Numeric Ground Image Systems Design

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Research Report 120-1

Numerical Ground Image

Research Study Number 2-19-68-120

Sponsored by
the Texas Highway Department
in Cooperation With the
U. S. Department of Transportation
Federal Highway Administration
Bureau of Public Roads

August 31, 1968

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University
College Station, Texas

Abstract

Although the systems approach to design is usually thought of as having applications only in the field of hardware systems design, from whence it came, systems methodology and philosophy are also applicable to the design of computer software systems. The NGI (Numeric Ground Image) Systems Design study is an example of the systems approach to the design of a computer software system.

The NGI System furnishes the highway engineer with a method for approximating the terrain surface with a numerical surface. Traditional highway design practice has required the use of cross-sections to represent the terrain. The use of the numerical surface approach, instead of the cross-section method, eliminates some terrain representation problems associated with the traditional cross-section method. For example, if the horizontal alignment of a roadway is shifted, a new and separate set of cross-sections corresponding to the new alignment must be obtained. This new set of cross-sections is necessary because the old set was directly referenced to the old alignment. This is not true of the numerical surface approach because it is not directly referenced to any specific alignment.

The NGI System is designed to interface with FORTRAN "driver" programs. In general, whenever the interfacing program requires an elevation at a specific horizontal position, it passes the X and Y coordinates of that position to the NGI System through the appropriate interface. The NGI System computes the Z (elevation) corresponding to the X and Y and passes it back to the original program through the same interface. The nature of the interfacing program can vary from, say, earthwork analysis to contour plotting.

The NGI System computes the required elevations in this manner. The ensemble of terrain data points (all measured with respect to the same coordinate system) is divided into rectangular sectors and then stored by sector in a direct access device. As the sector data points are required for elevation computations, they are brought from storage into the core. The cluster of data points surrounding the required point is then selected from the sector data. The elevation of the desired point is obtained from a surface which has been fit by least squares to the cluster of terrain data points.

At this stage of development the NGI System is not a general purpose engineering tool to be used by the unwary. However, once the operating characteristics of the NGI System are determined and surface technology is extended into engineering design, it holds the promise of becoming a highly effective highway design technique.

Acknowledgments

The authors are indebted to personnel from both the Texas Highway Department and the U. S. Bureau of Public Roads for their assistance throughout the course of this study. Of particular value was the work by Mr. Larry Walker of the Texas Highway Department who furnished valuable reference material and offered constructive criticism on many details of the research work.

Recognition should also be given to the personnel of the Texas A&M University Data Processing Center who assisted in processing many of the computer programs. Thanks are due Mr. Joseph S. Carroll who assisted in developing the computer programs and Mr. George Casares who assisted with the drafting of the figures.

The opinions, findings and conclusions expressed in this report are those of the authors and not necessarily those of the Bureau of Public Roads.

Table of Contents

List of Figures

CHAPTER I

NGI System Concepts and Objectives

During the past decade a great amount of time, money and human effort has been expended on the problem of applying systems engineering and optimization techniques to computer-aided highway design systems. Two of the most ambitious efforts are the Bureau of Public Roads TIES[1] (*T*otal *I*ntegrated *E*ngineering *S*ystem) project and the M.I.T. ICES[2] (*I*ntegrated *C*ivil *E*ngineering *S*ystem) project. In addition, several of the State Highway Departments and various private consultants have developed and are presently writing their own systems. Although the design philosophy of these systems may differ (as do ICES and TIES), the primary objective is generally the same: the more effective use of the information storage capacity and processing speed of systems as engineering tools.

One of the results of these efforts has been the recognition of some of the inadequacies of present highway engineering design technology. For example, using current state-of-the-art, it is possible to completely describe the design roadway as a mathematical surface, *i.e.*, for every horizontal position (X and Y) along the highway it is possible to calculate an elevation (Z). Unfortunately, this capability has not been extended to the description of the design terrain. Using current technology it is not possible to completely describe the terrain as a mathematical surface.

This study concerns itself with the development of the NGI (*N*umeric *G*round *I*mage) System for approximating the terrain surface with a mathematical surface. The NGI System describes the terrain surface as a mathematical surface thus making it possible to calculate a unique elevation (Z) for any desired horizontal position (X and Y).

The Traditional Approach to Terrain Approximation

Traditional and current highway design practice has required that the terrain be represented by cross-sections taken with respect to a previously established horizontal alignment. While other feasible schemes for representing the terrain (such as contour maps) have been developed and used with some degree of success, none have gained the universal acceptance that the cross-section method still enjoys. This widespread use of cross-sections continues in spite of some very serious limitations.

These limitations are inherent to the cross-section method itself and are more or less independent of the measurement or use of the sec In brief, these limitations are:

1. The horizontal alignment must be established before the cross-section data can be measured. This is true no matter what method is used to obtain the cross-section data.

2. A unique set of cross-sections is required for each and every horizontal alignment. Thus, for every horizontal alignment shift a new and separate set of cross-sections must be obtained either by shifting the original set to the new alignment or by measuring new sections.[3]

3. Gaps in the terrain coverage caused by conven-

[1]The documentation of the TIES System is currently incomplete. However, Johnson, A. E., *et al.*, "Total Integrated Engineering System (TIES)" gives an accurate description of its objectives and philosophy.

[2]The documentation for ICES is currently available from the M.I.T. Press, Cambridge, Massachusetts.

[3]Several schemes for overriding these first two limitations have been developed. The more important examples are given in the Appendix.

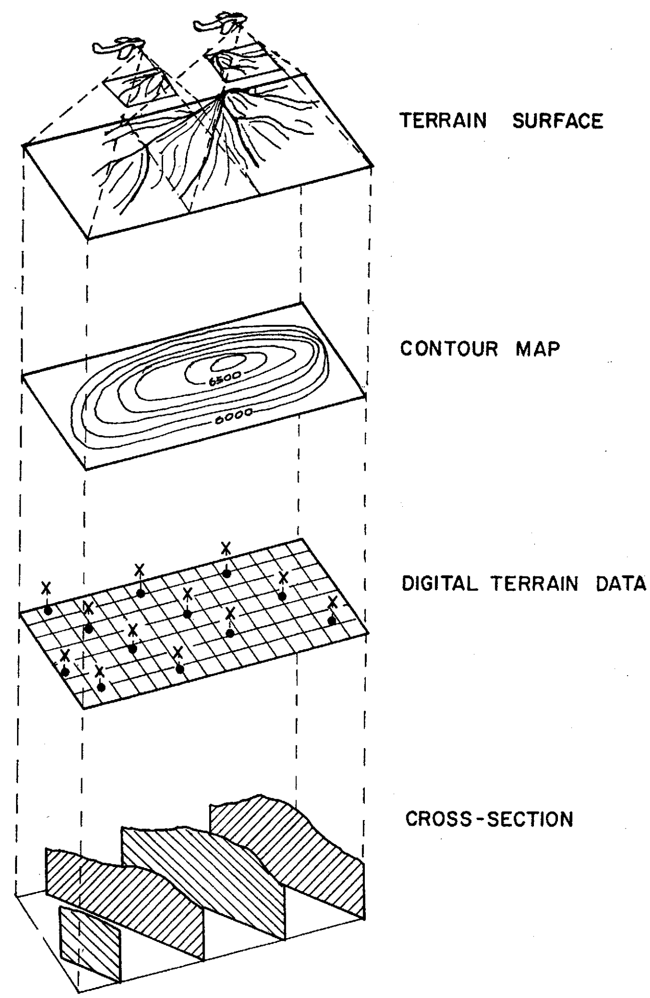

Figure I-1. Cross-section terrain approximation.

tional cross-section spacing practices creates a situation where significant terrain features may be poorly represented or omitted entirely.

4. The cross-section method does not easily lend itself to freeway interchange design. Horizontal alignments which are not parallel result in the overlapping of cross-sections. This creates a confusing situation during both the design and the layout of the facility.

Three major advantages to cross-sections are:

1. The technology of cross-sections is well known and highly developed. Thus, the design engineer feels "comfortable" working with cross-sections.

2. Cross-sections readily lend themselves to the design of rural highways where the design geometry is relatively uncomplicated; the occurrence of roadway intersections is minimal; and only the vertical alignment need be optimized.

3. Errors in cross-sectional approximation tend to be randomly distributed, minimizing errors in earthwork quantities over the long run.

The Numeric Surface Approach

All of the four limitations of the cross-section method mentioned above could be eliminated if the design

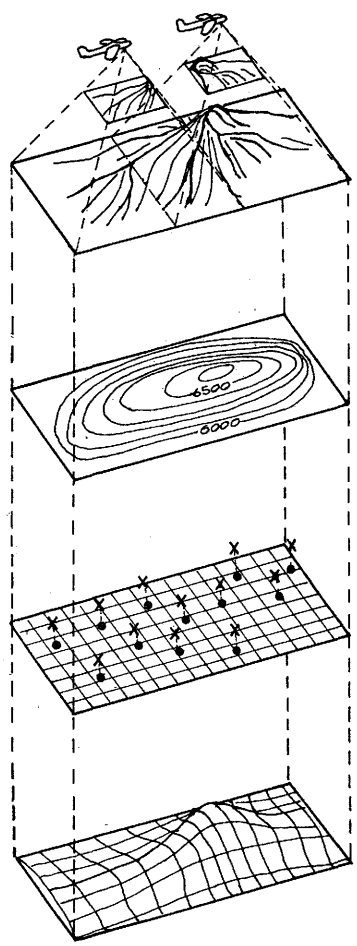

Figure I-2. Numeric surface terrain approximation.

terrain could be represented by a numeric surface. Some of the advantages of such a numeric surface would be:

1. The surface would be referenced independently of and prior to establishment of the horizontal alignment.

2. There would be no need to obtain new terrain data every time the horizontal alignment is revised since the terrain data are independent of the alignment.

3. There would be no gaps in terrain coverage due to spacing conventions since the surface would yield a continuous coverage as opposed to the intermittent terrain coverage associated with cross-sections.

While the numeric surface approach would eliminate the major limitations of cross-sections, a new set of problems would materialize. Some of the more obvious problems are:

1. The technology of numeric surface techniques applied to highway design is scant when compared to cross-section techniques. In fact, it is apparently nonexistent!

2. Numeric surface techniques will require a larger number of calculations than cross-sections. In fact, efficient use of these techniques would virtually mandate a digital computer to perform the necessary arithmetic.

Several techniques for representing the terrain as a mathematical surface have been previously developed. Unfortunately, these methods are not directly applicable to the highway design process, although they have been utilized successfully in their fields of development.[4]

The Purpose and Objectives of This Study

The purpose of this study is to develop an engineering tool to be used to approximate the terrain. As a result, development of the NGI System should be more strongly influenced by engineering applicability than by mathematical conveniences. Although NGI System development was limited by time and resource constraints, these limitations did not inhibit the analysis of the problem; only the extent to which the chosen system could be tested in an operating design environment.

In order to obtain a better tool for terrain-approximation, the following specific research objectives were pursued:

1. The investigation and development of several numerical surface techniques applicable to the highway design process.
2. The evaluation of these techniques after application to both theoretical and actual terrain data. Possible parameters used for this evaluation were:

   Accuracy: How well does each technique approximate the actual terrain?

   Effectivity: Which technique makes the most effective use of the measured terrain data?

   Computability: How well does each technique interface with other computer software?

   Generality: How well does each technique serve

[4]Some examples of numerical surface techniques are shown in the Appendix.

as a general case solution to the problem of terrain approximation?

Applicability: Are the results obtained from surface techniques consistent with present and future highway computer-aided design practice?

3. The determination of the optimum surface technique and design of the NGI System.

The Plan of Research

In a study of an exploratory nature where the object is to seek out an unknown or ill-defined concept, a specific and detailed plan of research is difficult, if not impossible to establish. In order to lay out such a plan of study the problem has to have been previously well defined. However, the following approach proved to be general enough to allow for the flexibility needed in research investigation, yet strict enough to keep the research efforts pointed toward the objective.

I. Conduct a literature search for existing relevant technology.

II. Obtain digital terrain data for testing and evaluation purposes.

A. Fabricate several fictitious terrain surfaces with known parameters. These data will be used to develop the surface techniques.

B. Obtain several sets of digital terrain data obtained from the natural terrain surface by photogrammetric methods. These data will be used to gain experience in dealing with operational problems in the computer and to compare with results obtained using fictitious data.

III. Develop an analysis methodology to formulate several alternative surface techniques for approximating the terrain.

IV. Evaluate each of the alternative systems of Procedure III and establish the optimum NGI System from one or a combination of these preliminary techniques.

V. Design the proposed NGI System.

CHAPTER II

Systems Design Methodology

Systems engineering is a relatively new innovation so far as highway engineering is concerned. Most of the systems literature that is currently available deals with aero-space and its related systems or automatic control systems, such as the Bell Telephone TD-2 Radio Relay System. Although systems engineering technology originated in disciplines other than highway engineering, and in many cases is not directly translatable to highway problems, systems philosophy and methodology can be profitably exploited in the solution of highway design problems.

A systems approach applied to a study of this type increases the probability of developing an innovative solution to the problem of terrain approximation while minimizing the effect of the investigator's previous biases. In this case the systems approach is used to lessen the effect of the well developed cross-section technology currently in vogue upon the design of final NGI System.

SYSTEM DESIGN CONCEPTS

Systems design is more of a philosophy than a procedure. Unlike the Scientific Method, systems design has no set of rules to guide the researcher and from this point of view is rather difficult to describe in a few paragraphs. In fact, the practitioners of the art do not even agree as to what comprises a system. However, some notion of the fundamentals of systems design may be conveyed by an examination of definitions of systems and an illustration of the abstract system design process.

Systems and the Systems Approach

Gosling[1] defines a system as an engineering artifact which is most easily analyzed, described, and designed as an assembly of independent but interconnected simpler parts.

Hall[2] depicts a system as a set of objects which have a relationship with their attributes when functioning in a given environment. The environment is the set of all objects outside of the system. Either a change in attributes affects the system, or the attributes are changed by the behavior of the system. This relationship is illustrated by the model in Figure II-1.

According to Drew,[3] a system is an array of components designed to achieve an objective according to some plan. He also defines an engineering design as a process consisting of data acquisition, data analysis, decision making, documentation, and implementation. By combining these two concepts the systems approach to engineering design can then be described as: (1) a creative form of problem solving, (2) a technique for dealing with the problem as a whole and not just the individual elements, (3) a rational process rather than an intuitive process, and (4) a procedure for applying formalized analysis techniques of mathematics and science to engineering projects.

Abstract Systems Design

If we assume that the system input, the system output, and the pertinent laws of nature (environment) are known, and that the number of possible systems is infinitely large, then in an abstract sense systems design can be described as the process of isolating the optimum feasible system from this universe of systems. This process can be divided into eight stages which are, in turn, grouped into four phases. A brief outline of these divisions follows.

Phase I. Synthesize a system specification which embraces only those systems which satisfy the system requirements.

1. Establish the requirements which the system must satisfy.

2. Partition the universe of systems so that only those systems which satisfy the system requirements are enclosed within the system specification. Conversely, those systems which do not satisfy the system requirements lie outside the system specification.

Phase II. Isolate the feasible alternatives that lie within the system specification.

3. Postulate a set of alternative systems that lie within the system specification.

4. Isolate the feasible alternatives from this set of alternatives.

Phase III. Isolate the optimum system.

5. Evaluate the operating characteristics of the feasible alternatives against prescribed performance criteria.

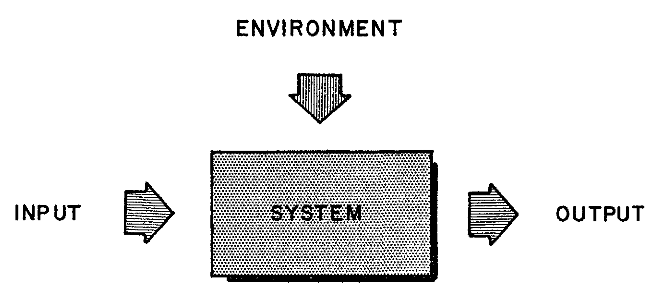

Figure II-1. Idealized system model.

[1]William Gosling. *Design of Engineering Systems,* (New York: John Wiley & Sons Inc., 1962), p. 11.

[2]Arthur D. Hall. *A Methodology for Systems Engineering,* (Princeton: D. Van Nostrand Company, Inc., 1962), pp. 60, 61.

[3]This definition is a paraphrase of comments by Dr. Donald R. Drew, Texas A&M University.

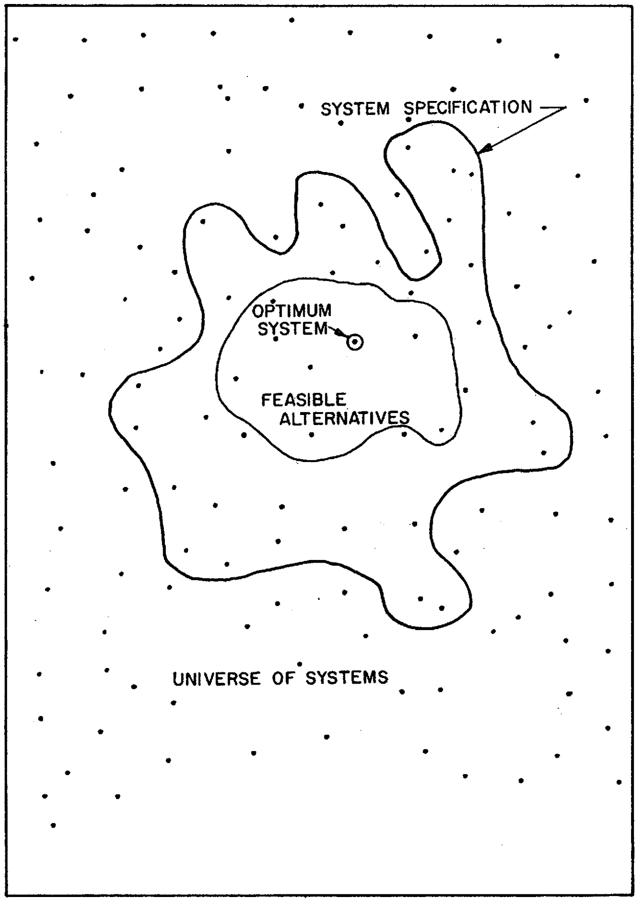

Figure II-2. Abstract systems design.

6. Describe the attributes of the optimum system.

Phase IV. Design the optimum system.

7. Describe the system architecture.
8. Define the functions of the system elements.

GENERALIZED SYSTEMS DESIGN

The generalized systems design techniques described in the remainder of Chapter II were originally conceived for and applied to the analysis of hardware systems, *e.g.*, a jet engine. In all cases this technology is not directly translatable from a hardware to a software milieu. However, sufficient technology is directly convertible to describe a generalized software design process.

Synthesis of the System Specification

In an abstract sense the synthesis of the systems specification consists of locating those systems that satisfy the system requirement and enclosing them within an envelope called the system specification. Thus, the universe of system has been partitioned such that the systems that lie within the system specification envelope satisfy the system requirement while those that lie outside do not. This, however, presumes that the system requirement can be explicitly defined.

[4]Gosling. *Design of Engineering Systems.* pp. 53-60.

In a real sense, the synthesis of the system specification is an iterative process that transforms an often vague system requirement into a statement of the physical properties of the system. For this discussion, assume that the system requirement is determined by a project sponsor. This requirement is then communicated to the system designer whose task it is to develop the system specification. Since the system requirement is at first often ill-defined, the first attempt at the system specification will be equally vague. This initial specification is then related to the sponsor who evaluates it in the light of his requirement. Modification of the requirement, if required, is made and it is submitted again to the system designer; *etc.* This iterative process continues until the sponsor is satisfied that the system properties described by the system specification are attainable. For example, if the system requirement is to put a human in orbit around the earth, then a system requiring antigravity would not be admissible. Since the success or failure of the system specification rests equally with the sponsor and the designer, it is in their best interest to establish a constructive dialogue during this phase of the design.

The System Requirement

The system requirement is a statement of the objective, purpose, mission, or function of the proposed system. For example, the system requirement for the NASA Apollo project could have been to "put a man on the Moon and get him safely back to Earth by 1970." An example in the field of highway engineering would be to "link all of the major population centers of the United States with controlled access highways by 1972."

The System Specification

The information that completely describes the set of admissible alternative systems which satisfy the system requirement is called the system specification. In real terms the system specification tells what the system must accomplish; where it must be located; and how it must perform. The performance (how) is described in terms of input/output and the environment (where) describes the location of the system. Thus, any system that fulfills the input-output, environmental, and performance specification is assumed to satisfy the system requirements.

The greatest difficulty in specifying the *system inputs* is separating the input elements from the elements which comprise the system environment. If environmental effects are included within the inputs, an overcomplex system may result. Conversely, if a true input is treated as an environmental effect, the system input will be incomplete. Thus, the usual strategy is to reduce the number of inputs to the smallest amount which still allows the system to function according to plan.

After the inputs to the system have been identified, then the problem of input standardization can be approached. Since all inputs are, in general, subject to some degree of variability, no input can be described in an exact manner. Therefore, the input specification must not only identify the form and magnitude of each input but must also give some notion of its expected range.

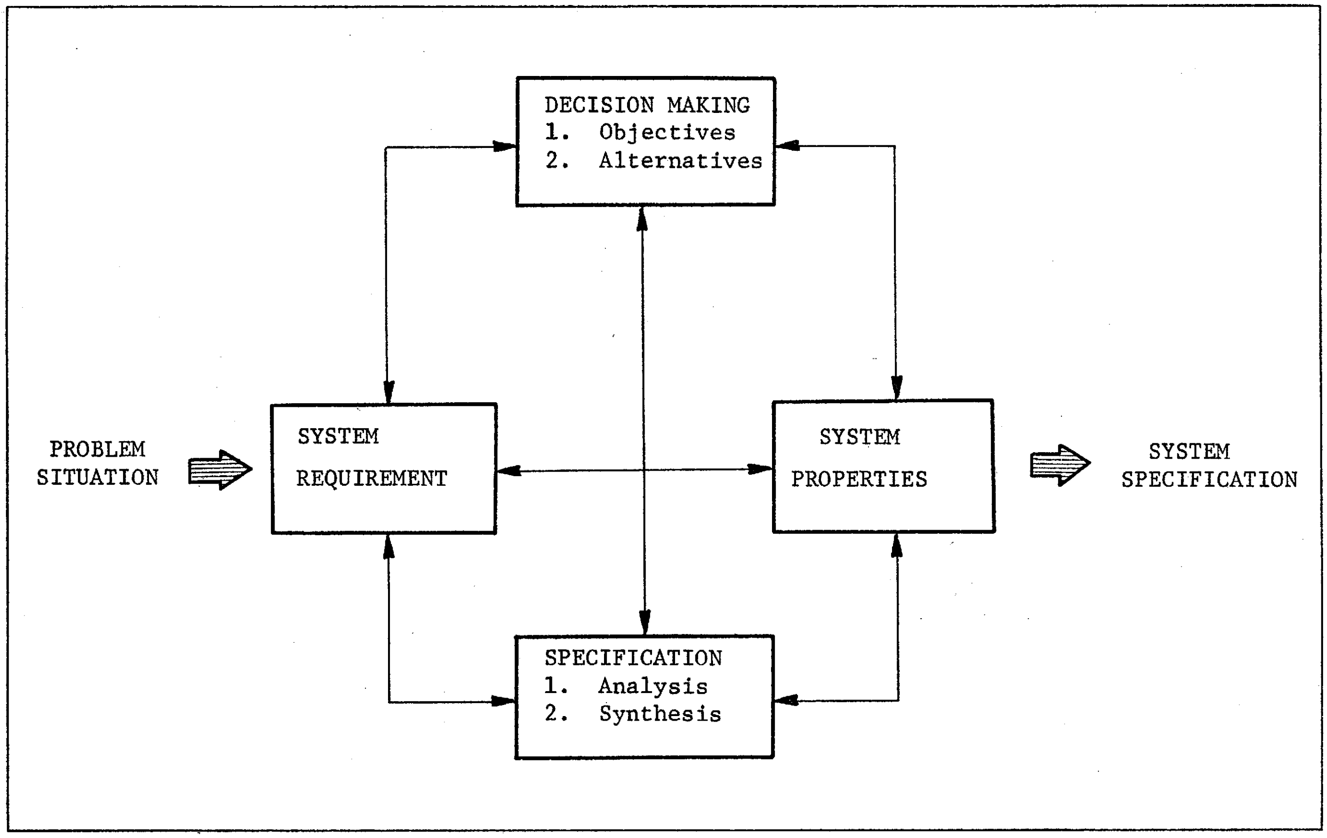

Figure II-3. Systems specification synthesis.

The *output specification* depends upon what the outputs of the system are to be used for. As was true in the system input specification the format, magnitude, and variability of the output must also be specified. *A priori* information about the variability of the outputs is particularly important if an error detection or feedback control system is to be employed to control the performance of the system.

The *system environment* embraces all of the relevant properties (excluding the system inputs) of the space which encloses the system. The environmental effects are difficult to establish at the onset of design because it is difficult to determine what properties of the system space will be significant until the system has been designed. Therefore, in general, it is possible only to establish a classification of environmental factors in advance of the actual design. Some of these relevant factors are: (1) the role of humans in the system, (2) the size of the system, (3) the weight of the system, (4) the location of the system, and (5) the physical properties of the space enclosing the system.

The *performance specification* describes the manner in which the success or failure of the operation of the system will be judged. In order for this to be possible, all of the desirable and undesirable traits of a system must be evaluated in terms of some numeraire. Only by comparison of common properties can alternative systems be objectively compared. This part of the system specification is sometimes difficult to define because measures of desirability are often impossible to quantify objectively.

Completion of the Systems Specification

Often the initial system specification is incomplete or inadequate because either the project sponsor or the system designer does not truly understand the system requirement. Often this requirement is not even established until some work is done on evaluating the alternatives. While it would be desirable to exactly define the system specification at the onset of the design process, this is seldom accomplished in practice.

Instead, the final specification is usually achieved through an iterative technique similar to the one previously described. The system design is begun with an incomplete specification based on easily available information. As the need for more accurate but more expensive information arises, then this information can be justifiably obtained. If later work proves that part of the specification is too restrictive or too permissive, then the realities of the design can be accommodated by a change in the specification. Care must be exercised in order to insure that earlier work is not compromised or that the original system requirement is not altered.

Isolation of the Feasible Alternatives

Once the system specification has been successfully established, the next objective of the system designer is to separate a set of feasible alternative systems from the set of all alternative systems that satisfy the system specification. The set of alternative systems embraced by the system specification is quite large; consequently, some systematic method of seeking out the complete set of feasible alternatives should be established. Such a systematic investigation of all alternatives is more likely to isolate a greater number of alternatives than an iterative approach. The iterative method tends to isolate fewer alternatives since: (a) the first alternative to be investigated receives the most attention at the expense of the others, and (b) the first alternatives are oriented to the disciplines which are familiar to the individual making the decisions.

Zwicky[5] says that the results of alternative selection are optimized if the number of alternatives investigated are maximized. He suggests the following four-stage procedure for insuring that a large number of alternative systems which fall within the system specification are investigated.

Define functional classes. A class of functional devices is defined for the purpose which these devices are supposed to satisfy. For example, the mathematical model which describes such terrain phenomena as hills, valleys, ridges, cliffs, *etc.*

Define class members. After each functional class of devices has been defined, all possible members of these classes are arranged in an orderly fashion in a so-called *Morphological Box* which, for our purposes, has been defined by the system specification. These members represent the possible variations of significant physical and mathematical parameters. The members of the functional class, mathematical model, could be a Fourier series, an exponential experimental series, a polynomial, *etc.*

Postulate the alternatives. If the functional classes are represented by the letters A, B, C, ... , then each class member can be represented by A_1, A_2, A_3 . . . , B_1, B_2, B_3, *etc.* The number of alternatives for evaluation so generated equals the by-product of the number of members within each class.

Any set of alternatives can be represented graphically with a diagram similar to the one in Figure II-4.

Isolate the feasible alternatives. Once the alternatives have been identified and organized in the Morphological Box then, and only then, is a technical evaluation allowed. First, the illogical alternatives, *i.e.*, those which by the definition are unattainable, are discarded; then the technically infeasible alternatives are eliminated; and finally only the feasible set of alternatives remain. The preceding can be accomplished by conducting the evaluation process from four different approaches: Are the system properties compatible with basic physical laws? Are the elements of the system compatible with each other and with the system environment? Are the properties of the system acceptable? How does the proposed system compare with the prior systems?[6]

Isolation of the Optimum System

Once the set of feasible alternatives have been determined, the isolation of the optimum feasible alternatives can begin. The first stage of this isolation process in-

[5]F. Zwicky, "Morphology and Nomenclature of Jet Engines," *Aeronautical Engineering Review,* (June 1946), p. 20.

[6]"The proof of the pudding is in the eating," so-to-speak; of the 23 recognized types of jet engines, Zwicky holds patents on 13 of them.

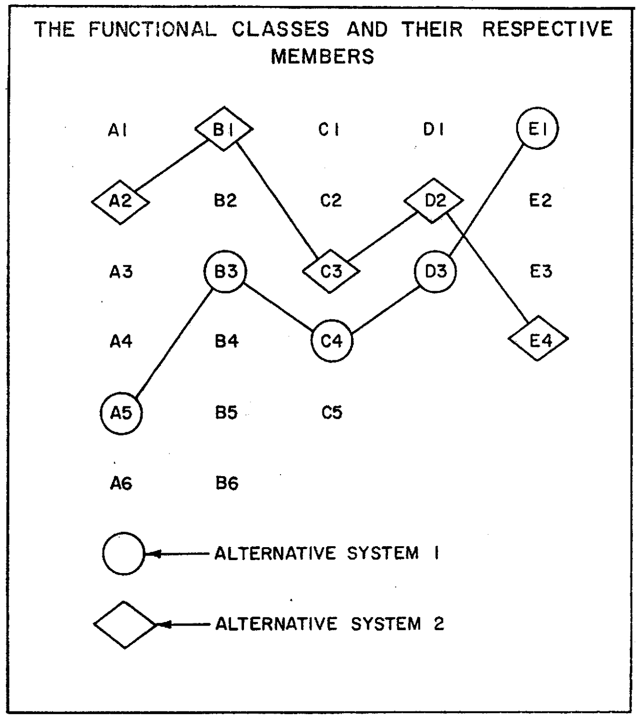

Figure II-4. Diagram of feasible alternatives.

volves selecting the performance criteria, collecting pertinent performance data, and determining the optimum alternative by some operations research technique, *e.g.*, linear programming. However, in this study only one parameter, relative accuracy, was to be optimized. Thus, there were no opportunities for trade-offs between the various performance characteristics. The usual optimization techniques were not pertinent. However, once the NGI System is designed and implemented, its operating characteristics can be examined and the classical optimization technique can be applied to achieve the optimum NGI System.

The second stage is the description of the attributes of the optimum system. This description includes not only a description of the functional properties of the system elements themselves, but also the nature of their interactions. Once the optimum system has been described, then the actual design of the optimum system can begin.

Design of the System

The design of the system is a two-stage procedure. The first stage is the design of the system architecture. This system architecture or structure is generally performed at the functional element stage; thus, leaving the details to programming personnel. The second stage is the comprehensive description of the function of each element represented in system architecture.

Classical systems design suggests that a design strategy should be employed in order to achieve an efficient design. Some elements of an effective design strategy are:

Cost-effectiveness. One of the currently popular (especially with the U. S. Department of Defense) concepts of the systems approach is cost effectiveness which: (a) maximizes effectiveness for a fixed cost, or (b) minimizes cost for a fixed level of effectiveness. If two or more competing numeric surface systems are capable of attaining a specified level of accuracy, then the system which operates at the minimum cost should be used because it yields the most favorable cost-effectiveness characteristics. This is an example of minimizing cost for a fixed level of effectiveness.

Sub-optimization. If the individual elements of the system have been optimized at the expense of total system optimization, a condition known as sub-optimization has been achieved. Every effort should be made in systems design to avoid sub-optimization by performing trade-offs between the various operating characteristics of the system. For instance, a greater number of significant digits is carried by the calculation process of the computer in double precision arithmetic than in single precision. However, double precision arithmetic has a slower throughput rate than does single precision. If the increased precision of the arithmetic obtained by using double precision is unwarranted because it is not required by the output specification, then sub-optimization exists within the system design.

Events of low probability. System design philosophy dictates that the fundamental concept of a specific system should not be compromised to accommodate events of low probability. For example, suppose a terrain approximation is designed so that it recognizes and deals effectively with discontinuities in the terrain surface and that a large percentage of the system throughput time is involved with this activity. If these discontinuities are in fact only of minor significance so far as the total terrain surface is concerned, then the overall system effectiveness has been compromised.

Feasibility Checking

During any stage in the design of a system there exists a probability that any alternative system can be successfully completed. An alternative is feasible if the probability that it can be completed can be shown to be above some specified level. Using this context, we see that many alternative systems are both conceivable and specifiable, but are not necessarily feasible. In other words, alternatives may be postulated but not attained.

Feasibility checking usually is performed in parallel with design and should not be neglected at any stage of the design. Checks during the later stages of the design may save the cost of continuing infeasible alternative prototypes, while early checks may save the entire design cost of an abortive alternative system. Advantage may be taken of these early assessments in order to terminate the development of unfavorable cases.[7]

[7]Gosling, *The Design of Engineering Systems*, p. 72.

CHAPTER III

Synthesis of the NGI System Specification

The NGI System sponsor, the Texas Highway Department (with the cooperation of the U. S. Bureau of Public Roads), initiated this study as part of the research and development for their proposed Interchange Design System. Although the NGI System will be developed for and as a part of the Interchange Design System, it could conceivably become a modular part of the BPR Total Integrated Engineering System. To insure compatability with both systems, a continuous sponsor-designer dialogue was maintained during all phases of the NGI System Study, especially during the development of the NGI System Requirements and NGI System Specification.

NGI System Requirements

At the inception of the study the Texas Highway Department suggested the following requirements for the synthesis of the NGI System:

1. All input and output to the NGI System must be digital (as opposed to analogue) in nature.

2. The NGI System must be able to process digital terrain data measured without regard to a predetermined pattern.

3. The accuracy of terrain representation must be consistent with that normally expected from present photogrammetric measuring techniques currently used by Division 19 of the Texas Highway Department. For example, for map compilation at a scale of $1'' = 40'$ elevation errors should be less than $\pm$ 0.2 feet.

4. The NGI System hardware should be compatible with the data processing hardware currently available to the Texas Highway Department. In mid 1967 an IBM System 360/50 with a 512 K byte core and twelve 2311 disk drives was installed and this general hardware configuration continued throughout the duration of the study.

5. The NGI System software should be independent of "local" system subprograms, *i.e.*, anything outside of the software normally furnished by the computer manufacturer should be contained within the NGI System software. This assumes that a FORTRAN IV, Level G or H equivalent compiler could be available.

6. The NGI System must be able to function as a modular element within the Interchange Design System and with BPR-TIES.

NGI System Specification

The following system specification is the result of the specification synthesis process. Fortunately, the initial specification remained intact during the evolution of the NGI System. Thus, extensive revision of the system in the later stages of analysis was prevented.

The Input Specification

The inputs to the NGI System are separated into three specific classes according to their functional relationship to the operation of the total system. The input specification explicitly requires that all inputs to the system must be digital in nature.

Terrain data. These data consist of the measured terrain data used by the NGI System to approximate the terrain surface. The general characteristics of these data are:

1. Each terrain point is represented by an ordered set (X,Y,Z) of rectangular Cartesian coordinates in 3-dimensional space.

2. Each coordinate (X,Y,Z) must be equal to or greater than 0.00 (this specifically excludes all negative coordinates) but less than 10,000,000.00.

3. The total number of data points must be greater than three but less than 10,000.

4. The unit of measure is assumed to be feet, but the system is independent of units of measure.

Control parameters. These parameters are used to specify internal data manipulation and computation options. The general characteristics of these data are:

1. The expected range and orientation of the terrain data must be represented in the same coordinate system and in the same units as the terrain data.

2. The internal and external data storage parameters must be established before data processing begins.

3. The error recognition parameters must be established before data processing begins.

Interpolation data. These data identify for the NGI System the information necessary to calculate an elevation (Z) at a required horizontal position (X,Y). The general characteristics of these data are:

1. The horizontal position (X,Y) for which an interpolated elevation is required must be represented in the same coordinate system and units as the terrain input data.

2. The desired horizontal position must lie within the range of the input data, *i.e.*, extrapolation is not allowed.

The Output Specification

The outputs from the NGI System are divided into two functional classes. Their general characteristics are:

Interpolated elevation. The calculated elevation (Z) corresponding to the required horizontal position (X,Y) has the following general characteristics:

1. The elevation must be in the same units and coordinate system as the input terrain data.

2. The elevation must lay within the range of the input data.

Control parameters. These parameters contain information concerning errors, if any, detected during the interpolation processes.

The Environment Specification

The environmental specification describes the relevant properties of the space in which the system is enclosed. Since the NGI System is a computer software system, the only relevant properties of the space enclosing the system are the physical properties and operating characteristics of the data processing equipment on which the NGI System will reside.

Hardware properties. In order to assure that the NGI System will be as machine independent as possible, only the general hardware properties need be specified. The NGI System requires the following equipment:

1. A central processing unit at least the equivalent of an IBM 360/50;

2. A core storage of 256,000 bytes or equivalent in 32 bit words;

3. At least one direct access (disk, drum) input/output device;

4. An on-line card reader or equivalent; *e.g.*, HASP;

5. An on-line card punch or equivalent;

6. An on-line printer or equivalent.

Software properties. The software properties need to be more specific than do the hardware properties. Although the NGI System is aimed specifically at the IBM 360/50, the characteristics of FORTRAN can change from computer to computer. Since the NGI System is assumed to be coded in FORTRAN IV the proposed software standards for TIES are considered as useful guidelines for inter-machine FORTRAN compatibility. More significant still is the variance in "local" system subprograms available from installation to installation. Therefore, these additional properties of the NGI software are proposed:

1. All software is to be coded in USASI X3.9-1966 FORTRAN IV.

2. Only the standard function subroutines furnished by the computer manufacturer are assumed to be available in the system library.

3. All software outside of (1) and (2) above is assumed to be built into the system itself.

The Performance Specification

Since there is little prior experience with this type of terrain approximation system, performance standards are difficult, if not impossible to establish. In the final analysis the worth of the NGI System will have to be established within an engineering design environment in competition *vis-a-vis* with cross-sections. This analysis is outside the scope of this study. Nevertheless, some common yardsticks are needed to judge the relative merit of the feasible alternative systems. Three parameters were selected for this purpose.

Accuracy. For purposes of evaluating the accuracy of the terrain approximation achieved by the NGI System, the term accuracy assumes a rather special meaning. In this study accuracy is defined in terms of sensitivity and range, where sensitivity is the percentage of total number of errors that fall within a specified range; and the range is defined as a percentage of the total relief. For example, if 75% of the elevation errors fall between -5.0 and $+5.0$ for a terrain sample which has a total relief of 20.0 feet, the accuracy of the approximation has a sensitivity of 75% within a range of 25% (or, 75% within 25%). Thus, for sensitivity measured within the same range the higher the sensitivity, the greater the accuracy.

Relating this definition to a practical situation, suppose that terrain data can be obtained using stereo plotting equipment to a tolerance of $\pm$ 0.50 feet, 95% of the time, over an area exhibiting a total relief of 20 feet. This measuring system would have a sensitivity of 95% within a range of 2.5% (or 95% within 2.5%). Likewise, if the NGI System approximates the terrain with a tolerance of $\pm$ 0.50 feet, 95% of the time, over an area where total relief is 20 feet, then it has an accuracy of 95% within 2.5%.

Data density. Data density is defined as the average number of data points per 1000 square feet. For example, a 125-point sample drawn from an area of 100,000 square feet has a data density of 1.25 points per 1,000 sq. ft. Since the NGI System approximates a three dimensional (X,Y,Z) surface area and not a two dimensional line (Y,Z, or X.Z) some increase in the data density over that required by cross-sections can be expected.

Throughput rate. Throughput rate is defined as the number of elevations per minute that the NGI System is able to compute. For example, if the NGI System is able to throughput 6250 elevation calculations in 10 minutes, it has a throughput rate of 625 points per minute. Since the NGI System considers the elevation as a function of two variables (X and Y), and the cross-sections method considers the elevation as a function of a single variable (X or Y), some increase in the throughput rate can be expected.

CHAPTER IV

Isolation of the Feasible Alternatives

The NGI System Specification, which was synthesized in Chapter II, describes the enclosure which circumscribes the NGI System (see Figure II-2). That is, within this envelope lies the set of systems that must satisfy the NGI System Specification. The first problem is to identify this set of alternatives. The next problem is to isolate the feasible alternatives from the ensemble of enclosed alternatives. Morphological Analysis (described in Chapter II) is used to identify the possible alternatives and to isolate the set of feasible alternatives for later evaluation.

IDENTIFICATION OF THE POSSIBLE ALTERNATIVES

The procedure for identifying the set of possible alternative systems is a two-step process. The first step is to establish the functional classes and the various members of these classes which are associated with these systems. In an abstract sense these classes define the dimensions of the morphological enclosure circumscribing the set of possible alternatives. In a real sense they describe the functional properties of these alternative systems. The second step is to identify all of the possible alternatives to facilitate their later evaluation.

Establish the Functional Classes and Class Members

The important rule that must be observed when establishing the classes and class members is that each combination of class members must be unique. That is, no two combinations of class members may describe the same alternative. Another important idea is that in order to maximize the coverage of the alternatives circumscribed by system specification each class should include all possible class members. The following functional classes and their class members conform to these two rules.

Coordinate System for Representing the Terrain Data Points

The NGI System Specification dictates that the terrain data points must be represented in a 3-dimensional (X,Y,Z) rectangular coordinate system. The following three members are some of the possible coordinate systems that are included within this class.

State Plane. The terrain data points could be represented by State Plane Coordinates (or some related surface coordinate system). Most of the photogrammetric mapping data which exist at the Texas Highway Department are in this system. By using a X-Y-Z coordinate scaler and stereo plotting techniques this type of terrain data could be easily obtained. Any existing cross-section data could be easily converted to State Plane Coordinates since the associated horizontal alignment is represented in this system.

Axis-of-flight. The terrain data points could be represented by X-Y-Z rectangular coordinates oriented in an axis-of-flight coordinate system. This coordinate system is compatible with present mapping procedures and the equipment necessary to measure terrain data in this system is currently available at the Texas Highway Department.

Local. The terrain data points could be represented by a local X-Y-Z coordinate system with an arbitrary origin and orientation. It would be possible to reference this system to other systems such as the State Plane Coordinate System by determining the translation and rotation parameters which relate the two systems.

Data Grouping Scheme for Data Processing Purposes

Regardless of the coordinate system used for representing the terrain data points, some scheme must be devised for the organization of these data both in core and on any direct access input/output devices used by the system. The idea here is to store all pertinent data in a direct access device and "roll-in" groups of data as required for processing. The three members of this functional class are:

Project. The data could be grouped by project or some similar designation. Using this scheme, the data for an entire project could be brought into core and dealt with as a complete set or ensemble of data.

Sector. The data could be grouped by sectors. A sector could be any logical subdivision of the ensemble of project data. Although it is conceivable that this sector could be defined by an irregular boundary, the NGI System is mathematically limited to rectangular sectors.

Cluster. The data could be grouped by cluster. The shape, size, extent, *etc.*, of this cluster must be determined by some previously defined rule. The rule established for the NGI System defines a cluster as the group of neighboring points closest to a particular horizontal position. The size of the cluster depends on the nature of the numeric surface used.

Type of Numeric Surface Used to Approximate the Terrain

No mathematical surface has been found that exactly represents the shape of the terrain in all cases; therefore, the terrain surface can only be approximated by a numeric surface. The several types of numeric surface approximations suggested below are by no means exhaustive, but they constitute a consensus of possibilities.

Triangles. The terrain surface could be approximated by a numeric surface of triangular planes with the data points at the vertices of the triangles. The elevation of a specified horizontal position would be calculated from the triangle embracing the point.

Polynomial. A polynomial surface[1] could be used to approximate the terrain surface. The order of the polynomial surface could be variable, *i.e.*, 1, 2, 3, ... *etc.*, for linear, parabolic, cubic, *etc.*, surface approximations of the terrain. The elevation of a specified point would be computed from the surface embracing the point.

Fourier series. A Fourier series surface[2] could be used to approximate the terrain surface. If the number of harmonics could be varied to conform to the shape of the terrain, the elevation of a specified point would be computed from the surface embracing the point.

Spline surface. A spline surface[3] could be used to approximate the terrain surface. The elevation of the desired point would be computed from the surface embracing the point.

Type of surface fitting technique

Four different types of surface fitting techniques were considered as members of spline surface class.

Exact. An exact fit implies that the surface fit to the data will pass through all of the terrain data points. This requirement can be met regardless of the type or the number of data points. This does not imply that the resulting surface "exactly" fits the terrain—only the terrain data points.

Least squares. The least squares surface fitting technique assures that the sum of the squares of the deviations between the fitted surface and the data points to which the surface was fit is a minimum. Again this does not imply that the resulting surface represents the actual terrain, but implies only that the surface is the "best" mathematical fit to the data points.

Weighted least squares. The weighted least squares technique is essentially the same as the least squares technique, except if, for example, a closer fit to the data is desired near the center of the data, the surface can be weighted to fit closer to the data points in this area. If the weights are properly applied, the resulting surface can be made to fit some of the data points with smaller deviations than with the other points.

Minimax. A minimax fit implies that a surface is fit to data points in such a way that the maximum deviation between the surface and the data points is held to a minimum.[4]

The Extent of the Surface Fit

No matter what type of surface is used it must be fit either to the ensemble of data currently in core or to some specific segment of these data.

En Bloc surface fit. This technique is used to fit a surface to the ensemble of data points currently within the core. This implies that there is only one surface for each ensemble of points.

Roving surface fit. This technique is used to fit a surface to only those points in the immediate area of interest, and ignores the remainder of the data ensemble. As the area of interest roves around within the data ensemble, the surface and the associated cluster of points roves with it. This implies that a unique surface exists for every such cluster of points.

Mode of Surface Data Storage

The terrain surface data could conceivably be stored in core in three modes.

Original terrain data. The terrain data could be stored in their original coordinate form.

Surface coefficients. The terrain surface could be stored as pre-fitted surfaces. Instead of fitting a surface to the terrain data whenever an elevation is required, the surface would already exist in storage for immediate use.

Both. A system could be designed making use of both original terrain data and surface coefficients. A possible use of this technique could use surface coefficients to solve for a first approximation, then use the terrain data to refine the surface solution.

Identify the Possible Alternatives

For purposes of formal identification the alternatives can be represented in matrix notation. Let A, B, C, D, E, and F represent the functional classes of the NGI System. Then let 1, 2, 3, and 4 represent the members within each class. Any individual class member can be represented by combining the class and member notation, *e.g.*, A1 is the first member of class A. Each possible alternative may then be uniquely identified by A1, B1, C1, D1, E1, F1; A2, B1, C1, D1, E1, F1; *etc.* When all possible combinations of the individual class members are formed 864 alternatives may be identified from the NGI System Alternative Diagram shown in Figure IV-1.

ISOLATION OF THE FEASIBLE ALTERNATIVES

The feasible alternatives are isolated using the general procedure described in Chapter II. First, remove any "absurd" combinations, then remove the infeasible combinations. Only the feasible combinations will remain. One of the values of this procedure is that, as the state of the art advances, alternatives which are infeasible at this point in time may become feasible at a later date. These alternatives may then be further investigated for feasibility.

Admittedly this procedure is subjective, *i.e.*, someone else could conceivably isolate a different set of alternatives. Nevertheless, it does assure that a large number of possible alternatives are investigated for feasibility.

Identify the Illogical Combinations

A cursory examination of the alternative diagram for the NGI System (Figure IV-1) reveals several illogi-

[1]W. C. Krumbein, *A Comparison of Polynomial and Fourier Models in Map Analysis,* (Evanston, Illinois: Northwestern University, 1966).

[2]William R. James, *FORTRAN IV Program Using Double Fourier Series for Surface Fitting of Irregularly Spaced* Data; *(Computer Contribution 5),* ed. by Daniel F. Merriam (Lawrence, Kansas: State Geological Survey; The University of Kansas, 1966).

[3]D. C. Handscomb, ed., *Methods of Numerical Approximation, (Oxford: Permagon Press,* 1966); pp. 177-180.

[4]Handscomb, *Methods of Numerical Approximation,* pp. 73-75.

Classes \ Class Members		1	2	3	4
Coordinate System for Terrain Data Points	A	State Plane	Axis-of-flight	Local	
Grouping System for Terrain Data Points	B	Project	Sector	Cluster	
Type of Numeric Surface	C	Triangles	Polynomial	Fourier Series	Spline
Type of Surface Fitting Technique	D	Exact	Least Squares	Weighted Least Squares	Minimax
Extent of Surface Fit	E	En Bloc	Roving		
Mode of Surface Data Storage	F	Orignial Data Points	Surface Coefficients	Both	

Figure IV-1. Alternative Diagram for the NGI System.

cal combinations (see Chapter II). These illogical combinations are:

Roving surface fit combined with surface coefficients. The roving surface fit technique is based upon the notion that there is a unique surface for each possible cluster of points. Considering the enormous number of surfaces that would be generated, it would be futile to store them all within the computer core. Therefore, any alternative which combines any storage mode except terrain data points with the roving surface fit is illogical. Referring to the matrix notation, alternatives containing E2 must also contain F1.

En Bloc surface fit combined with data point storage mode. Since the en bloc surface technique fits a surface to the entire set of data points currently in core, the data points become superfluous information once the surface coefficients have been determined. Therefore, it is pointless to retain the original terrain data, and any alternative combining an en bloc surface fit with the terrain data storage mode is removed from further consideration. In matrix notation, alternatives containing E1 must also contain F2, except as noted below.

In the cases where the triangle surface (C1) is used, the data points as well as the surface coefficients must be retained for computational purposes. Therefore, alternatives containing C1 and E1 must contain F3.

Triangle surface combined with type of fit. The triangle surfaces are formed by data points at each of the three vertices. Since three points define a triangular plane, anything but an exact fit is impossible. Therefore exclude any alternative containing the triangle surface that does not exhibit an exact fit to the data. In matrix notation alternatives containing C1 must also contain D1.

Identify the Infeasible Combinations

The infeasible combinations within the alternative diagram for the NGI System are located by examining each of the members of a particular functional class and making a quasi-rational judgment as to its compatibility in combination with members of other classes.

Terrain data point grouping. A cursory examination of surface fitting techniques indicates that, while it is possible mathematically, it would be difficult in practice to develop a numerical surface technique to deal with an unbounded set of data points. In fact, the least squares fitting of a Fourier Series surface requires that the data points be enclosed within a rectangular boundary. A boundary is required by the other surface techniques as a check to guard against attempts at extrapolation. Therefore, a rectangular boundary around the set of data points becomes a requirement.

From a data processing point of view the number of data points available for immediate use within the core is limited by the core storage capacity. Since it is unlikely that all of the terrain data for a single project could "fit" into core at once, these data must be segmented. Since the rate at which data are transferred from disk or drum storage into core is relatively slow, this activity should be minimized. Therefore, the segments of data residing in core should be as large as possible so as to reduce the need of bringing in new segments. Since the sector grouping scheme deals with larger groups of data than the cluster scheme, but still offers the possibility of reducing the ensemble of data to a usable size, the sector scheme is selected as the most feasible.

Thus, any grouping of data points for bringing data into core except for rectangular sectors is dismissed from further consideration. Referring to the matrix notation, only combinations including B2 are permissible.

Data point coordinate system. Once it was established that the terrain data should be enclosed within a rectangular sector, it seemed logical that this sector should be "aligned" as closely to the data as possible. This could be accomplished either with an axis-of-flight coordinate system or with a local coordinate system. For the sake of generality the axis-of-flight system seemed less desirable than a local system. Therefore, only the local coordinate system is permissible. In matrix notation, only alternatives containing A3 are allowable.

Spline surface. Since grid points are required to join spline surfaces together, this type of surface appears to be inconsistent with the requirement of quasi-random terrain data points. The cited literature does not indicate an easy application of this technique to this situation. Thus, because of the apparent analysis and programming effort involved, any alternative including this class-member is eliminated from the set of feasible alternatives. In matrix notation, all alternatives containing C4 are omitted from further consideration.

Minimax surface fitting. This curve fitting technique does not have a direct solution and must therefore be achieved either by linear programming or by an iterative procedure.[6] Although such a solution to a minimax surface fit is possible, the computer effort necessary to arrive at a solution would prohibit its feasibility. Therefore, any combination of alternatives containing a minimax surface fit was eliminated. In matrix notation, remove all alternatives containing D4 from further consideration.

Roving surface fit combined with surface type. The only type of surface used with the roving surface fit is the polynomial surface, since: (a) the Fourier surface has point distribution criteria that is not directly available to the roving surface fit technique,[7] *i.e.*, minimum distance between data points, and (b) the possibility exists for nonunique solutions with the triangle surface. Thus, alternatives containing E2 must also contain C2.

Describe the Feasible Alternatives

Now that the absurd and infeasible alternatives have been separated from the set of possible alternatives, only the feasible alternatives remain. These feasible alternatives are shown schematically in Figure IV-2 and are verbally described below. In both cases they are hereafter identified by type number.

Type I: Local coordinate system, rectangular sector, triangle surface, exact fit, en bloc model, data point storage, *i.e.*, A3, B2, C1, D1, E1, F3.

Type II: Local coordinate system, rectangular sector, polynomial surface, least squares fit, en bloc model, coefficient storage, *i.e.*, A3, B2, C2, D2, E1, F2.

Type III: Local coordinate system, rectangular sector, Fourier Series surface, least squares fit, en bloc model, coefficient storage, *i.e.*, A3, B2, C3, D2, E1, F2.

Type IV: Local coordinate system, rectangular sector, polynomial surface, least squares fit, roving model, point storage, *i.e.*, A3, B2, C2, D2, E2, F1.

Type V: Local coordinate system, rectangular sector, polynomial surface, weighted least squares fit, roving model, point storage, *i.e.*, A3, B2, C2, D3, E2, F1.

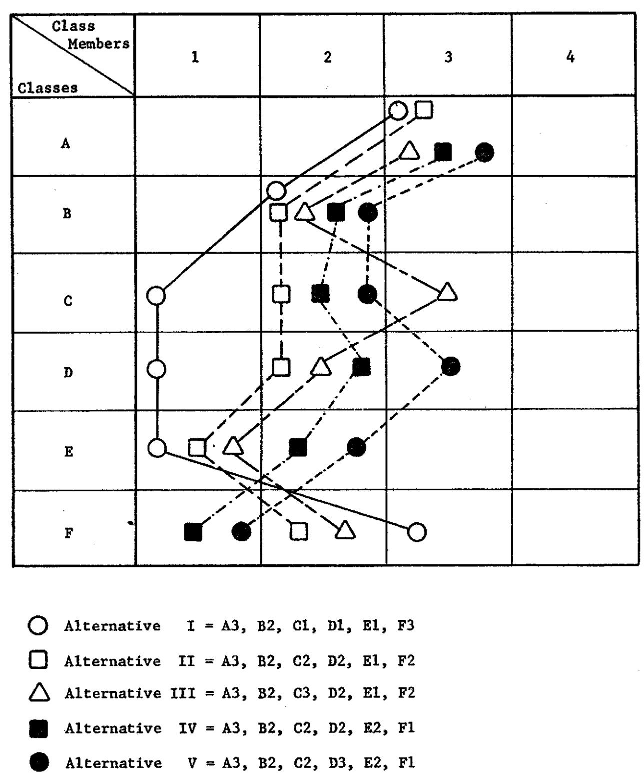

Figure IV-2. Feasible alternatives for the NGI System.

[5] D. C. Handscomb, ed., *Methods of Numerical Approximation*, pp. 217-220.
[6] Ibid., pp. 73-75.
[7] James, *FORTRAN IV Program*, p. 4.

CHAPTER V

Isolation of the Optimum System

A two-phase process is used to isolate the optimum system from the set of feasible alternatives. The first phase is to remove competing alternatives from the set of feasible alternatives by a step-wise elimination process until one system remains. The second phase is to completely describe the attributes of the last remaining alternative. This alternative then becomes the optimum system for design purposes.

ELIMINATION OF THE COMPETING ALTERNATIVES

The step-wise process for eliminating competing alternatives from the set of feasible alternatives proceeds in the following manner. Starting with the five feasible alternatives described in Chapter IV, an experiment is performed with the intent of eliminating one or more of the alternatives from further consideration at each successive step. The successful completion of an experiment requires that the following activities be accomplished: (a) establish an objective, (b) determine evaluation criteria, (c) collect the evaluation data, and (d) reach a conclusion based upon these experimental results. Thus, the choice of alternatives is narrowed at each successive step by the removing from further competition any alternative indicated by the experimental results. Then another experiment is performed, using the remaining alternatives, to further narrow the choice of alternatives. This process continues until there is only a single remaining alternative.

Data Collection Procedure

The experimental data are obtained by using a series of computer software packages specifically designed for this purpose. Accuracy test data and throughput rate are collected by making test runs with these packages on the computer. The pertinent test parameters for a test run in addition to accuracy, data density, and throughput rate, which are defined in Chapter III, are described as follows:

Terrain samples. Terrain samples used in the evaluation experiments are obtained by two methods. First, fictitious terrain data are calculated from mathematical surfaces. Secondly, actual terrain data are measured by photogrammetric methods. The relief pattern for the Airy-2LT sample conforms to the left side of the Airy[1] function surface in Figure V-1, and the Airy-2RT sample from the right side of the same Airy surface. The Dallas Grid sample conforms to the relief pattern of an actual terrain situation. Regardless of the terrain, each sample represents the terrain over a rectangular area 500 feet long and 250 feet wide. All samples drawn from the fictitious terrain are made up of data points which are randomly distributed in a horizontal position regardless of the relief pattern. The actual terrain samples are selected from the Dallas Grid terrain master sample which is a 2601 data point sample measured in a 10- by 50-foot grid superposed over an actual terrain area.

[1]A. O. Smirnov (Trans. by D. G. Fry), *Tables of Airy Functions and Special Confluent Hypergeometric Functions*, New York: Pergamon Press, 1960), p. 15.

Accuracy test. The accuracy test which was performed during each test run consisted of: (1) selecting 5 samples of 30 different points within the terrain test area, (2) comparing the actual elevation at each point with the elevation obtained by the NGI System and computing the error, (3) determining the sensitivity of the errors for each of the 5 samples for ranges of 0.5%, 1.0%, 2.5% and 5%, and (4) computing the mean sensitivity for the 5 samples for ranges of 0.5%, 1.0%, 2.5% and 5%.

Throughput rate data. The time required to fit a Type I, II, or III system to the ensemble of data (calibration time), and the total time required to collect the 150 test elevations used in the accuracy test (interpolation time) can both be determined from the computer's internal clock. These data were measured during all test runs for use in later throughput rate calibration.

Experiment 1

The objective of Experiment 1 was to determine what effect roundoff error in the computer has on the elevations computed by the 5 alternative systems isolated in Chapter IV. For purposes of this experiment errors created by the order of internal formula evaluation, truncation, loss of significant digits in floating point arithmetic, *etc.*, were considered as a single effect.[2]

[2]R. W. Hamming, *Numerical Methods for Scientists and Engineers*, (New York: McGraw-Hill Book Company, Inc., 1967), pp. 24-29.

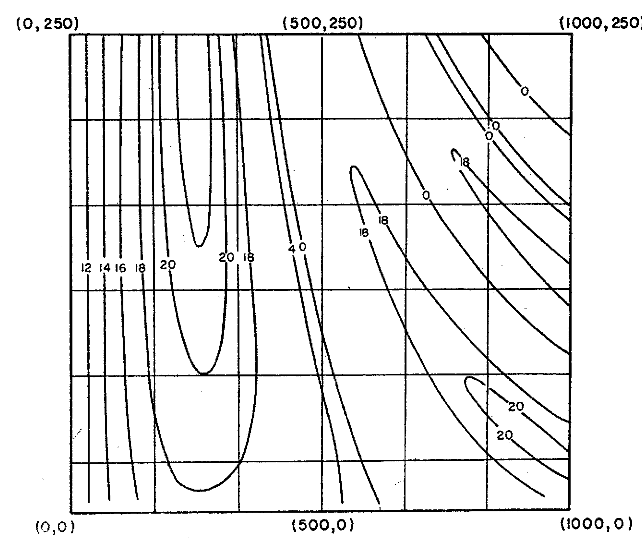

Figure V-1. Airy-2 terrain surface.

Since the objective was only to recognize the existence or nonexistence of significant round-off noise, no diagnosis was attempted.

Errors in accuracy data due to round-off noise that are greater than 0.01 feet are considered significant. The selection of 0.01 feet was an arbitrary choice. However, since the elevations which are output from the system were reported to the nearest 0.01, any error larger than 0.01 feet was detectable in the system output. This situation is undesirable so far as the operational use of the NGI System is concerned.

Test runs for all five system types were made using terrain samples with data densities of 1 and 5 points per 1000 square feet. The associated accuracy tests made use of data that each type of system should be able to fit exactly. For example, the Type I system was tested against data generated from a plane surface. Type II, IV, and V systems, using first to fifth order polynomial options, were tested using polynomial surface data. The Type III system using from 1 to 6 harmonic surfaces was tested against data generated from sine and cosine functions.

There exists a distinct possibility that significant round-off noise will occur whenever Type II, IV, and V systems are used with polynomials greater than third order; otherwise significant noise is not present in any of the systems. The round-off noise in the Type II system is so severe that the computed elevations were rendered meaningless for polynomials of orders greater than four and were even of questionable reliability at fourth order.

Experiment 2

The objective of Experiment 2 was to determine the optimum number of cluster points to use with the Type IV and Type V systems. The size of cluster that yields the greatest accuracy is considered the optimum cluster. If a tie in terms of accuracy exists, then it is necessary to break the tie in favor of the option with the highest throughput rate.

Test runs using 1.0, 1.5, and 2.0 times the minimum cluster size were made using terrain samples drawn from Airy-2LT (Density = 5), Airy-2RT (Density = 5), and Dallas Grid (Density = 1.36). The Type IV system was tested for the linear, parabolic and cubic surface options.

The resulting accuracy test data is displayed in Figure V-2. For the three cluster sizes tested, about 1.5 times the minimum appears to be the optimum cluster size. This conclusion can be reached by inspection of the sensitivity versus cluster size curves in Figure V-2. That is, the peak of the majority of the curves for ranges of 0.5% and 5.0% occurs at 1.5 times the minimum cluster size. Also, the percentage of errors in excess of 25% is at a minimum at this cluster size. Thus, the cluster size used with the Type IV and Type V Systems was 4 points with the linear surface option, 9 with the parabolic, and 15 with the cubic.

Experiment 3

The objective of this experiment was to determine whether the Type IV or the Type V system, *i.e.*, whether

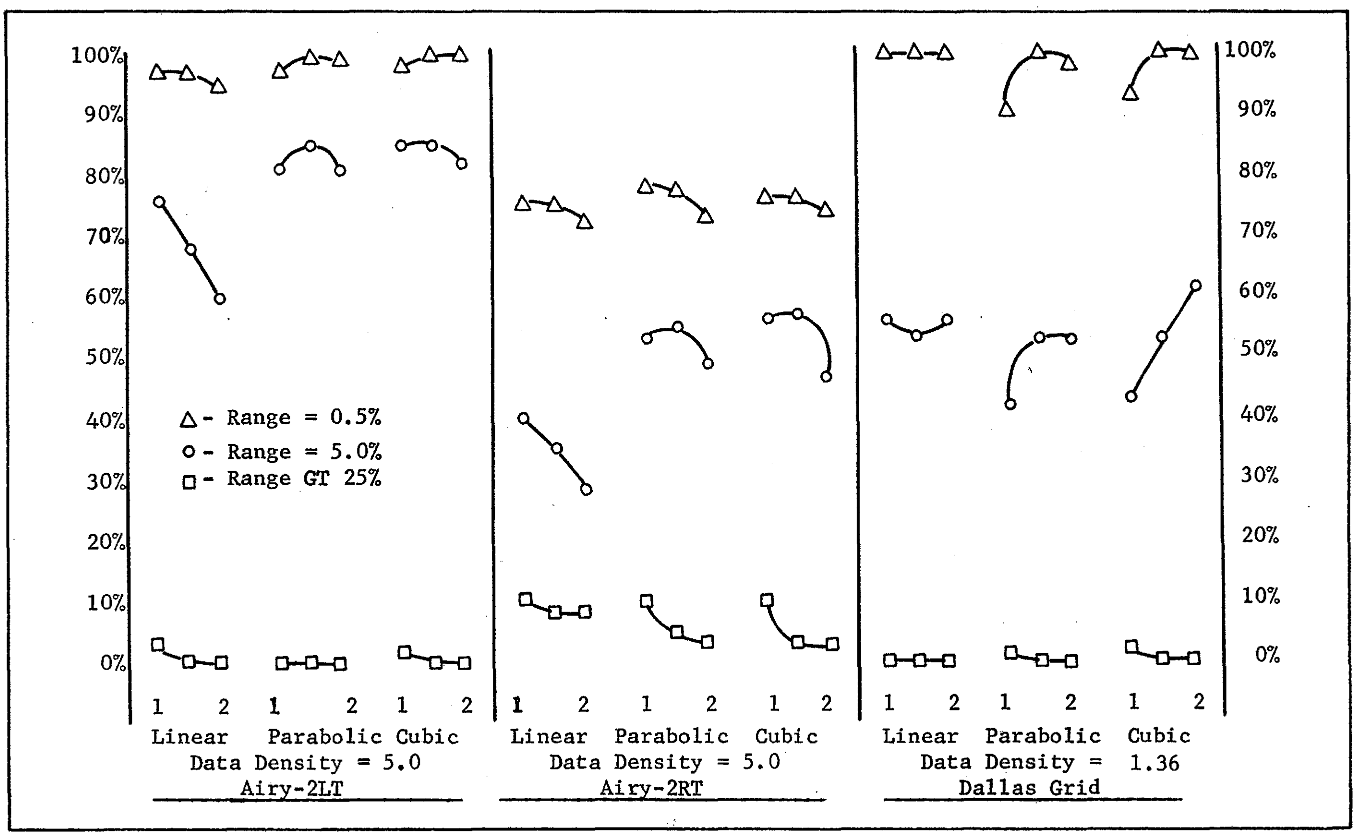

Figure V-2. Accuracy vs. cluster size.

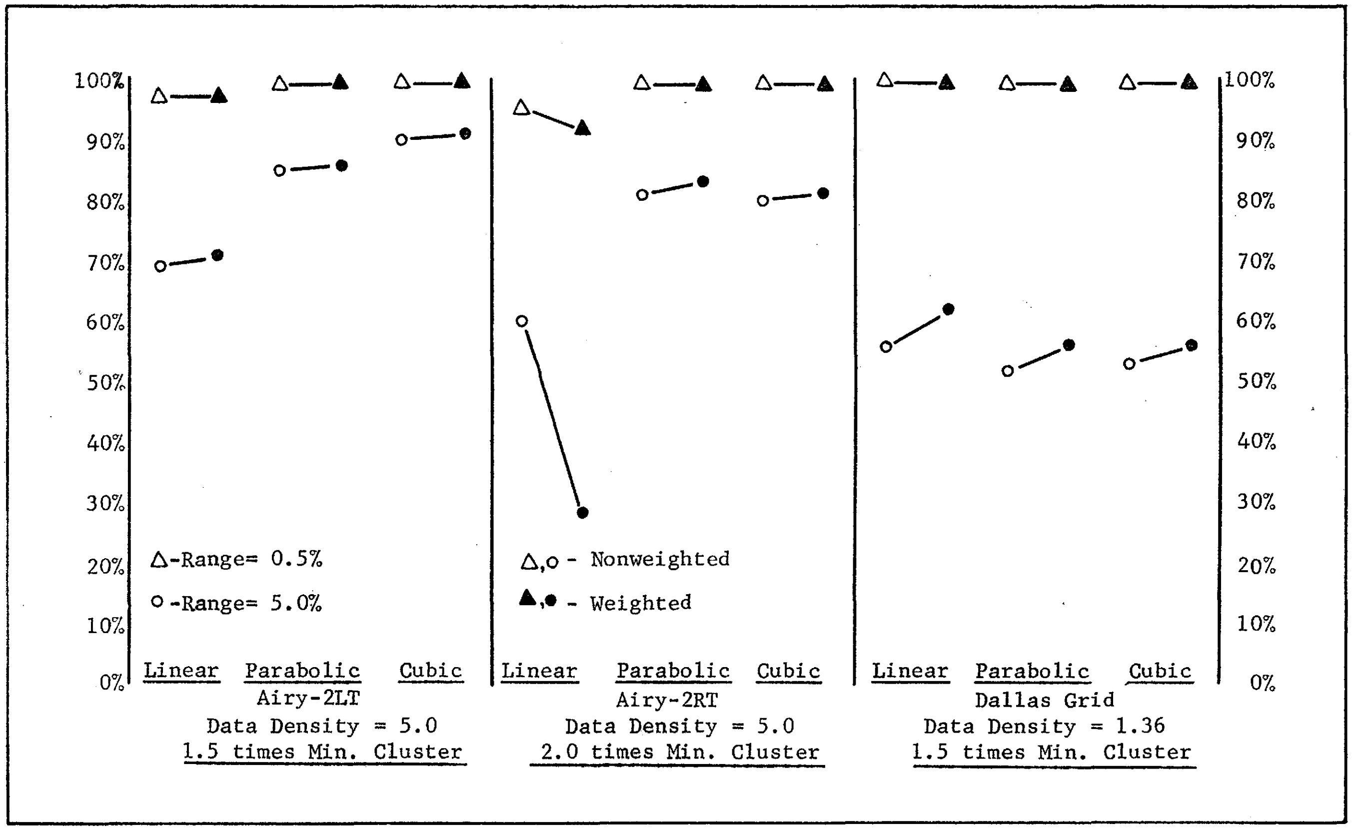

Figure V-3. Weighted vs. nonweighted least squares.

least squares or weighted least squares, yields the highest accuracy. The system which yields the highest accuracy should be retained in the set of competing alternatives. If a tie exists between the two, it is necessary to break the tie in favor of the system having the highest throughput rate.

Test runs were made with both Type IV and Type V systems using 1.5 and 2.0 times the minimum clusters. The terrain samples were drawn from Airy-2LT (Density = 5) and Dallas Grid (Density = 1.36) relief patterns. These two systems were tested with the parabolic and cubic surface options. The resulting accuracy test data are displayed in Figure V-3. From the inspection of the paired data points, there appears to have been no significant difference between the two types of systems in terms of accuracy. However, the Type IV system had a throughput rate approximately 2% greater than the Type V system. Therefore, the Type IV system dominated the Type V system and the Type V system was eliminated from the set of competing systems.

Experiment 4

The object of this experiment was to determine which of the remaining systems, *i.e.*, Type I, II, III, or IV is the most accurate. In addition the parabolic and cubic surface options for the Type IV system were to be compared. The system which exhibited the greatest accuracy for various data densities was considered as the optimum system. Any ties between equally accurate systems were broken in favor of the system having the greatest throughput rate.

Test runs using Type I, II, III, and IV (both cubic and parabolic options) were processed using Airy-2LT, Airy-2RT and Dallas Grid terrain data samples with density varying between 1.0 and 10.0. During the test both accuracy and throughput data were collected for evaluation purposes.

The accuracy test results are shown in Figure V-4. The data points are plotted both by terrain sample and by system type such that they become points along accuracy-versus-data density curves. The throughput rate results are displayed in Figure V-5 for each of the Type IV options as points along throughput rate versus sector-size curves.

On the basis of accuracy, the Type IV system is to be the optimum alternative by inspection of Figure V-4. Since the cubic and parabolic options for the Type IV system have similar accuracy characteristics, the throughput rate criteria shown in Figure V-5 must be used to break the tie. On the basis of throughput rate, the cubic option is eliminated from the feasible set. Therefore, the Type IV system using a parabolic surface becomes the optimum system by virtue of being the last remaining alternative.

DESCRIPTION OF THE OPTIMUM SYSTEM

The attributes of the optimum system are described if the properties of the system can be described and the operating characteristics can be determined. The physical properties of a software system are not pertinent to this design process so the discussion is limited to the functional properties of the system. The discussion of

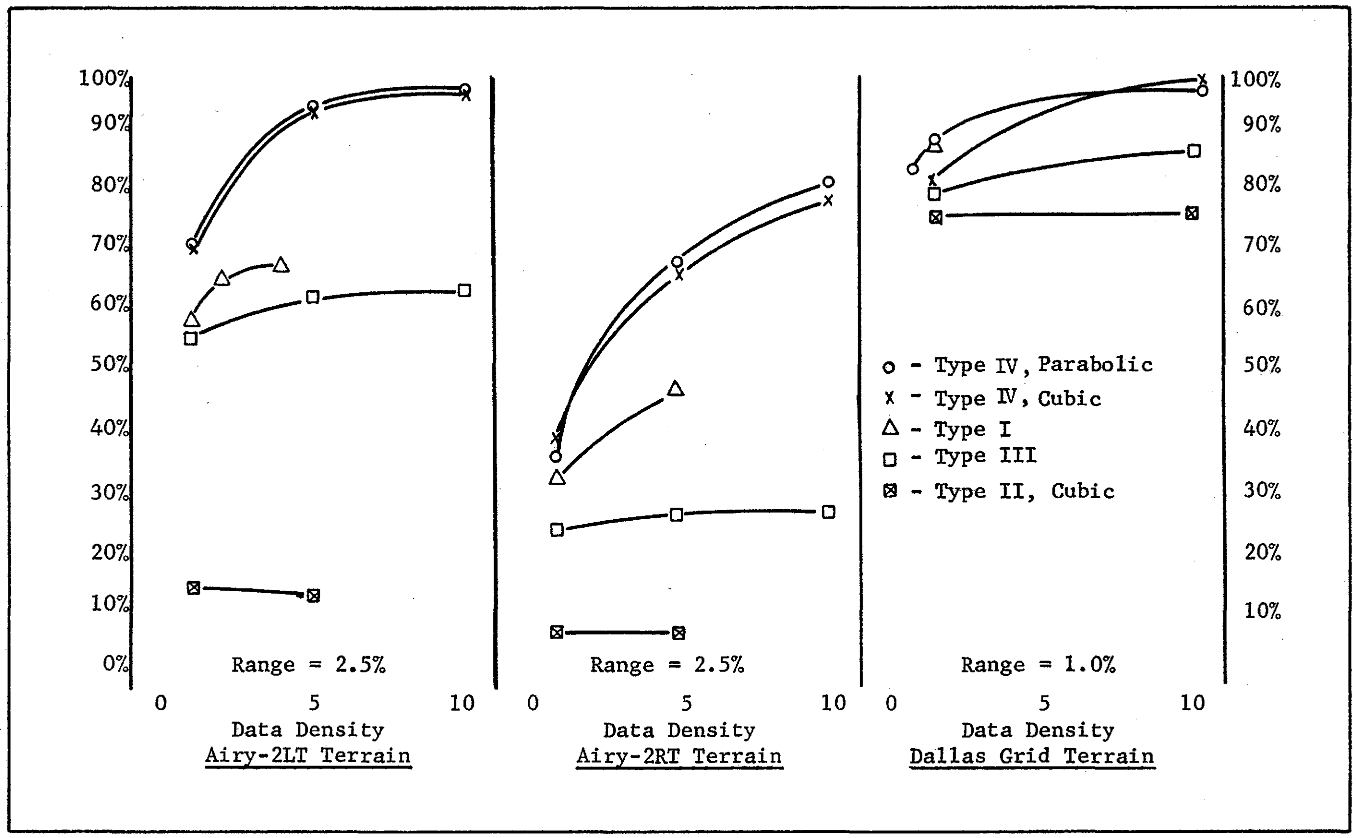

Figure V-4. Surface type vs. data density.

the operating properties is also limited to a discussion of the functional properties.

The Functional Properties of the System

The functional properties of the system are described in terms of the NGI System alternative diagram in Figure IV-1. The following discussion is therefore supplemental to the original description of the functional classes and class members in Chapter IV. The optimum system can be shown to be one of the possible alternatives represented by the alternative diagram, *i.e.*, A3, B2, C2, D2, E2, F1.

Data grouping scheme. The ensemble of project terrain data is grouped by sector. These sectors may be overlapping, nonparallel, or askew to the coordinate axis. The only requirements are that they completely enclose the ensemble of data points and they must be rectangular in shape.

Coordinate system. The NGI System uses a local coordinate system for each sector of data points. The origin (0, 0, 0) of the system is located at the lower left-hand (Southwest) corner of the sector. Each sector coordinate system is then related to the coordinate system of the project by appropriate translation, rotation, and scale constants.

Type of surface. The NGI System uses a parabolic surface to approximate the terrain surface. This surface is fit to a cluster of 9 data points.

Type of surface fit. The surface is fit to the cluster of terrain data points by a conventional least squares surface fitting technique.

Extent of the surface fit. The roving surface technique is used to select the cluster of 9 data points closest to the desired horizontal position.

Surface storage mode. The roving surface technique assumes that a new surface must be fit for every elevation calculation. Therefore, no surface coefficients are stored and only the data points remain in storage.

The Operational Properties of the System

The exact operational properties of the System cannot be determined until the final NGI System is implemented and observed while operating in a design environment. However, three of these properties can be discussed in general terms which give an idea of what to expect so far as actual operation of the NGI System is concerned.

Throughput rate. The expected throughput rates of the optimum system for various sector sizes can be determined from Figure V-5. This is probably a conservative value since the final NGI System will exhibit generally larger throughput rates than the text systems due to more efficient object code. For example, for a sector of 500 points a throughput rate of 350 elevations per minute can be expected.

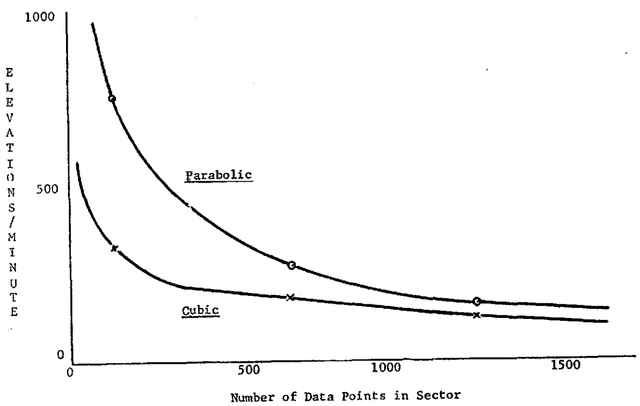

Figure V-5. Throughput rate vs. surface type.

Data density. The data density required to achieve a given accuracy (sensitivity) is a function of the relief of the terrain surface and the characteristics of the terrain sample data points. However, in general, as the data density for a given area is increased, the accuracy achieved by the system is increased. In fact, as the data density increases, the sensitivity-versus-data density curve approaches 100% sensitivity as a limit. The shape of this curve and its position in relation to the axis is a function of terrain relief and sample characteristics.

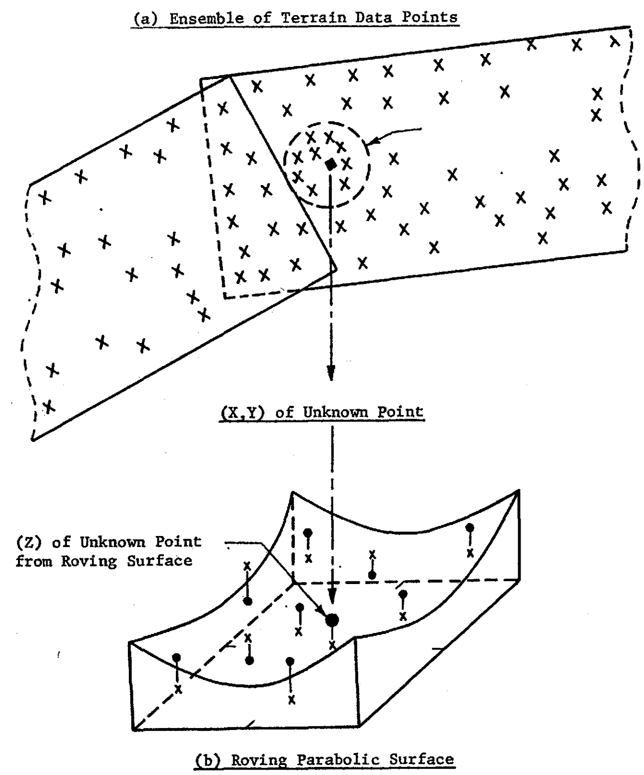

Figure V-6. NGI Data Grouping System.

CHAPTER VI

Design of the NGI System

Once the optimum alternative system has been isolated the problem of designing the necessary software to implement the system can be approached. Chapter VI describes the architecture and functional characteristics of the proposed software system to accomplish this implementation. The first phase of this design is to establish a design strategy or philosophy. The second phase is to describe the architecture of the system and the function of the system elements.

Design Strategy and Philosophy

The success or failure of the NGI System as a useful tool will depend upon a number of factors. The one overriding consideration is the maintenance of engineering integrity, *i.e.*, an engineer controlled, not a so-called automatically controlled, data processing system. Another primary consideration is the ease with which the NGI System can be interfaced with other systems. Several other considerations of lesser importance are the ease of program debugging, modification, and maintenance; and the minimizing of the system throughput rate.

System Architecture

The system architecture describes the functional and logical structure of the system. In terms of a general software system, this architecture is usually displayed in the form of a flowchart on which the flow of information through the system is indicated.

System architecture, in general, is characterized by six levels of complexity often referred to as the system hierarchy. In order of decreasing complexity, these levels are: system, subsystem, assembly, component, part, and material. In terms of software terminology these levels are defined as follows:

Subsystem. An independent group of assemblies performing a major but independent function within the total system operation, *i.e.*, a software package.

Assembly. A coordinated group of components combined to function as a complete unit, *i.e.*, a function or subroutine subprogram.

Component. The lowest functional part of the system, *i.e.*, a FORTRAN statement.

Part. A single fabricated item which is completely destroyed by disassembly, such as a constant or variable name.

Material. The basic material from which the parts are made, *i.e.*, alphameric or numeric characters.

Function of the System Elements

After the system architecture has been designed, the functions performed by the system elements can be defined. These definitions are expressed either verbally or mathematically. The detail of the explanation required depends upon the level of complexity at which the architecture is designed. Thus, for system design the functions of the elements are defined only in a gross sense. For subsystem design the explanation is more detailed, *etc.*

NGI System Design

Architecture of the System Elements

The NGI System has three subsystems. Each subsystem, although an integral part of the total system, functions more or less independently of the others. The only communication link between these three subsystems is the NGI Master Data File which resides on a system direct access input/output device (disk pack). The NGI System architecture is defined by the flow chart in Figure VI-1.

Function of the System Elements

NGI Data Subsystem. The function of the NGI Data Subsystem is to establish the NGI System Master Data File on the appropriate disk pack. A "driver" program which is interfaced with the NGI Data Package reads, edits, and arranges the sector parameters and terrain data in the proper sequence; then, passes these data to the NGI Data Subsystem through the correct interface. The NGI Data Subsystem checks the data for correctness and writes the NGI-Master Data File located on the proper direct access input-output device. Once this data file has been properly formed, the NGI Data Subsystem has completed its function.

NGI Master Data File. The function of the NGI Master Data File is to store all of the pertinent terrain and control data required by the NGI System. These data can then be accessed by the NGI Test and NGI Elevation subsystems whenever desired. The intent is to "roller towel" data into the core, sector by sector, from the NGI Master Data File as required by the other subsystems.

NGI Test Subsystem. The NGI Test Subsystem provides a means of testing the completeness of the NGI Master Data File and a means of predicting the quality of the results produced by the NGI Elevation Package.

Since a procedure for predicting the accuracy of the elevations calculated by the NGI System when it is operating in a design situation has yet to be developed, the accuracy tests used to evaluate the competing alternatives is no longer pertinent. However, a procedure for detecting blunders, *e.g.*, extrapolating instead of interpolating an elevation, can be designed so as to predict whether or not the NGI System will yield elevations free from blunders. This will prevent aborting a future processing run due to an excessive number of blunders while the NGI Elevation Package is interfaced with an application program.

NGI Elevation Subsystem. This subsystem provides an interface between the NGI System and application

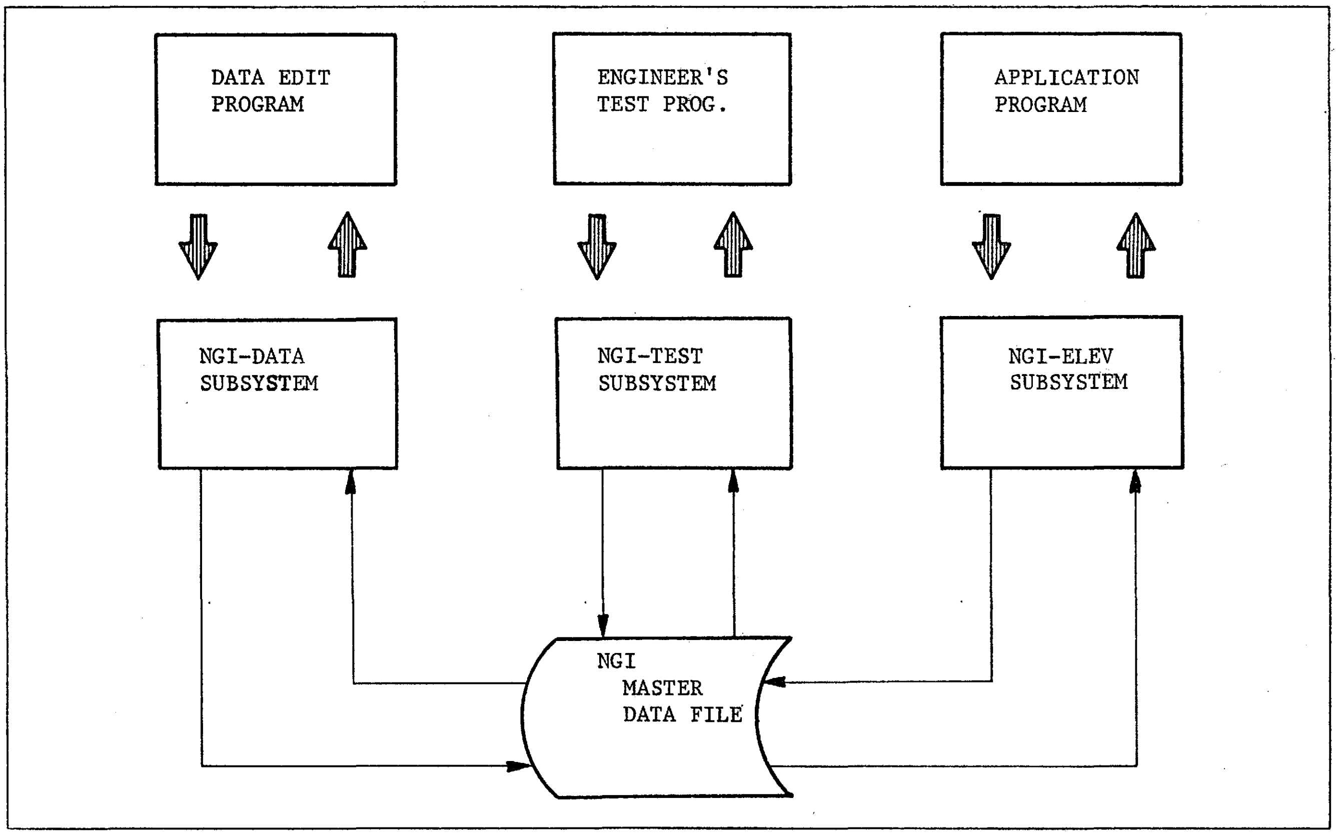

Figure VI-1. NGI System architecture.

programs so that the NGI Elevation Package can return an elevation corresponding to any valid horizontal position desired by the application program.

NGI Data Subsystem Design

Architecture of the Subsystem Elements

This software package must be interfaced with an appropriate data editing program in order to be executed. Two types of input are passed through the interface to NGI Data: (a) control input to describe the data ensemble and, (b) sector parameters and terrain input to describe the terrain data points. Any detectable errors are passed back to the driver program through the appropriate interface. Throughput flow in the package is shown by the flow chart in Figure VI-2.

Function of the Subsystem Elements

Ensemble input. The ensemble input defines the total number of sectors, total number of terrain points, and project identification code.

Sector control input. The sector input defines the sector boundaries and sector orientation, *i.e.*, the four vertices of the sector in both the sector and ensemble coordinate systems, and the proper ensemble identification code.

Terrain input. The terrain input contains the coordinates of the project terrain data points represented in the coordinates system of the ensemble. These data must be identified by the proper ensemble code.

Control input edit. The control input edit element checks the sector vertices for proper sequence and rectangular shape in the horizontal plane. If either of these conditions is violated an error indicator is set.

Control input reduction. The control input reduction element calculates the coordinate translation and rotation constants for each sector and writes all ensemble and sector control parameters on the Sector File.

Terrain input edit. The terrain input element searches the sector file for the sectors which embrace the data point. If no sector is found an error indicator is set and the point is rejected.

Terrain input reduction. The terrain input reduction element identifies all sectors which embrace the terrain data points, converts the original coordinates to the coordinate system of the appropriate sector, and writes the converted coordinates in the appropriate Terrain File of NGI Master Data File.

Control error output. An error code passed back through the interface indicates to the edit program the types of errors detected by NGI Data.

Terrain error output. The types of terrain errors, if any, are indicated to the edit program by an error code passed back through the appropriate interface.

NGI Master Data File

The NGI Master Data File is made up of a Sector File and a Terrain File. The Sector File contains: (a)

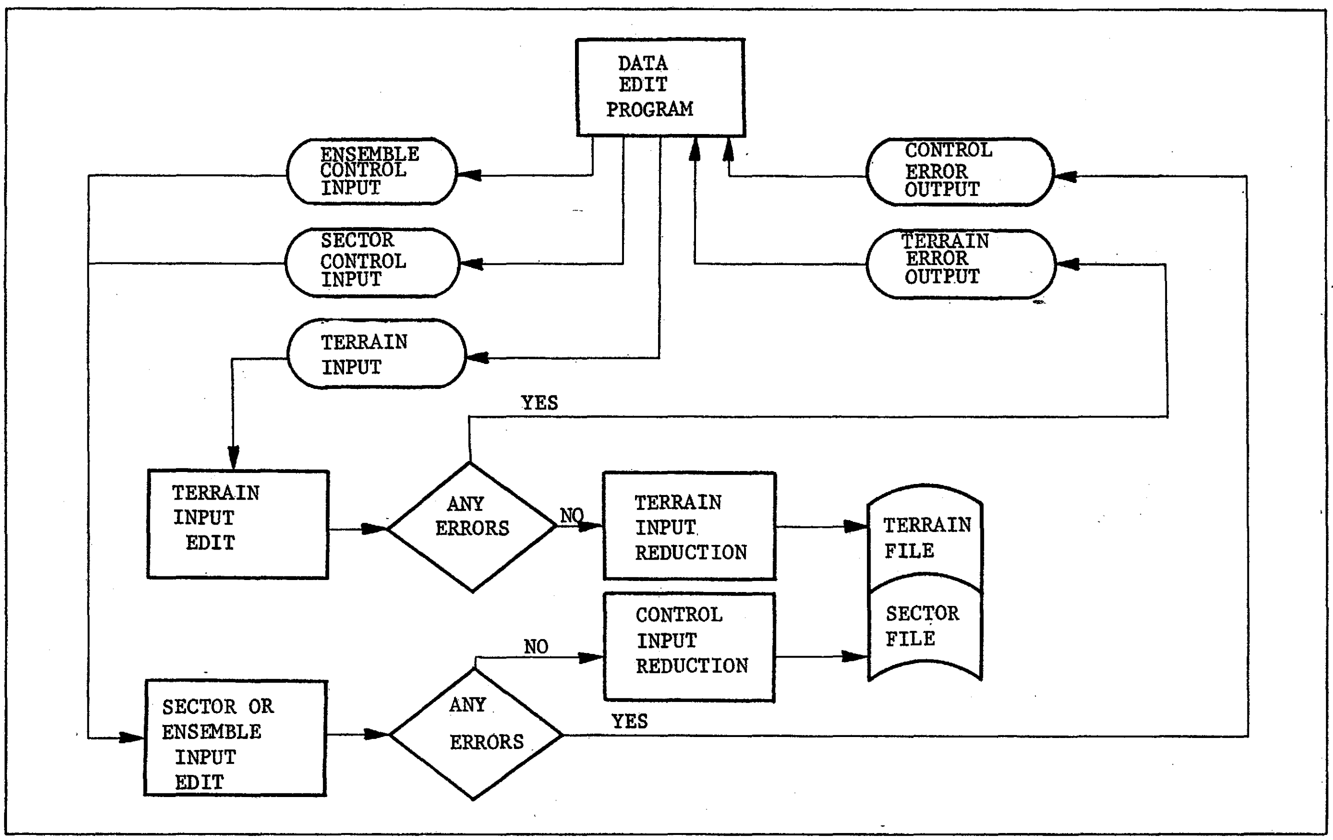

Figure VI-2. NGI Data Subsystem architecture.

the sector identification index; (b) the coordinates of the four sector vertices in both the ensemble and sector coordinate systems; (c) the translation and rotation constants for each sector; and (d) the starting location, length, and ending location of the corresponding Terrain File for each Sector File. The Terrain File contains the terrain data for each sector in "chained" form.[1] See Figure VI-3b for an example of the chained Terrain File.

NGI Test Subsystem Design

Architecture of the Subsystem Elements

The NGI Test Package must be interfaced with an appropriate "driver" test program in order to be executed. The X and Y coordinates (in the ensemble coordinate system) of the desired test point are passed through the interface to NGI Test by the test program and if any blunder conditions are encountered the appropriate blunder code is passed back to the test programs via the same interface. The throughput flow paths in the package are shown by the flow chart in Figure VI-3.

Function of the Subsystem Elements

(X,Y) input. The X and Y coordinates passed through the interface define the horizontal position (in the coordinate system of the project ensemble) of the

[1]IBM Corporation, *FORTRAN (G) Programmer's Guide*, (New York: IBM, Programming Systems Publications, 1966), p. 58.

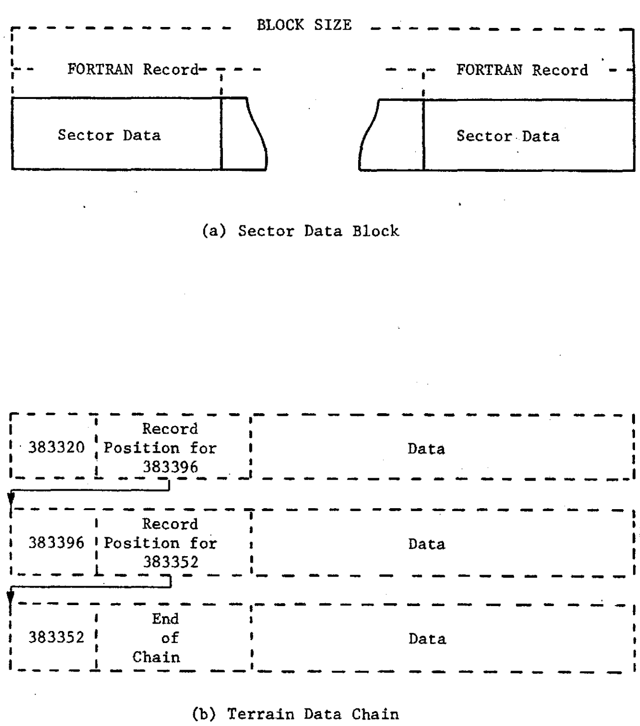

Figure VI-3. NGI master data file.

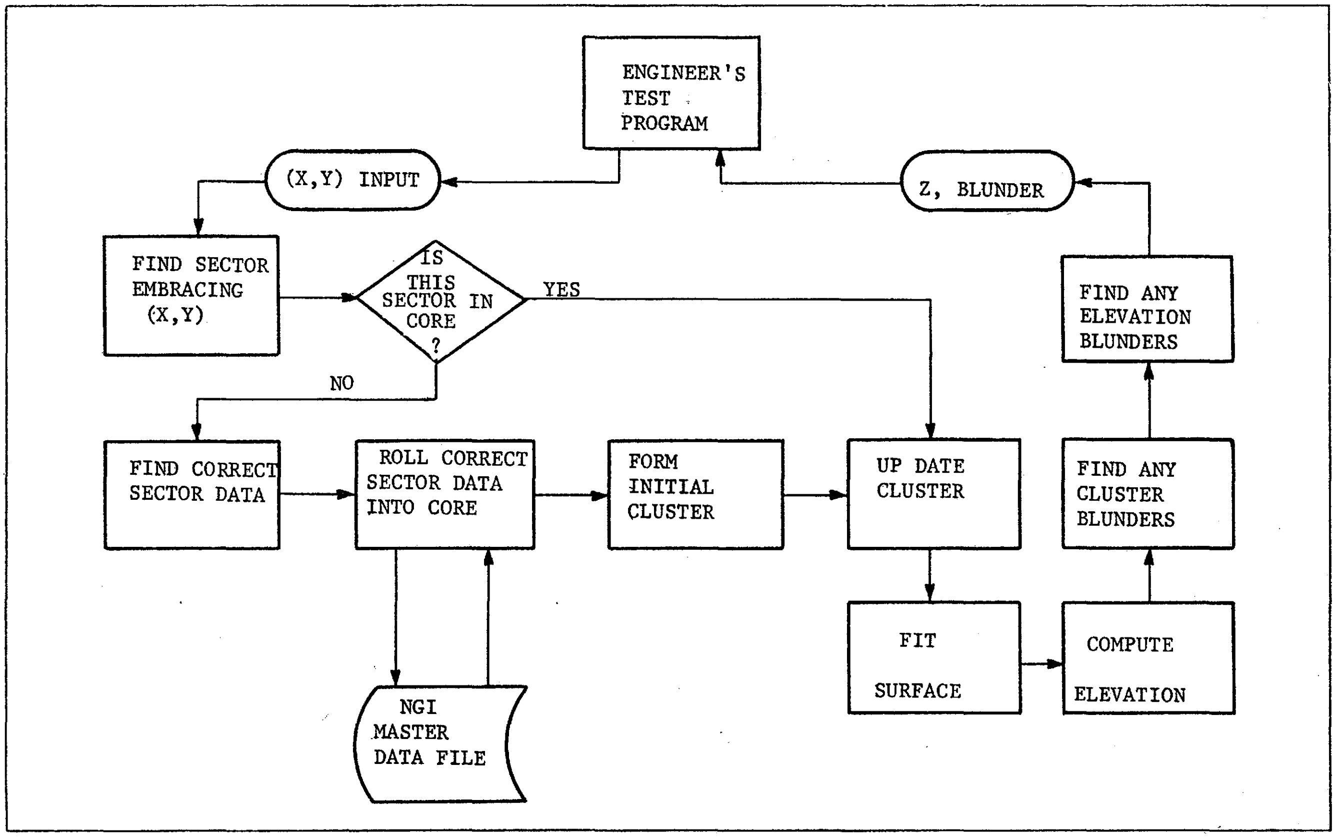

Figure VI-4. NGI Test Subsystem architecture.

point for which an elevation (Z) is required by the test program.

Calculate sector index. This element calculates the sector index of the point passed to NGI Test. The index is used to determine which sector contains the point.

Find correct sector. This element compares the sector index of the point to each sector index in the table of sector indices located in the Sector File. If a matching sector is found, the location of that sector in the Terrain File is saved. If no sector is found an appropriate error code is set.

Roll correct sector data into core. The sector and terrain data corresponding to the sector of the test point replace the sector information currently residing in core. These data are read from the NGI Master Data File and placed into terrain and sector tables.

Form initial cluster. The first nine points of the terrain coordinate table become the initial cluster. The distances between the data points and the test point are calculated and the terrain points in the cluster are reordered so that the closest terrain point occupies the first position of the cluster, the second closest, the second position, *etc.*

Update cluster. The remainder of the terrain table is searched to determine if any points in this table are closer to the desired point than any point in the cluster. If such a point is found it is substituted in the cluster, and the cluster is reordered as above.

Fit surface. A parabolic surface is fit to the cluster points by conventional least squares and the surface coefficients are stored in array for later use.

Computer elevation. The elevation of the test point is calculated from the surface coefficients stored above.

Find cluster blunders. Two types of blunders (as opposed to errors) are detected by the test package. The first type of blunder is cluster imbalance, *i.e.*, a poor distribution of data points about the test point. The other detectable blunder involves attempts to extrapolate, *i.e.*, the test point lies outside the limits of the cluster. If either condition exists an appropriate blunder code is set.

Find elevation blunders. If a calculated elevation lies outside the sector space, *i.e.*, outside the elevation range of the sector terrain data, an elevation blunder has occurred and a blunder code is set.

NGI Elevation Subsystem Design

Architecture of the Subsystem Elements

The architecture of NGI Elevation is very similar to NGI Test (see Figure VI-5), except that the blunder detection elements are omitted and no blunder code is passed back through the interface with the driver program.

Function of the subsystem elements. The elements of NGI-Elevation function exactly as the elements of NGI Test except where noted above.

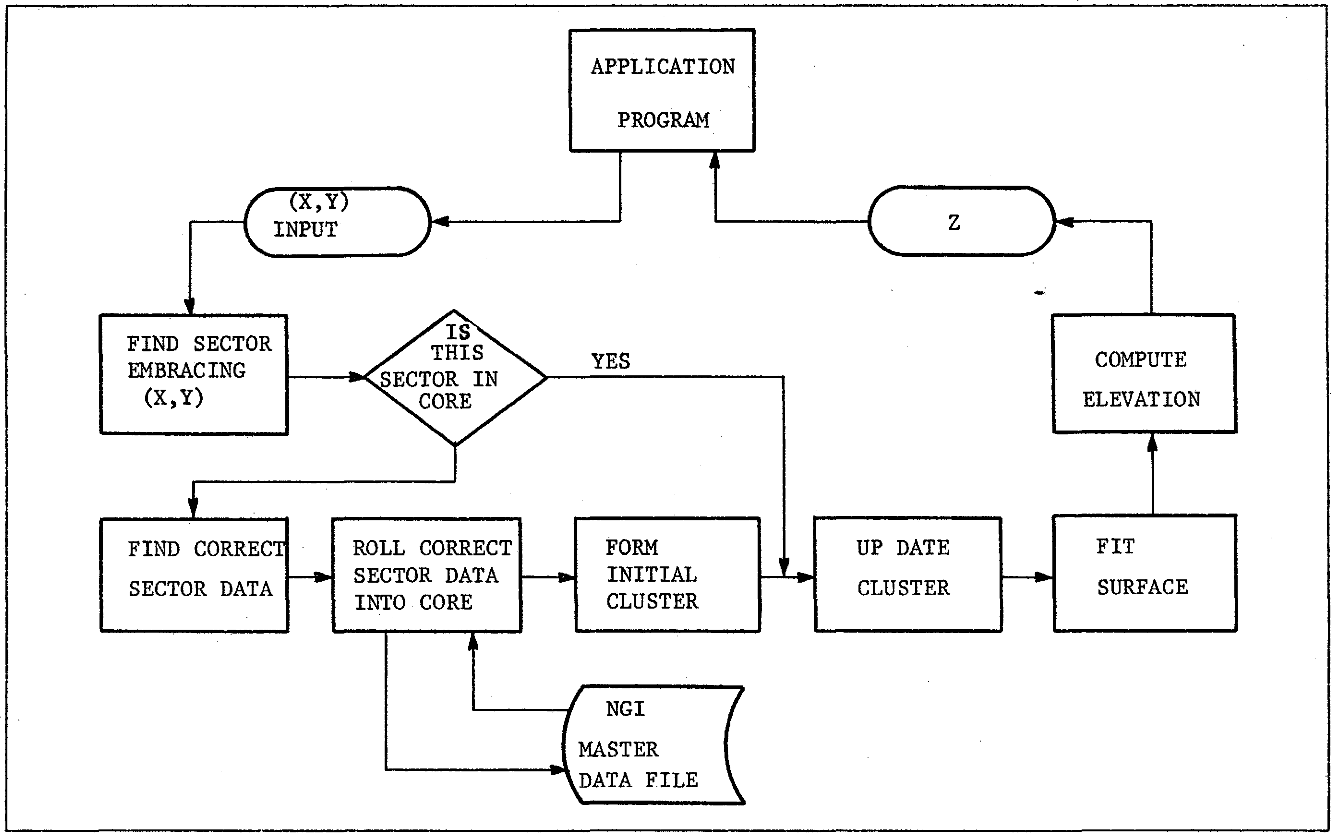

Figure VI-5. NGI Elevation Subsystem architecture.

CHAPTER VII

Conclusions and Recommendations

Conclusions

Since conclusions concerning the specific operating characteristics of the competing alternative system were stated during the isolation process in Chapter V, only the general conclusions concerning the evaluation guidelines suggested in Chapter I are required at this time. These conclusions should be considered as preliminary, not final, in as much as the final conclusions about the value of the NGI System as an engineering tool can be made only after its operating characteristics have been observed in an actual operating environment. Conclusions in light of these qualifications, are:

Accuracy. The accuracy obtained by the NGI System is limited by three factors: round-off noise, errors caused by assuming that the earth is parabolic in shape, and errors created by the terrain data. The errors caused by round-off noise are insignificantly small, *i.e.*, less than 0.01 feet or within a range of 0.50%. The errors introduced by the last two factors can be reduced by increasing the data density. How much they can be reduced by increasing the data density depends upon the terrain relief over the area in question. As the data density is increased, the sensitivity for a given range approaches 100% as a limit. Thus, the NGI System is theoretically capable of achieving any degree of accuracy desired. In practice, however, the resulting accuracy will be limited by data acquisition and processing constraints.

Effectivity. The NGI System makes the most effective use of uniformly distributed terrain data, allowing for slight increase in data density in the more difficult terrain situations, *i.e.*, rough spots. The experience resulting from this study indicates that the "strength of figure" of the data points (the uniformity of their distribution) counts for as much as the "intelligence" (placement of the terrain data points in regard to the relief pattern of the terrain) of the sample. For example, if the data submitted to the NGI System were originally measured in cross-section format, *i.e.*, along lines perpendicular to the center line at even stationing, the system would fail to obtain the accuracy expected with this data density. This decrease in accuracy occurs because the "strength of figure" of the terrain data is inadequate to support a fitted surface.

Computability. According to the definition of computability given in Chapter I, the NGI System has a high degree of computability. The system is designed to interface conveniently with any FORTRAN "driver" program. A high degree of modularity is also built into the System to facilitate interface modification at a later time.

Generality. The NGI System does not provide a general case solution to the problem of terrain approximation. This situation is caused by the fact that the NGI System assumes that the terrain surface is everywhere parabolic in shape when, in fact, the terrain surface is not parabolic. The effect of this assumption on the accuracy obtained by the System decreases as the data density increases. Thus, in the majority of cases the effect of this assumption can be minimized by utilizing an appropriate data density.

However, in the case of discontinuities in the terrain surface this assumption may not be valid. Unfortunately, the terrain data used to evaluate the System did not contain any discontinuities, so any prediction of how the NGI System behaves in the neighborhood of a discontinuity is speculative. However, several contrived situations can be shown to exist where the System will not achieve the expected results. This problem might be overcome if a method for describing a discontinuity in terms of the input to the System could be developed.

Applicability. The results obtained from the NGI System are consistent with those obtained from cross-sections when used with present computer-aided design practice. However, the value of the NGI System does not lie in its ability to directly substitute for cross-sections in such design phases as earthwork calculations, slope staking, *etc.* The value of this new technology lies instead in its ability to represent the Earth's surface as a numeric surface. By treating both the design roadway and the terrain as surfaces, computer-aided design technology can be drawn into new areas of application. For example, once the roadway surface has been designed, it can then be combined with the terrain surface such that perspective drawings of the design can be generated and displayed for easy reference during the design process. Alternate designs can be developed without measuring or shifting the terrain data for each alternate design; thus, making iterative optimization techniques a possible part of the design practice.

Recommendations for Future Study

The experience that resulted from this study indicates that there are several aspects of the terrain approximation problem which could be profitably investigated. The first three of these aspects are within the scope of this study but were excluded from the analysis because of time and resource constraints on the study. The last four are areas that lie outside of the bounds of the study.

Types of numeric surfaces. The polynomial surface may not be the most general approximation to the terrain surface. If a more general surface could be found, the NGI System would be able to make more efficient use of the measured terrain data. This would result in reduced data requirements for a given level of accuracy, or increased accuracy from the same density of data.

Clustering techniques. The clustering technique used by the NGI System assumes that the most accurate results are obtained from a cluster formed from the points closest to the unknown point. This study did not investigate the generality of this assumption. If an algorithm which yields a cluster more representative of the terrain surrounding the unknown point is discovered, then the NGI System could make more efficient use of the measured terrain. For example, if discontinuities could be recognized, then the clustering process could take them into account.

Surface fitting technique. The least squares surface fitting technique is used by the NGI System because it is the optimum fitting procedure according to the conclusions resulting from this study. However, the weighted least squares fitting technique gave equally accurate results for the terrain samples available to this study. Other weight functions and other more extensive terrain samples might indicate that weighted least squares are, in fact, the most desirable. A minimax surface algorithm might also be developed for use by the System.

Terrain roughness. If some method for quantifying the terrain roughness were available, then the data density required over a given area for a specified level of accuracy could be predetermined. This information could also be used to estimate what an increase in data density would obtain in terms of increased accuracy for a particular set of terrain data. Other supplemental terrain data which might result in a more effective system might also be explored.

Throughput rate optimization. Once the NGI System has been made operational in an engineering environment, then pertinent throughput data can be collected. After these data are collected, the trade-offs between the roll-in of data from direct access storage, the amount of data resident in core, and surface fitting speed may be accomplished in order to optimize the throughput rate of the total system.

Analogue terrain models. The possibility of using an analogue model for approximating the terrain for use in a computer-aided design environment might also be investigated.

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Appendix

PREVIOUSLY DEVELOPED DIGITAL TERRAIN MODELS

With the exception of the IBM Numerical Surface Technique, and the Map Analysis techniques reported by James and Krumbein, the Digital Terrain Models described below are an extension of current cross-section technology. That is, they are used for the purpose of calculating highway cross-sections from terrain data already existing in some other format. The IBM technique is apparently used to obtain contour maps of grossly defined phenomenon such as gravity fields or atmospheric pressures. The Map Analysis techniques are used to contour geologic stratigraphy in an equally gross scale.

These systems all fall into three broad classifications.

1. Digital terrain data are measured in a regular geometric pattern and the elevations of desired intermediate points are interpolated mathematically from this pattern. Some examples of this type are the M.I.T. D.T.M. System, the Modified Base Line D.G.M., the Bedford cc/Elliot D.G.M., and the Viatek D.G.M.

2. Digital terrain data are measured in a mathematically random pattern; the elevations of points which lie in a regular grid pattern are calculated from these data; and then the elevations of desired intermediate points are interpolated from the grid elevations. The IBM Numerical Surface Technique is an example of this type.

3. Digital terrain data are taken in mathematically random fashion and the elevations of the desired intermediate points are directly interpolated from these data. The *Ponts et Chaussees* D.G.M., the Nordisk D.G.M. and the Map Analysis system are examples of this type.

Although some of these methods are still in the development stage, they have been used with some degree of success in the highway design and location process. The salient points of these methods are described below.

M.I.T. "Digital Terrain Model System" [1]

Terrain data is measured so that a band-of-interest, along and on both sides of a base-line, is defined by cross-sections. These measurements can be taken from the field, read from contour maps, or gathered photogrammetrically. The base-line runs along the general direction of the proposed horizontal alignment and can be made up of connecting straight lines and/or circular curves. This base-line can be coincident to the project centerline except where transition curves exist. The cross-sections are defined in terms of a coordinate system with the X-value as the distance along the base-line, the Y-value as the distance right (+) or left (−) of the base-line, and the Z-value as the elevation of the data point (see Figure A-1).

[1] P. O. Roberts and J. A. Curry, *DTM Design System, 40K Program Manual,* (Cambridge, Massachusetts: Dept. of Civil Engineering, M.I.T., 1964).

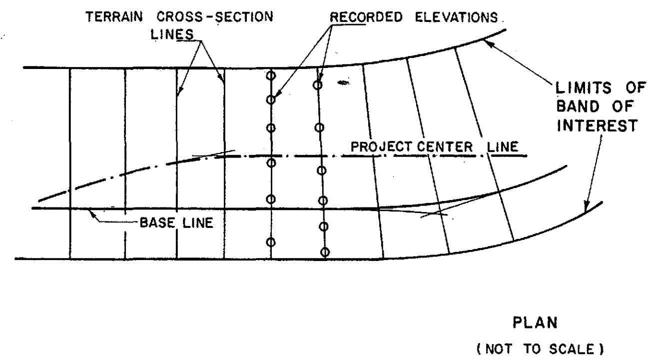

Figure A-1. M.I.T. D.T.M. System.

The design cross-sections can be obtained only where the original terrain cross-sections intersect the centerline. If the cross-sections are askew to the centerline then the design templet is rotated so that it is parallel to the cross-section. After the usual end area computations are performed in this plane, the resulting areas are rotated back to perpendicular to the centerline for volume calculations, etc.

Modified Base Line D.G.M. System [2]

The terrain cross-sections are measured in a fashion similar to the M.I.T. D.T.M. System. However, design cross-sections which are normal to the centerline instead of skewed are interpolated from the surrounding pertinent terrain cross-sections. This is accomplished by calculating the elevations of points on the terrain cross-sections which straddle the desired point and then interpolating the elevation of the desired point from these two points (see Figure A2).

[2] W. Craig and J. Burns, *Digital Ground Models in Location and Design,* (London, England: Road Research Laboratory, 1966), p. 6.

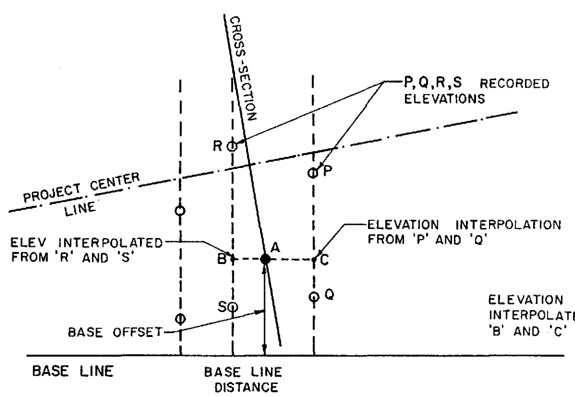

Figure A-2. Modified base line D.G.M.

Bedford/Elliot D.G.M. System[3]

The Bedford/Elliot System is based upon a 50-foot grid pattern of measured elevations. The system accepts terrain data collected either by field or photogrammetric methods. If the data are submitted in a quasi-random pattern the required grid pattern is obtained by computing the grid elevations by a simplified weighing method (see Figure A-3).

The elevation of a required point is obtained by mathematical interpolation from the elevation of the four corners of the grid containing the required point. In order to facilitate storage of a large number of data points blocks of terrain data are recorded on magnetic tape and these blocks of data are read into the computer in "roller towel" fashion as required.[4]

Viatek (Finland) D.G.M. System[5]

The Viatek Consulting Group (Finland) method represents the terrain surface by a system of triangles with a terrain data point at each vertex. The terrain data can be collected either in a quasi-random pattern (see Figure A-4a) or in a pattern forming systems of equilateral triangles (see Figure A-4b). The elevations of intermediate points are calculated either from a triangle whose vertices embrace the desired point or from a plane passing through the nearest three terrain data points. According to Craig and Burns this method was not yet fully developed in 1967.

IBM Numerical Surface Technique[6]

The IBM system uses digital terrain data measured in a quasi-random pattern. Then a grid system is superposed over the area of interest and an elevation computed for every mesh point in the grid. First, mesh point elevations are computed for every grid square which contains one or more data points. These elevations are determined from a plane which is fit to the surrounding data by weighted least squares. After these mesh points are evaluated then values are "extended" to the mesh points of squares not containing terrain data by various extrapolation schemes. When all of the mesh points are evaluated, then the elevation of any desired intermediate point is computed by orthogonal polynomials.

[3]This system was developed by Messrs. Lowe and Young of Bedford County, England, and Elliot Automation.

[4]Craig and Burns, *Digital Ground Models*, p. 8.

[5]T. Kokka and E. Viita, *The Development of Highway Planning*, (Rakennustecknikka, 1964), p. 276.

[6]IBM Corporation, *Numerical Surface Techniques and Contour Map Plotting*, (White Plains, New York: IBM, 1964), pp. 23-25.

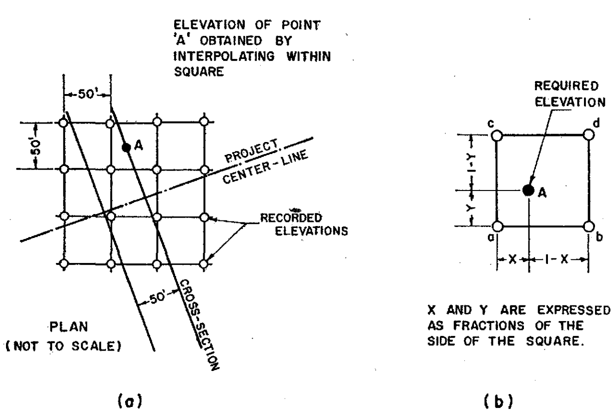

Figure A-3. Bedford cc/Elliot D.G.M.

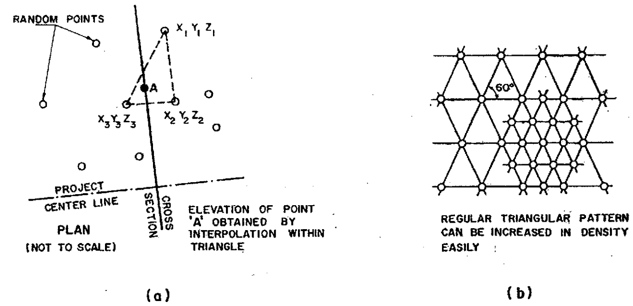

Figure A-4. Finland Viatek D.G.M.

Nordisk (Sweden) D.G.M. System[7]

This system is based upon the notion that the significant terrain features, *e.g.*, ridges, valleys, ditches and cliffs can be represented numerically as "terrain lines" (see Figure A-5). Subsequent interpolation of a required elevation is accomplished by first locating that line which (a) passes through the required point and (b) is the shortest path between the terrain lines nearest to that point. The required elevation may then be computed from the equation of this line. This method appears to have an advantage over other methods when used to represent sharp terrain features which tend to be smoothed out by other systems.[8]

Ponts et Chaussees D.G.M. System[9]

This system uses terrain data measured in a quasi-random pattern. A parabolic surface is fit by least

[7]This system is being developed by Nordisk, a Swedish Consultant, in association with the Federal German Government, and the Swedish Roads Board. Little documentation is available (1967).

[8]Craig and Burns, *Digital Ground Models*, p. 7.

[9]A. Thielout and J. L. Deligny, *Traces Electronic in Geometric Imposee; Suite 3 — Interpolation Du Terrain*, (Paris, France: *Ministere de L'Equipment*, 1966), pp. 4, 5.

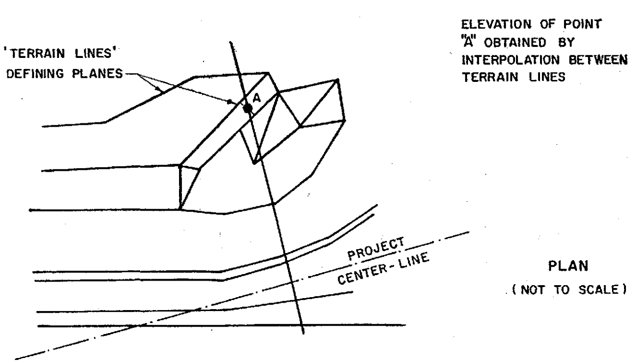

Figure A-5. Nordisk D.G.M. System.

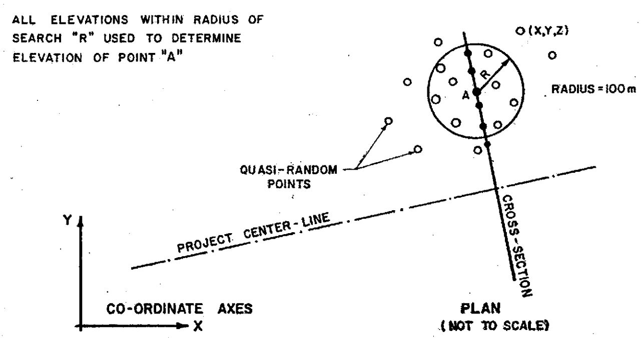

Figure A-6. French Ponts et Chaussees D.G.M.

squares to all of the terrain data points within a specified distance from the point where an elevation is required. The elevation of the required point is then determined from this surface. This method is used to generate cross-sections normal to the center-line to be used during the usual design procedure. The *Service Special des Autoroutes* in France developed the system and from all indications plan to use it extensively.

Map Analysis Models[10]

These models make use of digital terrain (or stratigraphy) data measured in a quasi-random pattern. Then a Fourier Series surface or a polynomial[11] surface is fit by least squares to the ensemble of available data and the surface coefficients stored for later use. Once the surface coefficients are available, then the elevation for any intermediate point may be solved for directly.

Although these models are primarily used for trend surface analysis they can be used to model the terrain without significant alternation. However, the reported accuracies and map scale preclude their direct application to highway design.

[10] William R. Jones, *The Fourier Series Model in Map Analysis*, (Evanston, Illinois: Northwestern University, 1966).

[11] W. C. Krembien, *A Comparison of Polynomial and Fourier Models in May Analysis*, (Evanston, Ilinois: Northwestern University, 1966).