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EVALUATION OF FUNCTIONAL AND STRUCTURAL CHARACTERISTICS OF  
ANALYTICAL PLOTTERS

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ABSTRACT

A hierarchical procedure for evaluation of analytical plotters is discussed in this paper with special attention to the check-out procedures. The procedure is based on the evaluation of the essential capabilities of the analytical plotters to perform a set of functions under certain well defined conditions, and on the evaluation of the structural or design characteristics of their hardware and software against the specified performance parameters.

INTRODUCTION

In an earlier paper dealing with evaluation criteria and performance tests for analytical plotters [Jaksic, 1978] it has been shown that the evaluation of an analytical plotter cannot be accomplished according to a deterministic scheme, the main reason being that the criteria for evaluation vary depending on the intended use of the instrument.

The evaluation criteria are defined by a set of specifications that identify the functions and parameters required by a particular user. Consequently the ability of the user to establish a set of specifications is a prerequisite for the meaningful evaluation and comparison of the technical characteristics of different instruments, for the estimation of the extent of allowable trade-off between the technical and economical constraints, for the assessment of the possible adaptation of an instrument to specifications (especially in respect to its application software), and for the final optimal choice of a particular instrument.

ORGANIZATION OF EVALUATION PROCEDURES

The material that is being prepared by the Working Group II/1 in the process of establishing a system for the evaluation of analytical plotters [Makarovic, 1978] should eventually provide the necessary information that will enable the user to prepare a complete set of specifications (i.e. a set of desired characteristics reflecting his particular needs) and to compile the corresponding sets of the actual characteristics of the analytical plotters he is considering. Comparison of these sets will result in an evaluation based solely on criteria defined by the user.

The individual entries or elements of the respective sets are functions, parameters and structural characteristics.

The functions can be classified in two groups: the functions concerned with the actions of the system's physical devices and the functions concerned with the transformation of some input data into some output data or some return data [Jaksic 1980]. The functional characteristics are predominantly of qualitative nature and cannot be in general represented by a quantitative indicator. They will normally require some descriptive indicators. Consequently their evaluation beyond the simple statement of presence or absence of a particular function, will tend to be somewhat ambiguous.

The parameters are quantitative indicators of performance or of dimensions (e.g. accuracy, speed, execution times, format of stages, memory capacity). These parameters can be determined by measurements. Their evaluation is based on well-defined testing procedures. Although not completely devoid of ambiguities these procedures are quite straightforward.

The structural characteristics concern the design and the organization of the hardware and software facilities for the performance of the functions (e.g. interrelation of hardware components, modularity of software, algorithms). The evaluation of these characteristics requires an intimate knowledge of the design principles of analytical plotters in general as well as detailed knowledge of the design properties of the hardware and software components and of the interaction of these components in each instrument under consideration. The ability of an instrument to perform the required functions under the conditions defined by the parameters is directly dependent on its structural characteristics. Due to the complexity of these interdependencies the evaluation of structural characteristics has to be based almost exclusively on inference.

It is evident that a combination of two kinds of procedures are required for the evaluation of an instrument. One is based primarily on measurements and the other on inference. These two kinds of procedures correspond respectively to the testing procedures and the check-out procedures of the W.G. II/1 system for evaluation of analytical plotters [Makarovic 1978].

The framework for the establishment of a specification set and the related sets of the actual properties of the instruments should consist of a number of lists corresponding to the major components of analytical plotters. The performance and design characteristics of components should be tabulated in these lists in a hierarchical order: first the functions and parameters and then the structural characteristics. For the users with less sophisticated requirements who are interested only in a coarse evaluation concerned simply with the availability of certain functions that are performed under certain conditions, the parts of the lists that identify the functions and parameters may already suffice [Fritz 1978]. The parts of the lists containing the structural characteristics would enable the user with more demanding requirements to establish his evaluation criteria on the level of finer detail.

Each of these lists should be supported by a detailed description of pertinent testing procedures and by extensive comments on the interdependence and interaction between components and on the significance of critical structural characteristics for the performance of the system as a whole. This information should assist the user in establishing the testing procedures and in acquiring the necessary understanding for the evaluation by inference in the check-out procedures.

## SELECTED EXAMPLES OF PROCEDURES AND RELATED PROBLEMS

Without attempting an exhaustive review of procedures several examples based on the material presented in [Jaksic 1978] have been selected to demonstrate the outlined approach for the establishment of the necessary information that will be used as the basic input for the system of evaluation of analytical plotters.

### Hardware

The hardware naturally subdivides into two qualitatively distinct groups: The computer and computer peripherals which are general purpose devices designed without any consideration for the requirement of photogrammetry and the measuring and viewing component (i.e. optical-mechanical component) which is specially designed to meet the needs of photogrammetry. Conceptually this component represents a special purpose computer peripheral for addressing of image points. For evaluation purposes it can be subdivided into three sub-components: the positioning and measuring devices, the viewing devices and the interface.

Positioning and Measuring Devices. According to the proposed hierarchical evaluation process the functions and parameters are considered first, without regard to the structure of the sub-component. The functions of this sub-component are the addressing of an image point and the measurement of its coordinates (function of the first group). Since the address is the set of coordinates of the image point, the measuring is in fact a function equivalent to the addressing.

The main parameters are: accuracy, resolution, speed, stability, delays and the format of the photo-stages. There are well-defined testing procedures for accuracy and speed. The evaluation of the accuracy involves the determination of RMS errors of coordinate measurements which is based on the familiar grid measurements. Although it should be noted that the grid tests do not fully reveal the dynamic accuracy which depends mostly on the performance of the feed-back controls of the positioning devices. The testing procedure for maximal speed is based on measurement of time and distance travelled under computer control. This test should also include a comparison between the desired distance entered via the computer and the actually travelled distance since an unrecoverable loss of counts may occur at high speeds. The maximal speed of positioning depends on the design of the positioning devices and the delays in the feed-back controls. The stability has two aspects: The overall stability of the assembly which can be evaluated on the basis of testing procedures for accuracy performed at longer time intervals and the stability of the feed-back controls which can be roughly tested visually by driving the carriages, under computer control, at different speeds with frequent stops and reversals of direction. A rigorous quantitative test can be performed only by the observation of pulses with an oscilloscope. Delays caused by unduly long response times of positioning devices can be observed visually in poorly designed positioning assemblies where the movement of the measuring mark obviously does not follow the operator's commands. A rigorous measurement of the delays can be made with the aid of oscilloscopes. The dynamic accuracy depends to a large degree on these delays. These shortly outlined tests would conclude the evaluation of the functions and the parameters on the level at which no regard is paid to the structural characteristics of the sub-component. As already indicated these characteristics have a decisive influence on the parameters. But they also influence the other properties of the system as a

whole because of the interaction between diverse sub-components and because of the interdependence between the hardware and the software. For example the separation of the positioning assembly from the measuring assembly may have considerable influence on accuracy, speed and stability. As described in [Jaksic 1978, 1980] a positioning and measuring device using motors and friction drives for the positioning and linear encoders for the measurement has considerable advantages over a device using a screw with shaft encoders for positioning and measurement. Since the performance of the latter depends strongly on thermal influence there is an unfavorable trade-off between the accuracy and the speed. In the former device the linear encoders are completely independent of thermal influences due to high speeds, consequently the accuracy and speed are not correlated. The speed is dependent only on the resolution of the encoders and the frequency response of the associated electronics. This arrangement also lends itself well to the fulfillment of Abbe's principle. The friction drives also offer better safety to the components since in the case of failure of limit switches the carriage will slip without damaging the positioning and the measuring devices. The structural characteristics of the motor controls will directly influence the accuracy and the stability. In order to improve the response time of the positioning devices the motor controls are often designed to regulate the speed of the motors in function of the magnitude of the error signals of the negative feed-back controls. This approach is only valid under uniform conditions. Non-uniform conditions will cause erroneous positioning and tracking as well as oscillations. If the logic circuitry of the motor controls also has the facility to respond to a feed-back signal indicating the actual speed of motion it can, by introducing a real-time correction to the speed, eliminate a temporary disturbance (e.g. sudden increase of friction) in some part of the range of the movement.

The influence of the structural characteristics of the positioning and the measuring devices on other properties and components of the system may also be quite significant. For example, a construction of carriages that move independently from each other is superior to a structure where both carriages move simultaneously and one of them moves differentially in respect to the other. The latter arrangement will obviously reduce the versatility of the system and cause unnecessary complications in the software (e.g. in on-line aerial triangulation). Also, in configurations with positioning assemblies separated from measuring assemblies with linear encoders there is an option to use linear encoders with indexes. This enables the conversion of the measuring assemblies from incremental to quasi-absolute, a property which significantly changes the basic characteristics of the whole system and has far-reaching influences on the techniques and the software.

These few examples are probably sufficient to convey the need for information on structural characteristics, and show the difficulties they cause when evaluation criteria are being specified. After all there is a distinct possibility that in spite of the advantageous structural characteristics incorporated in the design of an analytical plotter, it may still be inferior to those lacking some of these characteristics due simply to poor implementation of the design. The short review of testing procedures also revealed the need for the establishment and provision of information on some rigorous testing procedures such as the procedure for testing the dynamic accuracy and the delays.

Viewing Devices. The main functions of the viewing devices is the transfer of the image of the photograph to the operator without loss of

information and the provision of a fixed reference point for measurements. Other functions, mainly for aiding the observation and for supporting the implementation of some techniques are: setting of interpupillary distance, diopter correction or image focussing, correction for phoria or squint, change of illumination intensity, image magnification, image rotation, switching of viewing channels, binocular viewing of a single stage, image inversion (mirror image), computer-controlled changes of magnification and rotation of transferred image. The absence of some of these functions will reduce the versatility and universality of the instrument.

The parameters are: resolution, field of view, size and type of the measuring mark, magnification, field curvature, color correction, eye relief, exit pupil diameter, distortion, alignment, and stability of the alignment. To these should be added the limits for: setting of interpupillary distance, diopter correction, squint correction, image rotation and light intensity changes. For computer-controlled optical elements, the additional parameters are: the ranges of computer control, the smallest increment, and the angular or linear speed respectively for image rotation and magnification.

All these can be tested and evaluated by well established testing procedures on those instruments that have conventional optical trains, and by somewhat modified testing procedures for those with optical image transfer that are projecting the image on a screen. For the latter, the functions and parameters are also somewhat different.

On the level of structural characteristics a few details may be of interest. The overall accuracy of the instrument depends to a great extent on the stability and quality of the viewing devices which are defined by the parameters. Stationary optical trains seem to offer a better stability. For better stability the image of the measuring mark is usually optically joined with the transferred image as close as possible to the first element on the input side of the optical train. In trains with continuous magnification changes it is desirable to maintain the same apparent diameter of the measuring mark. This is achievable by manual insertion of measuring marks with different diameters (e.g. mounted on a turret) or by projection of a measuring mark the diameter of which varies continuously in function of the magnification (e.g. by changing the aperture of the projector in function of the magnification). It should be noted that the combined magnification and rotation of the image will result in a similarity transformation which is not able to eliminate the difficulty of stereo-viewing highly convergent photographs. The latest technological advances have brought the use of electronic image transfer into the range of feasibility. This alternative to optical image transfer with its inherent flexibility for transformation and enhancement of the image will require a new set of testing and evaluation procedures.

Interface. For practical reasons the feed-back controls of the positioning devices, the operator's primary commands and the external switches are included into the discussion of the evaluation of the interface. The discussion is based on the structure of the interface described in [Jaksic 1978].

The main functions of the interface proper is the transfer of data between the operator's primary commands and the computer, between the computer and the positioning and measuring devices and between the operator's primary commands and the positioning and measuring devices. They can be

tabulated as follows: two way transfer of data between the registers of operator's primary commands and the computer, two way transfer of data between the computer and the registers of the feed-back controls of the positioning devices, one way transfer of pulses from the pulse generators of the operator's primary commands to the registers of the feed-back controls of the positioning devices, one way transfer of pulses from the pulse generators of the operator's primary commands to the registers of the operator's primary commands, one way transfer of signals from the external switches to the computer, one way transfer of data from the registers of the feed-back controls of the positioning devices to the special purpose displays, and a one way transfer of data from the registers of the operator's primary controls to the special purpose displays.

The function of the operator's primary controls is the generation of pulses (e.g. encoders coupled with handwheels). The functions of the feed-back controls are: determination of the coordinate error signals, determination of the velocity error signals and control of the angular velocity and direction of rotation of motors. (These functions include the necessary digital-to-analog conversions of error signals and analog-to-digital conversion of encoder readings).

The functions of the external switches are software-oriented or hardware-oriented. Usually the actual functions of software-oriented switches are not fixed but determined by the software. They are: activation of a program or a group of programs from a particular software package, selection of a particular routine from a group of active programs and initialization of diverse actions in the course of the operation of a program. The functions of hardware-oriented switches are fixed. They are: exchange of axes (e.g. Y→Z), selection of manual or computer control of optical elements, control of auxiliary devices, selection of the photo-stage that will move during parallax measurements, mode selection (i.e. selection of "comparator" or "plotter" mode), and control of limits of movement of photo-carriages and other mechanical components.

The parameters for the interface are the data transfer times. The critical parameter is the data transfer time from the computer into all the registers of the feed-back controls and the registers of the operator's primary commands. A simple test procedure with the oscilloscope is used for the measurement of this parameter.

The parameter for the operator's primary controls is the number of generated pulses per full rotation of the handwheel or the footwheel. (A similar parameter can be defined for other types of controls). It can be easily checked with the aid of any available display.

The parameters for the feed-back controls are the frequency of determination of error signals for coordinates and motor velocity and the delay time between the arrival of the command from the computer and the completion of its execution. All of these are tested by straightforward measurements with oscilloscopes.

The structural characteristics of the interface and the feed-back control loops of the positioning and measuring devices determine the overall dynamic performance of the instrument. Besides the accuracy, the speed and the stability (i.e. absence of oscillations) of the instrument, they critically influence the capacity and versatility of the real-time processes. The potential of the time restricted real-time processes, that are active

in all the data collection phases of the orientation routines and in all the compilation routines will depend directly on the time available for computations. If one assumes a hypothetical primitive structure in which the dedicated computer has to perform all the controls for all of the feed-back loops and all the related housekeeping routines it is obvious that very little time remains for the performance of "useful" computations. In such a configuration, there will only be time for the implementation of very simple algorithms. The ratio between the time needed for the control and housekeeping routines in one cycle of the real-time program and the maximal allowable time for one cycle of the real-time program may be a good overall estimator of the structural characteristics of the interface and the feed-back controls. In the light of this simple example it is easy to grasp the meaning and the importance of the preferred structural characteristics presented in the following lines.

The feed-back control loops of the positioning and the measuring devices should be autonomous minor control loops independent of the dedicated computer. Individual minor control loops will allow for rapid parallel computations for all the control functions and for the reduction of the delays. The dedicated computer has to calculate only the input coordinates and to transfer these into the minor loops. It is freed from any other operation concerning the servo control. The minor controls may be special purpose hardwired devices or microprocessors. The latter firmware devices offer more flexibility for the manipulation of control functions but are for the time being slower than the hardwired controls. In either case the minor control loops are transparent to the computer and to the programmer, since the control processes are not included into the basic real-time program. The dedicated computer time saved is used to advantage in programming and execution of real-time routines. It is evident that, in this configuration, all the minor loops can be treated as separate peripherals and that their numbers may vary according to the needs.

Each minor loop should have two registers (or comparable facility) with a sufficient number of bites to store the full value of the coordinates. One of them, the request register will normally be used for the input from the computer of the coordinate of the desired position of the photo-stage. The other, the status register, will contain the actual position of the stage. The input to the status register will normally be from the encoder. The difference between the contents of the two registers is the error signal. There should be a facility for reading from and writing into both of these registers by the computer.

Three registers for accumulation of pulses (as full numbers) from the operator's primary controls should be available, with a facility for reading from and writing into these registers. The contents of these registers will normally represent the model coordinates X, Y, Z.

To enable the instrument to function in the comparator mode (without software intervention) communication channels between the pulse generators of the X and Y operator's controls and the respective request registers of the minor control loops  $x_1$ ,  $x_2$ , and  $y_1$ ,  $y_2$  should be available. Selective activation (manual or by software) of communication with the minor loops of both stages or with only one of them should be made possible by a hardware facility (internal logic switches).

The other facilities that would complete the preferred structure of the interface are: a facility for selective software-controlled switching of

motors (power on-off), a facility for the software-controlled sensing of limit switches and other external switches and a facility for the random access of all the registers.

To these, a "mode selection" facility for the enhancement of orientation procedures should be added which would enable the operator to observe the model in the "plotter" mode (that is, under the control of the basic real-time program) and to perform parallax measurements in the "comparator" mode. A simple hardware-based solution for mode selection that allows not only for measurement of photo-coordinates but also for the computation of corrected orientation parameters and the display of the residuals and their standard deviation after each measurement, has been described in [Jaksic 1980]. That solution is completely independent of the software and an external switch is the only necessary control for the selection of mode by the operator.

In spite of the fact that all the described functions and structural characteristics of the interface may be implemented in different ways on different instruments a careful and systematic analysis, along the suggested lines, will permit a meaningful evaluation. This example illustrates quite well how an apparently complex structure may be quite easily understood on the basis of a logical synthesis of its properly defined elements. However a user who is interested in the evaluation of an interface just from the standpoint of a particular application, may, in accordance with the proposed hierarchical procedure, limit his evaluation to functions and parameters. Only in the case of missing functions would the user have to resort to analysis of related details and even then only to the extent of their influence on the specific application.

Computer and Computer Peripherals. The computer and its peripherals are the facilities for the performance of all the functions of the second group (see p.2) encompassing all the computations and data manipulation. These hardware facilities ultimately determine the potential and limitations of the whole analytical plotter system.

The parameters of major importance are: memory cycle times, memory capacity, word length, instruction execution times, addressing modes and transfer rates between the computer and the peripherals. The parameters of the majority of available minicomputers match comfortably the performance criteria for dedicated computers of analytical plotters (except for the 16 bit word length). The actual testing procedures and diagnostic programs for their execution are supplied by the computer manufacturers.

Several structural characteristics related to the internal structure of the computer are of special interest when evaluating the capacity for the performance of real-time operations of an analytical plotter and the organization of functions in the interface. The hardware double precision floating point processor will assure a sufficiently short execution times for the real-time programs that are written in higher languages, and expedite the execution of all other programs. The type of memory will define the memory cycle times. If shorter cycle times are required the core memory may be replaced, for example, by bipolar memory. This will shorten the memory cycle times by about three times. The memory management unit will allow for memory extension and furnish the memory protection and relocation facility for a multi-user, multi-programming software operating system. The multi-level automatic priority interrupt system will permit a more flexible and versatile use of the interface.

The structural characteristics related to the choice and configuration of peripherals is also of interest. Evidently these characteristics may be altered at will by changing the number and type of peripherals according to need. The question of minimal configuration belongs into this category. It is worth noting that even in minimal configurations of peripherals, two disks with exchangeable cartridges (or their equivalent) should be retained since it offers a number of distinct advantages in normal production and especially in program development [Jaksic 1978].

It is evident that one cannot expect all the users to be fully versed in all the details about the properties of computers and peripherals. After all that is the duty of the designers and the manufacturers of the instruments. But in order to enable the user to prepare his specifications and to evaluate the dedicated computers and their peripherals in respect to his needs the most significant parameters should be tabulated and the most important structural characteristics should be explained along the lines sketched in this example. In this way the user may at least distinguish the most critical parameters and structural characteristics and make a rational evaluation of these components on the most general hierarchical level.

### Software

The hardware is the physical framework of the system that incorporates the facilities for the performance of functions. The software with the underlying algorithms implements the functions and organizes them into a meaningful dynamic process. Like the hardware the software can be subdivided into two qualitatively different evaluation groups: The software operating systems and the application software.

Software Operating Systems. The operating systems supplied by the computer manufacturers provide the facilities for the development and execution of programs written for a particular application. They are designed as single-user or time-sharing systems for real-time or batch processing. Most of them support higher languages. Some of them support only the execution of application programs that were developed with the aid of another compatible operating system.

The evaluation and choice of a software operating system will depend mainly on the intended use of the instrument (as a stand-alone system or as a component of a larger information system) and whether the user intends to develop his own application programs or execute only the application programs supplied by the manufacturer.

Application Software. The functions performed by the application software may be classified on several levels. On the most general level the functions are: communication with the positioning devices and the operator's commands and conventional processing and manipulation of data. Each of the real-time routines would comprise both groups of functions, while the routines that do not involve dynamic processes would comprise only the second group of functions. On the next level the functions can be related to the performance of well-defined photogrammetric processes. In this case the application programs can be classified into three major groups: orientation programs, compilation programs and support programs. The first group consists of routines such as inner orientation, relative orientation, model restoration. The second is concerned with the collection and processing of data from oriented models such as line digitizing, digital

terrain model generation, editing, graphical plotting. The third group is concerned with back-up operations such as system calibration, diagnostics, control file manipulation. (The application programs may be grouped into separate packages residing, for example, on separate discs such as a basic software package for aerial frame cameras, an on-line analytical triangulation package, a close-range package. Each of these will have groups of programs corresponding to the three major groups mentioned above).

A truly meaningful evaluation could be conducted only on the lowest level of this classification. For example, after determining that the group of orientation programs has a particular routine for relative orientation one can analyze the available functions (e.g. mode selection, automatic positioning of the measuring mark in predetermined patterns, deletion, addition, and replacement of measurements) and the constraints (e.g. maximal number of parallax measurements accepted by the adjustment routines). A detailed example of check-out procedures for this case is given in [Jaksic 1978].

The complexity of the evaluation of the application software already on the functional level is evident from the number, variety and virtual openness of programs. The evaluation on this level would suffice for the user who is not interested in program development. The evaluation procedures would consist of systematic checking of all the available routines using one or several pairs of photographs.

The parameters are, in essence, the execution times of the routines which can be determined by the computer clock. The flexibility, convenience of operation and other properties of a qualitative nature can be evaluated in conjunction with the check-out procedures of the functional characteristics.

The users intending to develop their own application software by modifying the routines existing in the package supplied by the manufacturer or by adding to it new routines will have to examine and evaluate the structural characteristics of the software. These characteristics are dependent on the design of the software, on the choice and implementation of the algorithms and on the structural characteristics of the hardware (in particular the interface). The main criterion that will indicate the relative ease of extension and modification of software is simplicity. Simplicity in this context means that the design of the software was based on the successive functional decomposition of programs into highly independent modules which can be individually compiled and called by any other module in the program. In FORTRAN, the modules are equivalent to subroutines. It is of interest to note that for the communication with the positioning devices and the operator's commands only six modules (macro-commands) will suffice for most versatile and flexible communications, in interfaces fulfilling the conditions described in this paper. These modules are independent of the geometry of the images [Jaksic 1980]. Another criterion is the type of interconnection between the subroutines. The fewer and simpler the interconnections the easier it is to understand or modify each subroutine without reference to, or effect on, other subroutines. It is evident that full documentation of the software and the hardware, including the listings of all the programs in source code, as well as the full description of the algorithms, is required for the evaluation of the application software on the structural level.

## CONCLUDING REMARKS

The hierarchically arranged evaluation sets, accompanied by the information on testing and check-out procedures and the information on the functional and structural characteristics of the hardware and the software represent a logical foundation for a system of evaluation of analytical plotters. If established along the lines discussed in this paper, they would provide the necessary input to a more comprehensive system that is being developed by the W.G. II/1 and at the same time satisfy an immediate practical and educational need by enabling a potential user to define his own specifications and procedures for the evaluation of analytical plotters and by providing the practicing photogrammetrist with a better insight and understanding of analytical instruments.

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