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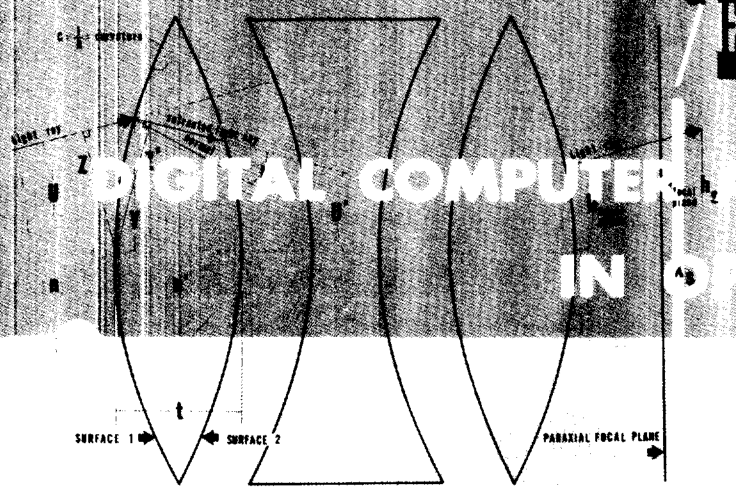
DIGITAL COMPUTER AIDS IN OPTICAL SYSTEMS DESIGN



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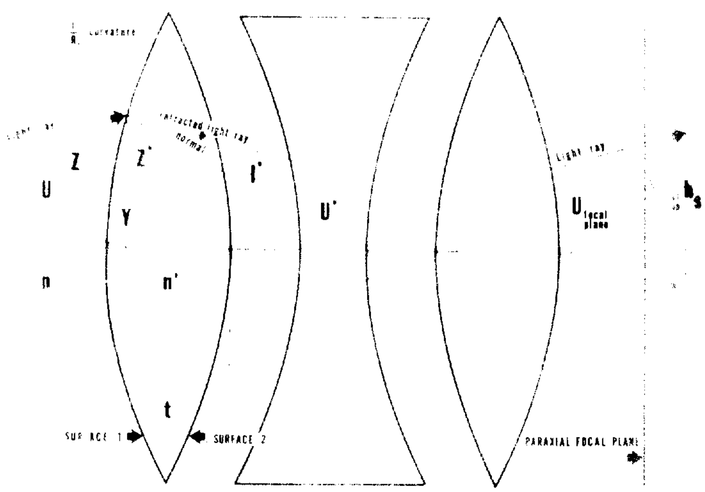

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Common to the successful solving of practically all design problems in the development of today's highly complex physical systems is the mass of computations that must be continually processed as the work progresses.

How well this load of computation is managed may well be the determining factor in the profit or loss aspects of a new development; at the least, it strongly influences the degree of precision attained in the final product.

The formulation of the basic approach, the selection of the appropriate theories and concepts, the garnering of the necessary data, and the establishment of the correct design procedures, these are all matters within the technical control of the design engineer.

But the rapid and accurate evaluation of mathematics that represent the system's performance is not. For this, the design engineer today is dependent on the extent and appropriateness of the computing and calculating equipment that is available to service him at the right time and at the right place for maximum speed in the handling of this mathematical load.

Mathematical evaluations on what any system will accomplish when it is built is called "proving out" the design philosophy. And unless continuation of the design approach can be maintained by frequent mathematical evaluations accomplished quickly, it will either delay final production of the system or waste a great deal of the design group's time – a serious cost penalty in today's era of "profit-squeezing." Design complexity, with its associated volume of mathematical problem solving and performance prediction, is especially prevalent in the field of advanced optics.

Diagram (above) illustrates parameters involved in mathematical representation of path of light ray through optical systems. System performance is measured in terms of aberrations which are deviations of actual image from image derived assuming perfect lenses.

In optical system development, the mathematics employed actually predict the performance of the lenses and lens systems in terms of the deviations of light rays passing through the system from those optical paths that would give the desired object-image relationship.

These actual deviations from the theoretically required paths are imposed by the physical limitations of optical materials. Also, there exists always some finite difference between the nature of the point-source world and physical reality.

This relationship frequently imposes severe problems and involved calculations in optical design because the product of these deviations is the difference between the object as considered by the optical system and the image actually produced by the system.

The difference between the image and the object are grouped under such nomenclature as focus, resolution, depth of field, and other representative optical performance parameters.

No one has ever constructed a perfect lens system. This is a physical impossibility. Fortunately though, it is possible to accurately predict what degree of imperfection any given system will have.

But this process of predicting lens system performance is highly complex, and its solutions require not only long but also tedious mathematical calculations. The extent of the mathematical labor borders on the fantastic and can frequently price a system right out of the realm of practicality, certainly remove it from a competitive cost range.

The length and complexity of the mathematics required can rapidly be appreciated by considering that, prior to the advent of electronic computing methods, a competent lens designer often spent two or more years developing and perfecting a lens system of average complexity. Now, with the rapid advances in the field of optics, manual calculations by a designer could take a lifetime.

The majority of the designer's calculating time is not necessarily spent in formulating the basic system design. In most instances, he has to crank through the arithmetic involved in determining the effects of various adjustments in the component characteristics of the overall system. This means that, whenever he substitutes one component for a more suitable lens part, he has to recalculate these changes and how they effect the overall system.

optical firms and computers

Before electro-mechanical desk calculators first came along, the designer would spend years calculating any given project. The new calculators reduced the figure to months of computing time. But even this considerable

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reduction left the overall cost in time too heavily balanced in favor of essential computing time.

Although the later developed electronic computers are now frequently applied in the more complex segments of general industry, their use by optical firms has been relatively rare.

This lack of utilization might possibly be explained by the fact that, although optical manufacturers have had very definite need for their own computers, the initial cost of computing systems in relation to the potential sales volume of optical systems was difficult to justify by cost-conscious management.

On the other hand, a management team in the optical industry, aware of all contributing phases of their industry's problems, needs to balance a considerable first financial outlay against direct savings in design labor costs and indirect saving resulting from more rapid completion of final deliveries of the systems.

In a great many cases it has been proven that the introduction of fully electronic computers greatly reduced the amount of time spent in optical system development and changed the status of optical designers from arithmetical monitors to creative engineers.

Under the regime of the electronic computer, calculations as well as evaluations of the complex mathematical representations of optical system performance requires not months, but minutes, and more often seconds.

To the casual observer the mathematics predicting the performance of a single lens or the composite of lenses in a multi-lens optical system might seem rather elementary in comparison to the highly complex forms in use in today's technology. And, no optical designer would take issue with this observation. However, it is not the degree of mathematical sophistication involved, but the sheer weight of the computational burden that has turned the optical designer to the use of digital computers.

This mass of mathematical labor is the result of optical design being more of an art than science. While the relationships between the behavior of light rays and the characteristics of various media are exactly bound by unequivocal equations, the utilization of these relationships to produce high performance optical systems depends to a major degree on the judgement, experience and patience of the optical designer.

The various optical aberrations that constitute the deviation of the actual image prodnced from that produced by a theoretically perfect lens system cannot be singled out one by one and corrected without certain penalties in other aspects of system performance. This interaction between the several forms of aberrations require that optical designers operate in a constant state of compromise to arrive at the 'optimum' design.

This necessity for compromising advantages and weighing disadvantages sets the requirements for the ability of the designer to follow very carefully the performance trends of the system as shown by the computations. On the basis of the calculations, complemented by his experience and design judgement, the designer must make those interacting changes and adjustments in lens configuration, material, and system concept that will eventually result in satisfactory system performance.

This cut-and-try procedure is as old as optical system design, but at least relief from the drudgery of the computations has been provided by the digital computer.

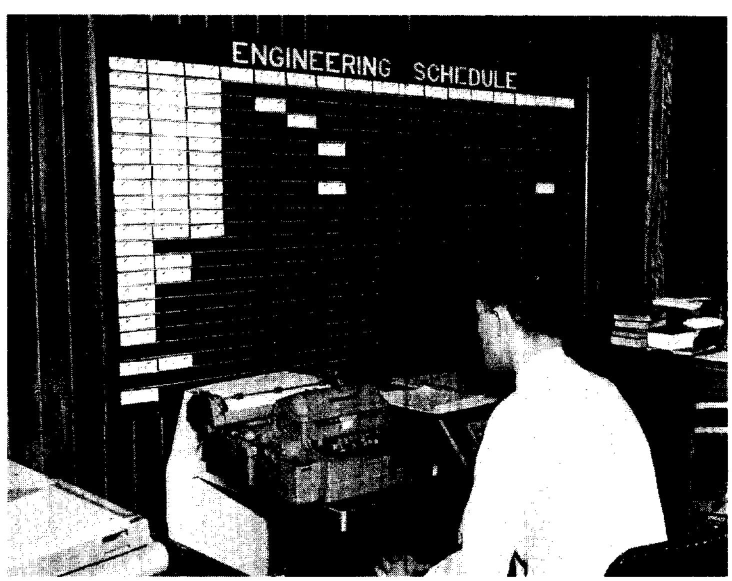
optical mathematics

The figure on page 42 is a functional diagram of the relationship between light rays and optical surfaces that form the basis of optical system design. This interaction and its associated mathematics must be investigated at each optical surface of the system and for a large enough assortment of light rays from various portions of the object to give a proper evaluation of the system performance. Opening and surface equations would express the relationships at the first surface. Transfer equations would relate the results of the first surface effects of the second surface where the surface equations must be applied again. Closing equations would establish the coordinates of the light ray as it reaches its focal point at the end of the system in terms of height above the optical axis and distance from the theoretical focal plane.

The final coordinates of the ray and the intermediate orientations are exact traces of the ray's path through the system. The deviations of this path from the path predicted by assuming perfect lens performance are a measure of the optical system's performance.

The final design of a lens system requires the thorough investigation of system performance by means of this

Royal McBee's LGP-30 desk-sized digital computer is now operating in the design department of Pacific Optical Corporation. The computer's flexibility and memory capacity make it well suited for the field of optical systems design, according to Pacific officials.



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exact ray trace method. As many as thirty rays testing the performance of various portions of the lens surfaces must be carried surface-by-surface through the system. The lens designer observes the system performance in terms of the ray orientation and distribution, and makes adjustments and modifications required to optimize the system.

Fortunately, the nature of optical aberrations is such that they may be pitted against each other to achieve overall improvements. That is, carefully chosen use of certain aberrations in some lenses may result in a countering of the aberrations resulting from other lenses to the end that the final overall system aberration is much smaller than the individual lens contributions.

This portion of the design procedure places the greater portion of responsibility for success on the designer's mastery of the "art." His ability to recognize the nature of the aberration, his knowledge of the most efficient corrective action, and his appreciation of the effect of the corrective action on various other system parameters, marks the difference between success and failure of the design. It is in this area of the design effort that the digital computer, by furnishing the designer with rapid evaluations of the effects of his design judgement, proves most valuable.

two design aids

To permit rough estimates of system performance during the preliminary design stages, optical designers employ approximations to the ray trace equations which provide reasonable evaluation of the third order aberrations and overall system performance. The usual procedure is for the designer to prepare, on the basis of past experience and theoretical performance calculations, the complex of lenses and optical surfaces he deems necessary to perform the required optical task.

Once the basic system has been established the third order aberrations are computed. At Pacific Optical, the LGP-30, purchased from the Royal McBee Corp , has been programmed to perform this series of computations. The capability of the program is such that systems consisting of as many as forty optical surfaces may be analyzed.

To use the computer, the designer feeds in the curvature, thickness, and index of refraction associated with each surface of the system. The output of the computer consists of the following aberrations: spherical, coma, astigmatism, distortion, transverse longitudinal color, transverse oblique color, and Petzval curvature.

These values are printed out in terms of the contributions of each surface, and the total value of each form of aberration is also printed. Plotting these values permits the designer to re-evaluate the performance of the system and begin the series of modifications that will lead to the final design.

Previously, the majority of design work was done using the third order aberrations, except for the very final system modifications, since the amount of computation was drastically reduced in comparison to the exact ray trace procedure. However, the utilization of the LGP-30 has permitted more frequent application of the ray trace technique. The entire ray trace procedure has been programmed on the LGP-30.

As in the programming of the third order aberrations, forty optical surfaces may be considered, and the inputs of curvature, thickness, and index of refraction associated with the several surfaces are all that are required. Computer output consists of Y, sin I, and sin U, at each surface plus values of Y, U, h_s, and X_s, at the focal plane.

Consideration of the capabilities of digital computers in optical design problems have led to the concept of utilizing the computer as a means of accelerating the optimization process. Under the proposed system the basic optical system would be established and the corresponding sur face data fed to the computer. A suitable criterion for optimal system performance would be established as the computer objectives. A program would be proposed permitting the computer to make adjustments in the characteristics of the surfaces on the basis of systematic trial and error operations.

Pacific Optical Corporation is devoting considerable effort in the development of such a computerized design program. In fact, the anticipation of the long range necessity for and advantages of such a program had considerable weight in making the choice of computers be purchased. The flexibility and storage capabilities of the LGP-30 make it suited for application to these computing concepts, according to Pacific Optical officials.

In considering any segment of our rapidly advancing technology, no part can be isolated from the whole. Every science today is being buffeted and shaped by the needs and demands of other sciences.

Our recent leap into space with missiles and satellites has loosed a flood of demands for more precise and elaborate optical systems for visual tracking, astranavigation.

The streamlining of industrial manufacturing is opening a broad market for optical measuring techniques yielding increased resolution in process control systems.

Television is impatiently awaiting improved camera lenses, motion pictures are desparately searching for better depth dimension effects, and the progress of aerial photo reconnaissance and mapping in three dimensions is hungry for improved equipment.

Nor is the matter entirely one of merely broadening and refining the product Along with expanding applications has come a compacting of the time with which these new demands for optical equipment must be satisfied.

On both of these counts, broadened application and sharply constricted delivery schedules, the in-plant, readily available computer has become inevitable if optical systems manufacturers are to meet their responsibilities in the years ahead.

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