each steel bridge member consists of many surface elements. The surface elements can be large or small. The sizes of the surface elements directly represent the cost of material used and time needed to sandblast and spray. Therefore, surface elements with larger areas are more significant, and should have a higher probability of being inspected, and vice versa. In the generation of random sampling spots, the chance of a lot to be chosen is proportional to the size of the surface. The algorithm is described as follows:

First, the surface elements within one lot are selected and grouped. Then the surface elements are normalized between 0 and 1. For example, there are four surface elements with area sizes of 1, 2, 3, and 4 square feet. The sum of the surface element is 10 square feet. So, the surface elements are normalized to be 1/10, 2/10, 3/10, and 4/10, as shown in the following way:
0 - 0.1 : point to surface #1.
0.1 - 0.3 : point to surface #2.
0.3 - 0.6 : point to surface #3.
0.6 - 1.0 : point to surface #4.

The way of normalization consists of distributing the probability of "being picked" proportionally to the area of the surface elements.

Then, a random number generator, which will produce a real value between 0 and 1, is used to pick up a surface element according to the normalized sequences. For example, if the random number obtained is 0.34, falling within the third group, then the surface #3 should be chosen.

After one specific surface element is selected, an inspection spot needs to be assigned on this surface element. Two stages are employed to pick one inspection spot.

First, pick up one of the two triangles forming the quadrangle surface element (refer to Figure 2). To choose which triangle should be selected, the same logic in choosing the surface element is used. The probability of being chosen is proportional to the area of the two triangles.

After one of the two triangles is chosen, the inspection spot should be assigned. As shown in Figure 5, two vectors: V1 and V2, along the edges of the triangle are generated. By assigning two random numbers, designated as R1 and R2, the inspection point is selected. The algorithm is derived as follows:

V1 = [x2-x1, y2-y1, z2-z1]
V2 = [x3-x1, y3-y1, z3-z1]
SP = R1 * V1 + R2 * V2
IP = pt1 + SP

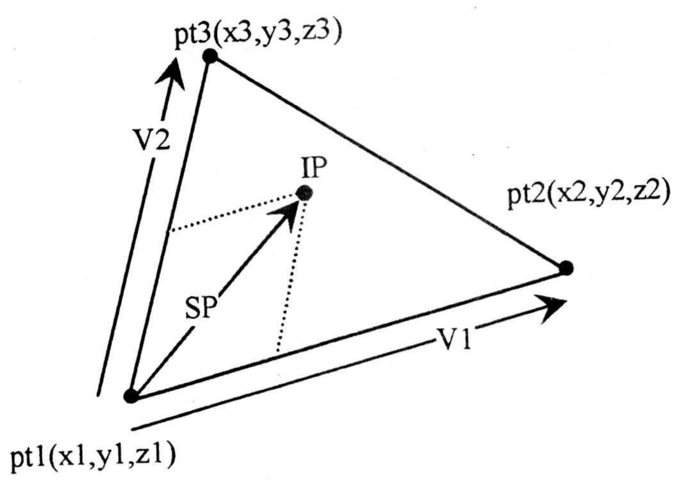


Figure 5: Inspection Spot Generated by Two Random Vectors

However, the above algorithm may generate an inspection point (IP) outside the triangle when "R1 + R2" is larger than 1. To solve this problem, when the "R1 + R2" is larger than 1, the inspection point will be mirrored back into the triangle. The algorithm is as followed:

If (R1 + R2) > 1, then R1 = 1 - R1 and R2 = 1 - R2.

With the algorithm, the generated inspection spots will be randomly guaranteed inside the triangle. In summary, the random inspection spots are generated in the following steps:

1. Assign probability of being selected to each surface element.
2. Randomly pick one of the surface elements of the lot.
3. Randomly pick one of the two triangles forming the quadrangle.
4. Randomly generate two vectors along the edges of the chosen triangle to pick an inspection spot.
5. Repeat steps 1-4 for another inspection spot until the required sample size is reached.

Random Number Generator

The proposed algorithm for random inspection spots requires a method of generating randomnumbers. The methodology of generating random numbers has a long history. The random number generator adopted in this research is called "linear congruential generator" (LCG) developed by Lehem (1951). The random numbers are a sequence of integers Z1, Z2, ... defined by the recursive formula:

$$Z_i = (aZ_{i-1} + c) \text{ (Mod m)}$$

where a, m, c and Z_0 are non-negative integers. The Z_0 is usually called seed. The following values are adopted in the research: $m=2^{31}-1$; a=630,360,016; c=0. For testing and verification of this random number generator, please refer to the work of Law and Kelton (11).

6. IMPLEMENTATION

The proposed system is implemented into a computer package named "I-CAD" to generate a stratified sampling scheme and random inspection spots through a CAD database. The major environment for I-CAD is AutoCAD. The I-CAD consists of two types of programming languages: AutoLISP and C++. Inside the AutoCAD, the AutoLISP is programmed to build parametric surface modeling, to retrieve geometric data of surfaces, and to write surface information to an external data file. On the other hand, C++ is programmed to read and process geometric data files. Many classes have been programmed to map the surface object.

The I-CAD consists of four stages including 1) Parametric Modeling, 2) Stratification, 3) Random Sampling, and 4) Visualization. The following figures illustrate the example of the functions of I-CAD.

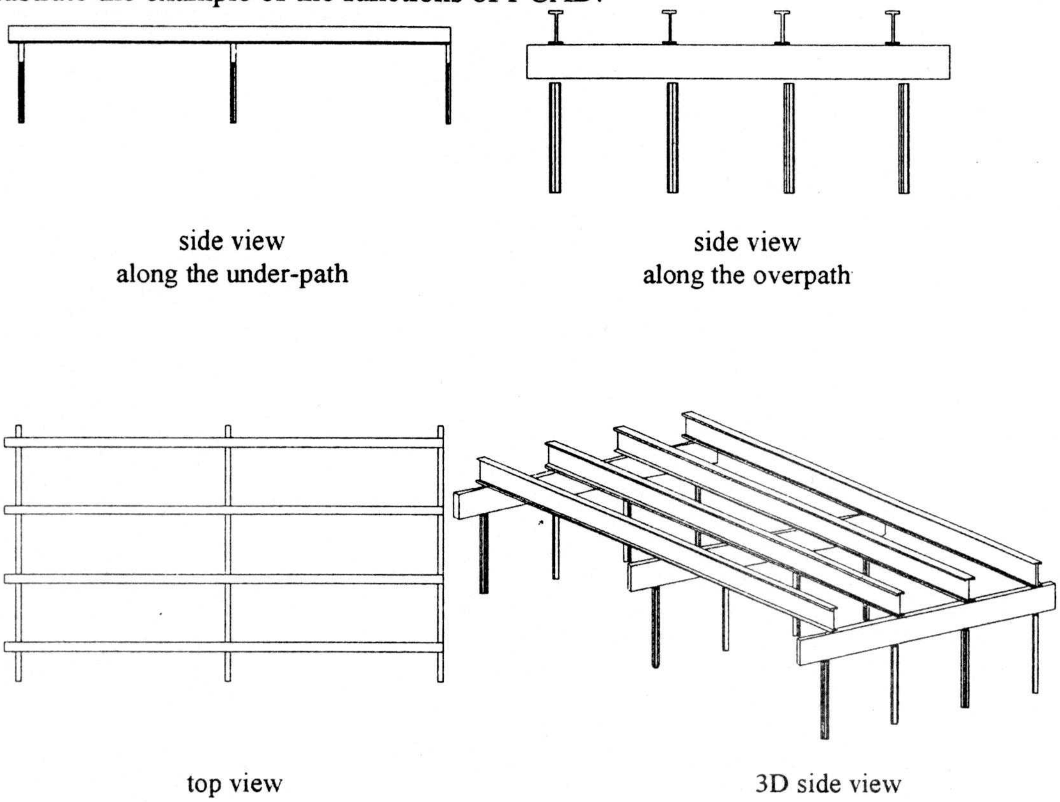


Figure 6: Top and side views of the bridge model generated in I-CAD

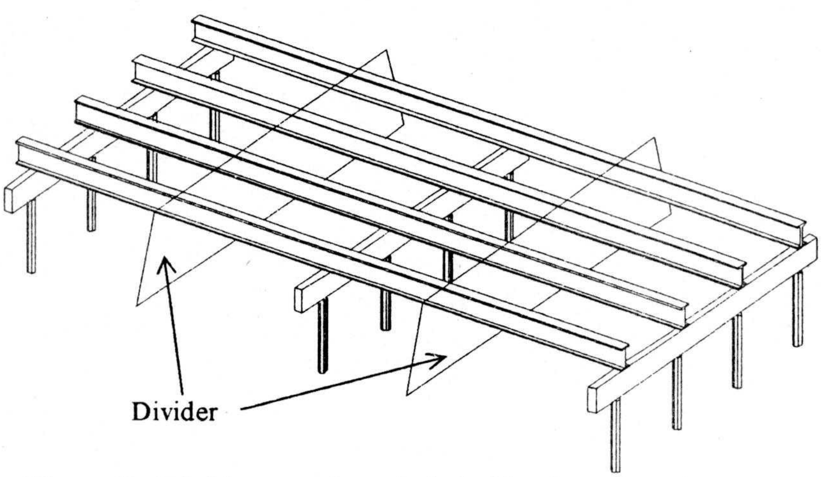


Figure 7: Dividers cut the whole bridge into three lot zones.

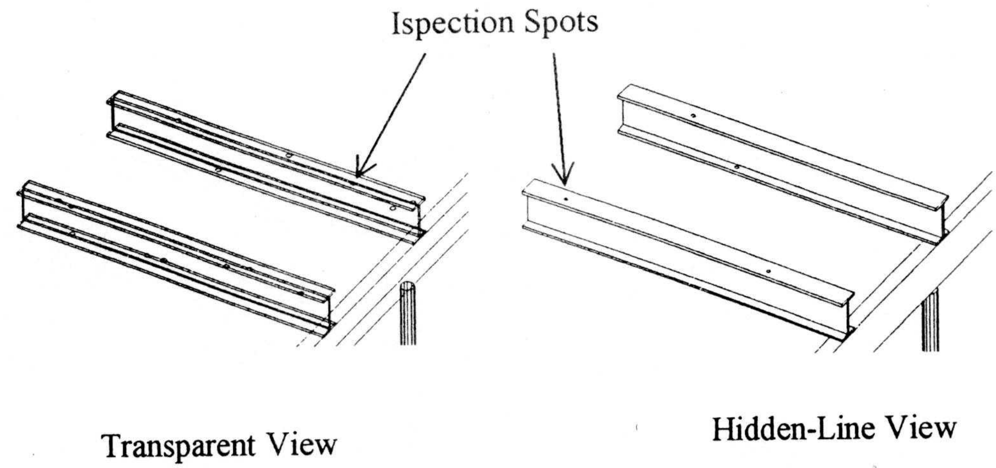


Figure 8: Transparent and hidden-line views of stratified random sampling spots

7. CONCLUSION

In the research, basic geometric representation was defined: a surface element with four vertexes. To meet the need of creating stratified sampling schemes, several types of geometric operations were identified. The algorithm to generate random inspection spots was also defined. The concept is implemented in the package: I-CAD.

Users first need to input the bridge model into the CAD environment through the parametric input interface. The program inside the CAD system, written in AutoLISP, will then retrieve bridge's geometric data. A program written in C++ will process the geometry of complex bridge surface elements, and generate random sampling spots. Finally, the produced stratified random sampling plan is visualized in the CAD system.

Inspection steel bridge painting have been an important, but also risky work. The construction site for steel bridge painting may be over a river or a highway. Accessing the bridge structures imposes danger to inspectors. Robotics have been helping the inspection work in certain construction areas for years. By cooperating with the CAD database, the robots can possibly be controlled to handle a camera and a probe to test the quality of painting where it is difficult for human beings to access.

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