A Computerized Technique for Mission Profile Design Analysis

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A working computer simulation program has been developed to analyze several interrelated performance variables, which are functions of a common set of independent parameters. Performance values are determined by several performance modules that are linked through an executive routine to a constrained parameter optimization algorithm. This simulation technique has been applied to the problem of obtaining an Earth orbital mission profile that satisfies specified mission, spacecraft, and subsystems equality and inequality constraints and optimizes a weighted linear combination of the performance variables. This technique is more efficient than procedures now in use and provides extensive qualitative data to support results.

Introduction

IN any design problem the normal sequence of events is to determine the objectives, establish the design specifications or constraints, trade off alternative concepts, and establish an acceptable design. For reasonable constraints this process can yield as many different acceptable designs as there are designers, and as many different optimum designs as there are criteria for measuring performance, e.g., weight, cost, size, etc. The design specifications are often so restrictive that the preliminary design goal is simply to define any design which meets these requirements. Design improvements are then made by small variations to design parameters in order to improve one or more of the most important performance measures. In mathematical programming terminology, the process of determining an acceptable design is referred to as "targeting" and the process of determining the best design of the acceptable designs is "optimization." This paper presents the development and application of a computer Program for Optimum Profile Selection (POPS) of an Earth orbital mission. The greatest obstacle in developing such a program is the determination of a quantitative criterion for measuring the degree of optimality of the profile, which is a function of several performance variables. That is, the relative importance of the different performance measurements require subjective judgment on the part of the designer because they are usually in different units and cannot be combined directly. In this model the relative importance (weights) of the performance measurements is supplied by the user in accordance with his interpretation of the mission objectives. The application of the model shows that the capability to obtain a targeted solution, which satisfies all of the constraints for any set of performance weights, is of primary importance for preliminary mission profile design. That is, an optimum solution, for any set of the somewhat subjective weights, is usually not much different from a targeted solution. The generation and presentation of sensitivity information, which relates performance variables, profile parameters, constraints, and weights, provides a numerical feel for the interrelationships of the problem.

Mission Profile Design

Design of a spacecraft mission profile requires selection of the best or acceptable values for such items as final orbit elements, transfer orbit elements, and launch date. These items are referred to as profile parameters and should be selected in such a way that mission objectives and requirements are met, relevant hardware constraints are not exceeded, and system performance is maximized. Ensuring that this occurs in a spacecraft project engineering organization requires integration of several systems analysis disciplines such as power, thermal, sensor performance, orbital mechanics, etc. Usually several analysis iteration cycles (Fig. 1) must be performed to determine the best profile design. In the preliminary phase of mission design, all of these analysis interfaces result in either an expensive and time-consuming "first cut" mission profile with eleborate supporting rationale, or a "broad brush" approach, which may ignore some effects and interactions and, thereby, arrive at a nonoptimum result. An alternative approach to preliminary mission profile design is to couple a targeting-optimization algorithm with a combination of parametric systems performance data and simplified performance models, to generate an optimum mission profile, and produce sufficient sensitivity information to understand the results. This approach to mission design, when computerized, enables a systems analysis engineer, with the aid of a computer programming assistant, to design a mission profile and generate the required supporting information.

The importance of this type of automated approach to mission design will be realized much more on future missions with the advent of the versatile Space Shuttle and the Space Tug. Most of the current Earth orbital missions involve a single spacecraft and a single or predominant objective. For these types of missions, mission profile design is usually straightforward and requires a minimal number of iterations. A Shuttle or a Shuttle/Tug combination has the capability of delivering and returning multiple spacecraft and/or experiment packages, which may require different orbits, phasing orbits, rendezvous, and specific ground track requirements in a single mission. These complications plus the large quantity of payload candidates existing in the Shuttle mission model make it highly desirable to develop automated computer tools to aid in mission design for the Shuttle era.

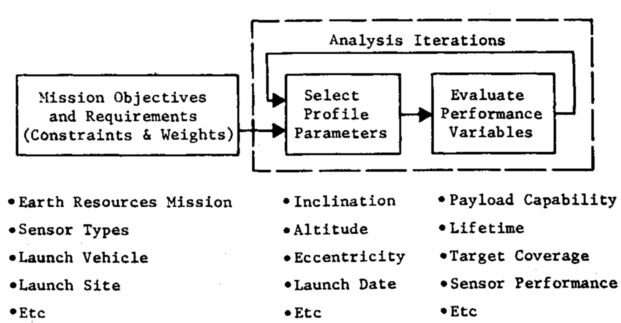

Fig. 1 Mission profile design iteration process.

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Technique

The automated approach to preliminary mission profile design must meet several requirements to be effective. These requirements derive from the nature of the design cycle and demand that the computer program be flexible and modular to accommodate changes in design requirements and constraints.

To allow the computer program to adapt to varied problems, the technique must accept any performance variables and any profile parameters, provided that some functional relationship exists. The purpose of the design analysis, from preliminary design at one extreme to operational verification at the other, is to determine the accuracy requirements and, subsequently, the complexity of these relationships that will provide an acceptable level of confidence in the solution. The program must contain the capability to include any reasonable level of accuracy or complexity in the parametric relationships. The program must be able to include any performance variable required for a particular analysis. The user should be able to assign his own code names to variables for easy computer output understanding. During the first design cycles, the primary mission objectives are investigated for feasibility within the system capabilities. At this level, determination of the important parameters is desired and in all probability simple trend data will provide the necessary accuracy. After the important parameters are determined, the following design cycles may require more accuracy for a better evaluation of mission performance and for investigation of secondary mission objectives. This can usually be achieved by using simple to moderately complex analytical expressions or algorithms which have usually already been computerized by the subsystem groups into simple routines with simple input and output. An automated profile design program should be capable of using either tabular results from these existing routines or accepting the routine itself as a modular subroutine to the program. The final design stages usually include very complex analytical techniques which are much too expensive and cumbersome to be considered as internal routines. The parametric output of such routines must be tabulated or a curve fit made to provide performance information over the range of the profile parameters to be used by the program. Thus, three basic types of parametric data input are required during the design cycle: 1) tabular data, 2) simple analytical expressions, and 3) moderately complex analytical algorithms. All must be compatible with the program's input routines or internal structure.

Computer Program

The basic elements of the computer program for automated mission profile design are the input tabular parametric data, the internal routines to determine performance or performance models, the optimization algorithm and the control or supervisor routine. The over-all concept for such a program is presented in Fig. 2.

The supervisor provides the logic to handle the input and output and to numerically evaluate the performance variables given a profile parameter vector. To evaluate performance, the functional relationships must be recognized and the calculation sequence determined. An ordering process to handle the variable nesting conditions is set up and then used automatically by the program at each calculation step.

The technique for data input includes tape storage of the tabular parametric data. This will provide a data base from which the profile designer can draw. Data for various configurations, different assumptions, and different parameters can be stored and recalled, as required, by a simple flagging technique.

In addition to the tabular input, the capability to input coefficients to a simple general analytical expression is required. The expression allows a performance variable to be a function of up to two profile parameters with relationships including general polynomial, trigonometric and logarithmic expressions. The general form used was

$$\begin{aligned} F(X_1, X_2) = {} & C_1 + C_2X_1 + C_3X_1{}^2 + C_4X_1{}^3 + C_5X_1{}^4 \\ & + C_6 \exp(C_7X_1) + C_8 \ln(C_9X_1) \\ & + C_{10} \sin(C_{11}X_1 + C_{12}) + C_{13}X_2 + C_{14}X_2{}^2 \\ & + C_{15}X_2{}^3 + C_{16}X_2{}^4 + C_{17} \exp(C_{18}X_2) \\ & + C_{19} \ln(C_{20}X_2) + C_{21} \sin(C_{22}X_2 + C_{23}) \end{aligned} \quad (1)$$

F = performance functions, X_1, X_2 = two different profile parameters, and $C_1 \ldots C_{23}$ = constant coefficients supplied as input by the user. Additional functions and cross terms can be easily added to accommodate special cases.

In order to minimize table lookup times, the tabular data were restricted to either monovariate or bivariate. To provide relationships among more than two variables, a product and sum technique was used to combine tabular and simple expression information. As an example, this technique is useful when a performance variable is a function of three profile parameters, two of which are tabularized and the third is a scale factor. To accommodate most encountered relationships, the general expression for the performance variable, P, defined by

$$P = \prod_{i=1}^{4} F_i(X_j, X_k) + \sum_{i=5}^{6} F_i(X_l, X_m) \quad (2)$$

was found to be satisfactory. Each bivariate relationship described in Eq. (2) can be either a table or a simple analytic expression, as required. The program, once informed of the relationships and the source of data, was designed to handle the calculations and interpolations without further supervision. This was accomplished through the use of flags, which are input with the data.

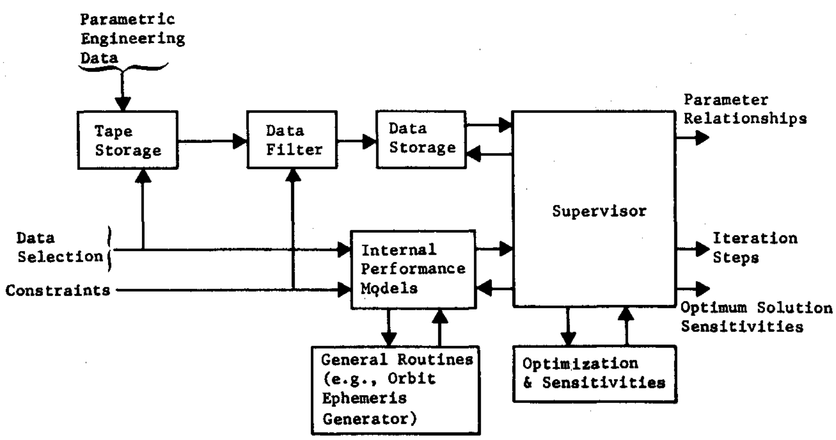

Fig. 2 Computer program flow.

M STAT	*Internal model to determine time over tracking stations.*
M RESL	*Internal model to determine sensor resolution.*
M TØS	*Internal model to determine earth resources time over site.*
M MNVR	*Internal model to determine weight losses due to orbit maneuvers.*
M PCS1	*Tabular data for payload capability into the insertion orbit for Shuttle.*
C LES	*List of constraints common to low earth Shuttle missions.*

Fig. 3 Input codes for problem formulation.

The program was designed to minimize the user effort required to establish and change a design problem. In particular, each tabular or analytical expression stored on tape and each internal data model are assigned an identification code. When a problem is formed from the available data and models, only the identification codes are referred to for assembly. If a model contains more performance variables than necessary they can simply be ignored. This technique eliminates much of the input and coding error usually encountered when integrating several routines and tables of data. An example of the input and resultant problem assembly is presented in Figs. 3 and 4. To further save on core storage requirements a data filtering technique is used. All of the variables used in the formulation of a problem have useful ranges, available ranges, or even constraints. The program scans all of these values, if they exist, and determines the narrowest range. This guarantees that data will be available throughout the range. For example, a payload capability table may have a range of circular insertion altitudes between 50 and 300 naut miles, while the orbit lifetime model used may only be valid from 120 to 500 naut miles. Since both payload capability and lifetime must be calculated to determined optimum performance, the intersection of the two ranges cannot be exceeded, i.e., 120 to 300 naut miles. The payload data outside of this range are not required for this problem and are not stored in the core. Each of the tables used is filtered in a similar manner. Because of the potentially large quantity of tabular data used by this program, an interpolation point memory scheme was incorporated that significantly reduced the computer time required to perform table lookup functions. Performance models can be used to compute one or several performance variables. The information flow for a typical model is shown in Fig. 5. If these performance variables are to be defined by parametric data the supervisor goes to a general routine, defined by Eq. (2), instead of a model. The optimization algorithm is used to

Parameter Relationship Matrix

Performance Variables (*User Defined Performance Variable Codes*)

Profile Parameters	TØS	TØSSUN	TØSBET	ENØCLD	DIFLØN	PCI	TØSTAT	GRPTS	GRR	PCF	TTØR
CIRALT	X	X	X	X	X	X	X			X	X
INC	X	X	X	X		X	X				
LDATE		X	X	X							
FAZALT	X	X	X	X	X		X			X	X
FAZREV	X	X	X	X	X		X			X	X
FINALT	X	X	X	X	X		X	X	X	X	X
PCI										P	P

User Defined Profile Parameters Codes (row labels); *Functional Dependence* (matrix entries)

Fig. 4 Derived functional relationship matrix.

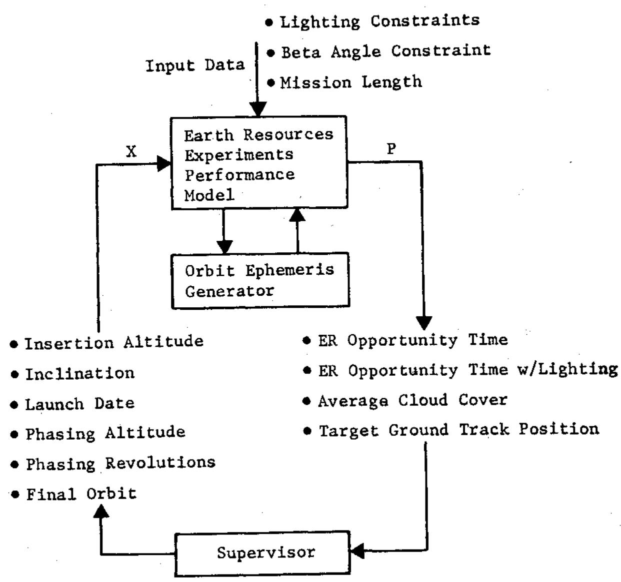

Fig. 5 Interfaces of a typical Earth resources model.

determine the set of profile parameter values that optimize a score based on performance without violating constraints on either the profile parameters or the performance variables. Because the requirements for preliminary mission design tend to be soft and the relative importance of different objectives are subjective, it is important that visibility and a variety of sensitivities be provided to aid the designer in his decisions.

Unless the mission under consideration has only one objective, expressible in terms of one performance variable, the score will need to consider the combination of several performance variables each with some measure of importance. Also, since different performance variables can have different units and the degree of optimality of each variable is not necessarily proportioned to its numerical value, the performance variables must be normalized. To accomplish this a score, S_i, calculated for each performance variable, P_i, relative to the performance value at the initial guess, $P_1{}^0$

$$S_i = P_i / P_i{}^0 \tag{3}$$

With the total score S, a linear combination of the S_i's based on relative weights, W_i assigned by the user

$$S = \sum W_i S_i \tag{4}$$

For the solution of the constrained optimization problem, an existing parameter optimization computer routine was used that is a numerical iteration technique known as the Projected Gradient Method (Ref. 1). For a totally unconstrained problem the optimization algorithm operates in a mode similar to the steepest descent method. When constraints are encountered, a net cost technique is used. Experience with several optimization algorithms indicated that for this general type of constrained nonlinear problem the Projected Gradient Method is the most stable and efficient algorithm available. In addition, it was easily adapted for use with the various input forms encountered and can be used with a minimum of experience with optimization programs.

The iteration method used for solving the constrained optimization problem is summarized in three steps. First, provide an initial guess that will satisfy as many constraints as possible but is not necessarily optimum. Second, determine a correction step to improve the total score, S, and to satisfy the constraints. Third, test for convergence and iterate until S is maximized within a specified tolerance.

The sensitivities information computed for evaluation by the analyst includes: 1) the change in performance with respect to changes in the profile parameters ($\partial P_i/\partial X_j$), which are the standard sensitivities used by the optimization algorithm; 2) the ratio of the changes in performance due to changes in the weighting ($\partial P_i/\partial W_j$), which are calculated from the above sensitivities and the computed change in direction of search for a change in weighting; 3) the change in the performance and the profile parameters due to changes in any tight constraints at the solution ($\partial P_i/\partial C_j$) and $\partial X_i/\partial C_j$), which are determined from the new gradient direction obtained when constraint C_j is relaxed. These sensitivities are all computed by closed form expressions (see Ref. 2 for derivations) at each iteration step and provide an accurate accounting of how the targeting-optimization algorithm arrives at the solution, and how the solution relates to the input constraints and objectives.

Sample Problem

As an example, a typical mission design problem was formulated and treated using this automated technique. Mission objectives and requirements were defined, then interpreted as performance variables and constraints, and finally weights were applied to the desired performance variables. The problem was then input to the program and various trade studies performed as in a real design problem. The primary mission objectives of this sample problem were selected as 1) gather Earth resources data over the USA during a 7-day mission, 2) find ground tracks that coincide with the ground tracks from a previous mission to control and verify data, and 3) use as many sensor systems as possible (maximize payload). The requirements follow: 1) The final orbit parameters would be 50° inclination with a 200-naut mile circular orbit altitude. These were the orbit parameters of the previous mission and so are required to satisfy the ground track objective. 2) The insertion orbit altitude will be 100 naut miles. 3) A single circular phasing orbit will be used. 4) Launch will be on July 3, 1975; the launch date selected was arbitrary, but at a time when good sunlight coverage of the USA could be obtained. 5) The angle between the Earth-sun line and the orbit plane during Earth resources passes should be less than 50° to satisfy thermal and electric power considerations.

Four performance variables were defined to satisfy the objectives of obtaining Earth resources data over the USA: TØS, the unconstrained time when the spacecraft's nadir point was over the USA; TØSSUN, and TØS when the sun elevation angle was between +10° and +60°; TØSBET, the TØS when the angle between the orbit plane and the Earth-sun line was less than 50°; and ENØCLD, the expected percent of cloud free conditions for the sunlit passes. DIFLØN was defined to satisfy the ground track objective and was equal to the error between the ground track of the orbit under consideration and the target ground track. The desire was for DIFLØN to be zero. To include as many sensor systems as possible, the payload capability to the final orbit, PCF, was used. To obtain PCF, the payload capability at insertion, PCI, is determined and then reduced by the amount of weight loss during the phasing orbit maneuvers. The amount of time of communications, TØSTAT, was determined as a performance, but was not weighted as were the two measures of sensor resolution, GRPTS and GRR. To help eliminate the possibility that much of the mission could be wasted during the phasing orbit, the time from initial orbit insertion to insertion into the final orbit, TTØR, was defined. The value used was actually the negative of the time because the program maximizes performance. In this way actual TTØR will be minimized. Performance variables were assigned weights as follows: TØS = 1, TØSSUN = 2, PCF = 3, and TTØR = 2.

These performance variables were modeled as a function of the following six profile parameters: CIRALT, the altitude of the initial circular orbit; INC, the orbit inclination; LDATE, the launch date; FAZALT, the altitude of the circular phasing orbit; FAZREV, the number of revolutions in the phasing orbit; and FINALT, the altitude of the final circular orbit.

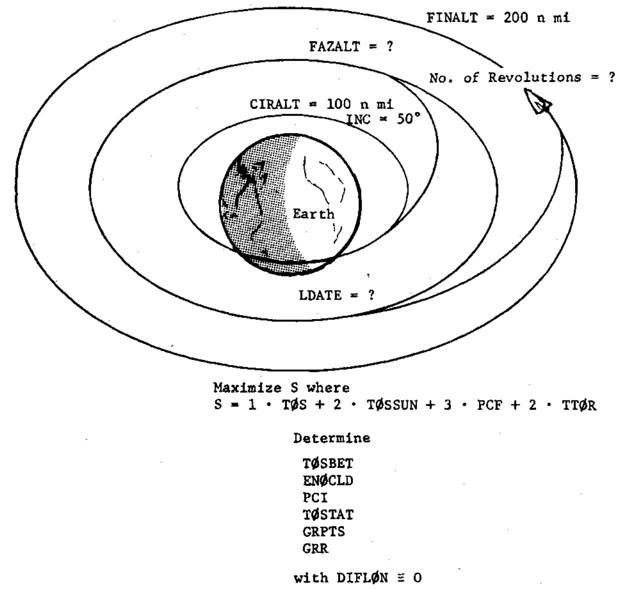

Fig. 6 Example problem.

To satisfy the orbit requirements, CIRALT was fixed at 100 naut miles, INC at 50°, and FINALT at 200 naut miles. Therefore, the profile parameters that were varied to obtain the optimum performance were LDATE, FAZALT and FAZREV. LDATE was constrained to July 3, 1975, FAZALT between 100 and 200 naut miles, and FAZREV between 0 and 16 rev.

The problem, then, was to determine the values of FAZALT, FAZREV and LDATE that would satisfy the DIFLØN constraint and maximize the overall sum of the weighted performances as depicted in Fig. 6. The program setup was accomplished as presented in Figs. 3 and 4. The initial guess and the resultant performance were determined through the appropriate models and tables and are presented in Table 1. The first step was to target the DIFLØN constraint. The result is shown in Table 2. The constraint on DIFLØN is

Table 1 Initial guess data

Initial profile parameter values			
CIRALT	=	1.00000000E+02	naut mile
INC	=	5.00000000E+01	deg
LDATE	=	1975.00000000E+00	CALDATE
FAZALT	=	1.50000000E+02	naut mile
FAZREV	=	8.00000005E+00	revs
FINALT	=	2.00000000E+02	naut mile
Initial performance			
TØS	=	2.56213127E+02	min
TØSSUN	=	2.29702025E+02	min
TØSBET	=	2.56213127E+02	min
ENØCLD	=	1.00000000E+02	percent
DIFLØN	=	−4.35663235E+00	deg
PCI	=	4.71000000E+04	lbs
TØSTAT	=	3.39626728E+02	min
GRPTS	=	1.21522310E+03	ft
GRR	=	3.82747432E+05	ft
PCF	=	4.59646990E+04	lbs
TTØR	=	−1.49803363E+01	hrs
Initial score			
1.00000000E+2			

Table 2 Target to DIFLØN on iteration 1

Iteration 1 profile parameter values			
CIRALT	=	1.00000000E+02	naut mile
INC	=	5.00000000E+01	deg
LDATE	=	1975.00000000E+00	CALDATE
FAZALT	=	1.08352031E+02	naut mile
FAZREV	=	8.99002192E+00	revs
FINALT	=	2.00000000E+02	naut mile
Iteration 1 performance			
TØS	=	2.49081996E+02	min
TØSSUN	=	2.21697457E+02	min
TØSBET	=	2.49081996E+02	min
ENØCLD	=	1.00000000E+02	percent
DIFLØN	=	−3.93946891E−02	deg
PCI	=	4.71000000E+04	lbs
TØSTAT	=	3.40147034E+02	min
GRPTS	=	1.21522310E+03	ft
GRR	=	3.82747432E+05	ft
PCF	=	4.59647271E+04	lbs
TTØR	=	−1.62195780E+01	hrs
Score		9.62652165E+01	

Table 3 Data at the solution

Iteration 6 profile parameter values			
CIRALT	=	1.00000000E+02	naut mile
INC	=	5.00000000E+01	deg
LDATE	=	1975.50027232E+00	CALDATE
FAZALT	=	1.00398883E+02	naut mile
FAZREV	=	8.62872710E+00	revs
FINALT	=	2.00000000E+02	naut mile
Iteration 6 performance			
TØS	=	2.49066249E+02	min
TØSSUN	=	2.49066249E+02	min
TØSBET	=	2.49066249E+02	min
ENØCLD	=	1.00000000E+02	percent
DIFLØN	=	2.91876177E−05	deg
PCI	=	4.71000000E+04	lbs
TØSTAT	=	3.35943325E+02	min
GRPTS	=	1.21522310E+03	ft
GRR	=	3.82747432E+05	ft
PCF	=	4.59647390E+04	lbs
TTØR	=	−1.56414135E+01	hrs
Score		1.00594516E+02	

essentially met but at the cost of the score. At this point, the algorithm began the optimization and after five more steps converged with the final result presented in Table 3. The final value of FAZALT was approximately equal to CIRALT which indicates that PCF was maximized when no phasing orbit was used and the revolutions needed to satisfy DIFLØN were completed in the initial orbit. A launch date was found that gave the maximum TØSSUN available, which was the entire time spent over the USA during the mission.

Other weighting values were used on this same problem which caused no change in the solution because of the constraints placed on DIFLØN and FAZALT. In this problem the targeting capability proved to be the dominant asset.

Conclusions

The completed program satisfied the requirements for preliminary mission profile design and at the same time appeared to be relatively fast. The program easily accommodated new problems and the targeting-optimization algorithm was stable and easy to follow. The sensitivity information provided an understanding of the formulated problem. Use of the program for preliminary design has been limited to date and new problems will be used to further test the technique. As the program was written to accommodate any functional relationship of any defined variables, it can conceivably be expanded to enter technical areas other than aerospace mission analysis.

References

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