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STANFORD UNIVERSITY

CENTER FOR SYSTEMS RESEARCH

Annual Progress Report on Guidance and Control of Flight Vehicles

Principal Investigators

Professor J. V. Breakwell
Professor A. E. Bryson, Jr. (Coordinating)
Professor G. F. Franklin

December 1971

Guidance and Control Laboratory

under

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on

GUIDANCE AND CONTROL OF FLIGHT VEHICLES

in the Departments of

Aeronautics and Astronautics, and Electrical Engineering

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This report summarizes progress during the past twelve months under a continuing research grant for the period beginning January 1971.

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RESEARCH RESULTS

A. Studies in Attitude Control and Orbital Rendezvous Supervised by Professor J. V. Breakwell

1. Attitude Control of a Halo Satellite (J. V. Carroll)

This research, completed in 1971, examined the stability of a dual-spin halo satellite in the presence of radiation pressure torques as well as gravity-gradient torques. An almost spherical exterior surface is assumed, either rotating or non-rotating, while the inertia tensor is assumed to be axially symmetric.

For a general non-symmetric non-spinning satellite, three-axis orientation may be controlled in the presence of radiation pressure torques by moving interior masses and hence also the location of the overall center of mass relative to the center of the exterior surface. Since no solar torque is obtained (to first order in the non-sphericity of the surface) about the sun direction, the time constant associated with such a control scheme is necessarily long.

The final draft of doctoral dissertation is nearing completion.

2. Minimum-Fuel Orbital Rendezvous between Neighboring Low Eccentricity Orbits (J. Jones)

A computer program has been completed which can obtain, generally by iteration, the minimum-fuel N-impulse rendezvous (within a given duration). The equations are linearized about the target orbit, if circular, or about a neighboring circular orbit, otherwise. This linearization should provide very nearly optimal policies in many realistic situations. At the same time, the linearized problem has the great merit that all locally optimal rendezvous strategies, whether unique or not, are globally optimal.

The iteration is started from the solution of a simpler rendezvous problem for which the solution is known. The simpler problems used are of two types, (i) the "transfer" problem, in which the "phase" in the final orbit is not specified, and (ii) the coplanar circle-to-circle rendezvous problem. In (i) the linearized analysis leads to three distinct types of strategy, one of which permits substantial freedom in the location of the impulses, and hence in the phase obtainable for the same fuel expenditure as in the transfer problem. If the desired phase is not within the range obtainable "for free," the program enters the iterative phase, where careful step-size control on the desired phase is combined with the possibility of increasing or decreasing the number of impulses in optimal fashion. For large desired phase change, starting type (ii) is preferable. As many as six impulses can be required, although five- and six-impulse situations are sufficiently rare that four-impulse (or less) sub-optimal strategies may be computed with negligible fuel cost.

RESEARCH RESULTS

B. Studies in Optimization, Estimation, Identification, and Control Supervised by Professor A. E. Bryson, Jr.

1. Estimation of the Local Attitude of Orbiting Spacecraft (W. Kortüm)

This work, completed in 1970, has been published in Automatica, Vol. 7, pp. 163-180, 1971, under the title above.

2. Optimum Three Dimensional Turns for a Supersonic Aircraft (J. K. Hedrick)

This work, also completed in 1970, has resulted in three published papers:

(i) "Minimum Time Turns for a Supersonic Airplane at Constant Attitude," Jour. Aircraft, Vol. 8, No. 3, March 1971, pp. 182-187;

(ii) "Three-Dimensional Minimum-Time Turns for a Supersonic Aircraft," Jour. Aircraft, Vol. 9, No. 2, February 1972, pp. 115-121;

(iii) "Three Dimensional Minimum-Fuel Turns for a Supersonic Aircraft," Jour. Aircraft, Vol. 9, No. 3, March 1972, pp. 223-229.

3. Square Root Filtering and Smoothing for Discrete Processes (P. G. Kaminski)

This work was completed in 1971 and published in SUDAAR Report No. 427, July 1971. A summary paper was published in IEEE Trans. on Auto. Control, Vol. AC-16, No. 6, December 1971, pp. 727-736, entitled "Discrete Square Root Filtering: A Survey of Current Techniques," by P. G. Kaminski, A. E. Bryson, Jr., and S. F. Schmidt.

The excellent numerical characteristics and reasonable computation requirements of the square root approach make it a viable alternative to the conventional Kalman filter in many applications, particularly when computer word length is limited, or the estimation problem is badly conditioned.

4. Combining VOR/DME Measurements with Air Data and with Inertial Data (J. C. Bobick--also supported by NSF traineeship and NASA Grant Ngr-05-020-431)

The first part of this work, dealing with air data, was presented at the AIAA Guidance, Control, and Flight Dynamics Conference, Hofstra University, August 1971, and is to be published in the Journal of Aircraft in June or July 1972 under the title "Improved Navigation by Combining VOR/DME Information and Air Data." A summary was given in last year's Progress Report.

The second part of Mr. Bobick's research deals with updating or aligning an inertial navigation system in flight using VOR/DME signals, and is summarized below:

The use of VOR/DME information with an INS has thus far been limited to the use of a DME/DME position fix to reset the position display (no filtering involved). This, of course, does not result in decreased velocity or platform attitude errors.

Assuming a locally-level, north-pointing stable platform, we have studied the possibility of using the information from one or two VOR/DME stations as inputs to a filter which estimates the errors in the inertial navigation system. The states are the easterly and northerly components of the position and velocity errors, the angles of rotation about the east, north, and vertical axes which relate the desired and actual orientations of the platform, a drift in each of the three gyros, an error in the east and north accelerometers, and a bias error in each VOR and each DME.

The estimates of the states determined by the filter can be used to torque the platform to its desired orientation, or, as long as the platform attitude errors remain small, we can simply compensate for them without realigning the platform. Using such a filter, we have determined the RMS errors in the estimates of position, velocity, and platform attitude (φ_E = tilt about east axis, φ_N = tilt about north axis, and φ_U = azimuth error) for a 30-minute flight using (a) one VOR/DME to update the INS, and (b) two DME's, to update the INS. The present method of ground alignment takes about 15 minutes with the final platform tilts, $(\varphi_E)_f$ and $(\varphi_N)_f$, equal to about 0.005 degrees and the final azimuth error, $(\varphi_U)_f$, equal to about 0.05 degrees. We conclude that the accuracy of in-flight alignment using two DME's is about the same as for ground alignment, whereas the accuracy of in-flight alignment using one VOR/DME is worse than ground alignment by a factor of 2 or 3.

Although the need for initial in-flight alignment of inertial systems onboard commercial aircraft is questionable, the in-flight re-alignment of the system before leaving the U. S. airspace on a trans-oceanic flight (e.g., from Los Angeles to London or Chicago to Hawaii) could result in significant improvements in navigational accuracy. Also, realignment of the system upon entering the U. S. airspace after a transoceanic flight could prove useful since the result would be accurate position, velocity, and attitude information in the terminal area.

We found that the suboptimal filter resulting when the gyro drifts, accelerometer errors, and DME biases are neglected, performed nearly optimally during the periods of time the filter operates (20 to 30 minutes). Hence, the results presented can be obtained by using an eighth order filter when using one VOR/DME or a seventh order filter when using two DME's to update an INS.

5. Optimum Inputs for Identification of Linear System Parameters (D. B. Reid--also supported by NASA Grant NgL-05-020-526)

A major portion of this study was completed in 1971. This included determining a suitable criterion for evaluating inputs and numerical solution of two aircraft identification problems. The criterion used was to maximize the trace of the information matrix for the parameters to be identified. The problems solved were (a) optimum elevator input to identify the pitching moment damping derivatives C_{m_q} and $C_{m_{\dot{\alpha}}}$ from pitch rate measurements, and (b) optimum aileron/rudder inputs to identify the yawing and rolling moment damping derivatives $C_{n_r}, C_{n_p}, C_{\ell_r}, C_{\ell_p}$ from yaw rate and roll rate measurements. All of these inputs were of the bang-bang type, so solutions required finding the switching times from maximum to minimum deflection, or vice-versa. A report is in preparation.

6. Guidance Logic for Orbit Transfer Using Low Thrust (L. J. Wood)

This study was nearly completed in 1971. The major new result is a guidance scheme for non-autonomous systems with open end time, with a detailed example.

Minimum-time low thrust orbit transfers were computed for a typical spacecraft from Earth to Mars and from Earth to Jupiter. Neighboring optimum feedback gains were determined for the minimum-time Mars transfer including a time-to-go logic for entering the gain tables and the nominal trajectory tables. This latter scheme was simulated on the computer and worked well even for very large initial errors (i.e., deviations from the optimum nominal path). To our knowledge, this is the first demonstration of a workable minimum-time guidance scheme for a non-linear system of this complexity.

An explanation was found for the unexpected retro-thrust period that occurs in the middle of interplanetary transfer path: low thrust achieves outward radial velocity partially by a radial component of thrust, but also by a tangential component to increase speed so that centrifugal force exceeds the sun's gravitational force. By the same token, to decrease radial velocity, a backward component of tangential thrust (retro-thrust) is used in the middle of the transfer path.

A report is in preparation.

7. Automatic Landing Logic for Aircraft (W. E. Holley)

This investigation has only begun. Preliminary work indicates that the use of integral control concepts and/or filters to estimate the wind velocities combined with quadratic synthesis techniques provides significant improvements in autoland accuracy in the presence of winds. Statistical wind models were studied in relation to the data available.

RESEARCH RESULTS

C. Studies in Identification
Supervised by Professor
G. F. Franklin

1. Identification of Linear System Parameters from EEG Signals (D. H. Utter)

The problem under investigation is to see if it is possible to identify parameters of a linear model of low order which will adequately describe the changes in the electroencephalograph process during anesthesia. The results of the investigation can be used in on-line identification of a parametric model for any stochastic process when only the output signal can be measured. We want to know what the important parameters are in terms of sampling rates, estimate accuracy, and the assumption of stationarity in making a low order model of a very complex process.

The particular problem arises from a study of the level of anesthesia in patients undergoing surgery. It has been observed that electroencephalograph (EEG) recordings of these patients usually exhibit the characteristics of a stationary stochastic process over short time periods, and their spectra show recognizable changes with changes in anesthesia conditions. One standard procedure for EEG monitoring has been to process the signals by spectral analysis. This method preserves all the information in the signal but produces a large number of parameters: the signal power at many discrete frequencies. So much information would be overwhelming to the busy anesthesiologist during surgical operations and very difficult to use in a control algorithm, should such be desirable. For these applications, a more meaningful procedure appears to be to represent the stochastic process by a parametric model consisting of a linear filter of low order driven by white noise with the EEG signal as the output.

For the identification, it is assumed that the white noise is normally distributed with unity variance. The filter output signal is measured at discrete time intervals of T seconds separation and stored as a finite-length sample of N data points. The parametric model is a linear difference equation representing the output at the i^{th} time point as given by Eq. (1):

$$y_i = -\sum_{j=1}^{n} a_j y_{i-j} + \sum_{j=0}^{n} b_j u_{i-j} \tag{1}$$

where u_i is the white noise input at the i^{th} time point. The coefficients a_j and b_j are the parameters to be identified. The index n is the assumed order of both the denominator and the numerator of the discrete filter function and is a parameter to be chosen in the identification algorithm.

Results to date indicate that the a_j coefficients can be estimated efficiently and quickly from an algorithm similar to one discussed by Zetterberg [1]. The estimate is asymptotically unbiased. It is derived using the fact that the expected value of the product of future noise input and present filter output is zero. If we multiply (1) by y_o and take expectations, then for $i > n$ the terms of u_k vanish. Thus the equations for $i = n+1,\ldots,m$ can be arranged in matrix form as Eq. (2):

$$\underline{r} = -R\underline{\hat{a}} \, . \tag{2}$$

Here $\underline{\hat{a}}$ is the n-vector of estimated a_j coefficients, $\underline{r}$ is a vector of $(m-n)$ autocorrelation coefficients such that $\underline{r} = (r_{n+1}, r_{n+2}, \ldots, r_m)^T$ with m a parameter $\geq 2n$ to be chosen later. The matrix R is comprised of $(m-n)$ rows and (n) columns of autocorrelation coefficients such that each row of Eq. (2) forms the Eq. (3):

$$r_k = -\sum_{i=1}^{n} r_{k-i}\hat{a}_i \, . \tag{3}$$

Equations (3) are the well known Yule-Walker equations for the given assumptions [2]. The autocorrelation coefficients, r_k are estimated from the sample of N points by Eq. (4):

$$\hat{r}_k = \frac{1}{N} \sum_{i=1}^{N-k} (y_i-\bar{y})(y_{i+k}-\bar{y}) \tag{4}$$

where $\bar{y}$ is the sample mean. The constant 1/N is used rather than 1/N-k , the constant used in the standard formula for computing autocorrelation coefficients from a finite-length sample, and is equivalent to using a weighting factor of N-k/N in order to give less importance to the correlations of greatest time shifts. The formula may also be seen as a "window" on the data for estimation of r_k . Using (4) in (2), the equations are solved by standard least squares methods to give the characteristic equation coefficients of the model.

The $\hat{\underline{a}}$ are converted into z-plane (sampled data) roots z_i by solving for the complex roots of the polynomial equation

$$1 + \sum_{i=1}^{n} \hat{a}_i z^{-i} = 0 . \tag{5}$$

Finally, in order to relate the parameters to known spectral features, the equivalent s-plane (continuous) roots of the denominator are computed by Eq. (6) for real roots and Eqs. (7) and (8) for complex roots:

$$s_i = \frac{1}{T} \ell n\ z_i \quad , \quad z_i \ \text{real} \tag{6}$$

$$\mathrm{Re}(s_i) = \frac{1}{T} \ell n\ |z| \tag{7}$$

$$\mathrm{Im}(s_i) = \frac{1}{T} \arctan \left[\frac{\mathrm{Im}(z_i)}{\mathrm{Re}(z_i)} \right] . \tag{8}$$

This algorithm for estimating the a_j coefficients has been applied to steady-state EEG data from different patients at various levels of anesthesia, as identified by Dr. J. Bimar, an anesthesiologist who specializes in EEG monitoring. The data samples contained $N = 1024$ data points at intervals of $T = 1/64$ seconds. Several values of the parameters n and m were tried. Visually consistent results were obtained for $n = 5$ and $m = 200$. Figure 1 shows the s-plane root locations obtained from 17 samples from a single record of steady-state data at a moderate anesthesia level designated by Dr. Bimar as MAC1. Typically, three of the five roots identified are plotted for each sample: one real root and two upper-half-plane complex roots. Figure 2 illustrates the s-plane root locations identified from 16 samples of another record at a deeper anesthesia level designated MAC2 by Dr. Bimar. In each figure the lower of the two complex roots is plotted as "+" while the real root and the higher frequency complex root are both indicated by "x". The fact that these roots cluster is taken as a measure of the stability of the identification technique. The fact that the clusters are in different parts of the s-plane is taken as a sign that these parameters can be used to distinguish between these different states of anesthesia.

The investigation continues into effective methods for estimating the b_j coefficients.

References

[1] L. H. Zetterberg, "Estimation of Parameters for a Linear Difference Equation with Application to EEG Analysis," Mathematical Biosciences 5 (1969), pp. 227-275.

[2] G.E.P. Box and G. M. Jenkins, Time Series Analysis Forecasting and Control, Holden Day, San Francisco, 1970, p. 55.

FIGURE 1
s-plane roots identified from
17 samples of MAC1 EEG data

N = 1024 points per sample
n = 5th order filter
T = 1/64 sec. Data interval
m = 200 Autocorr. coeffs.

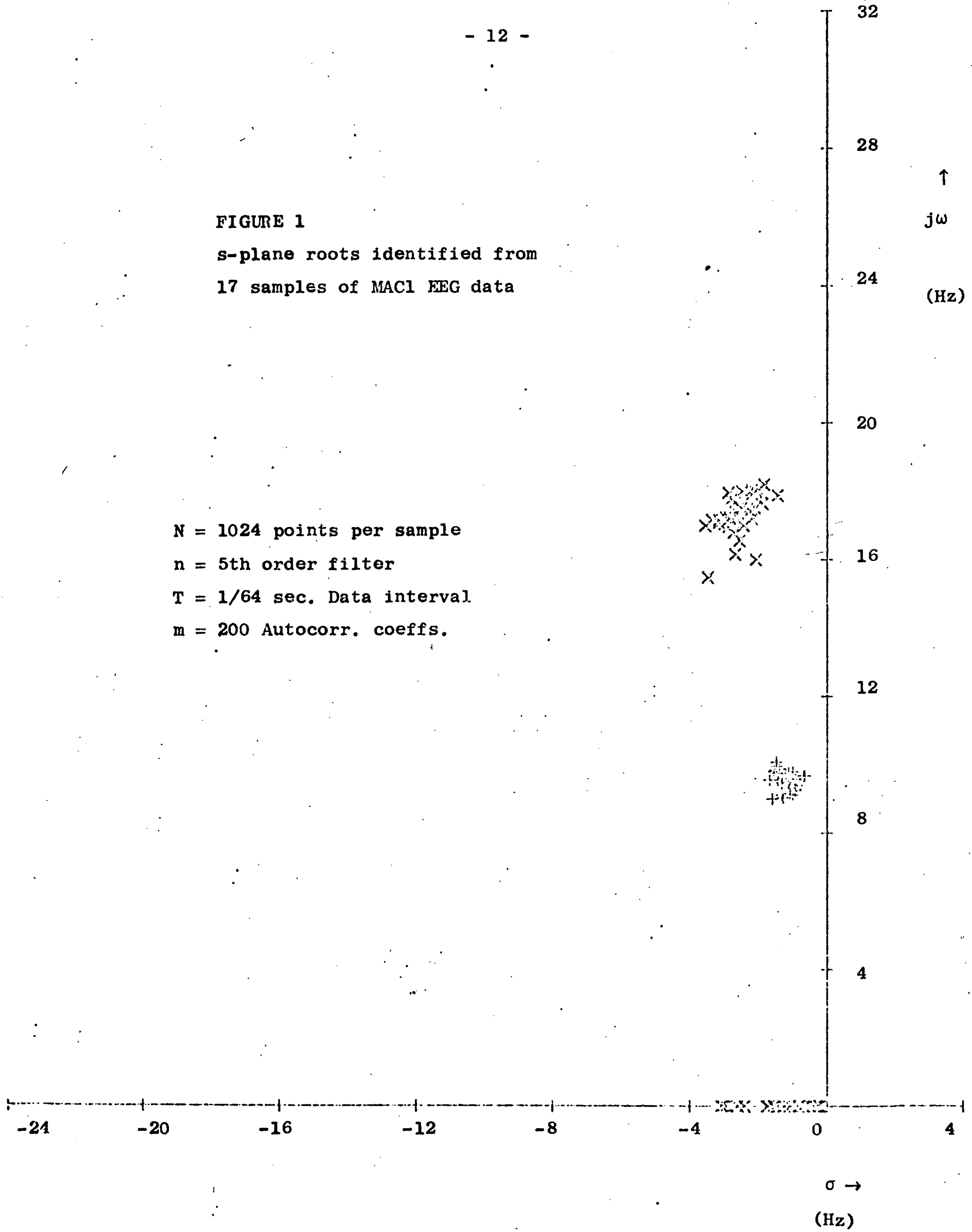
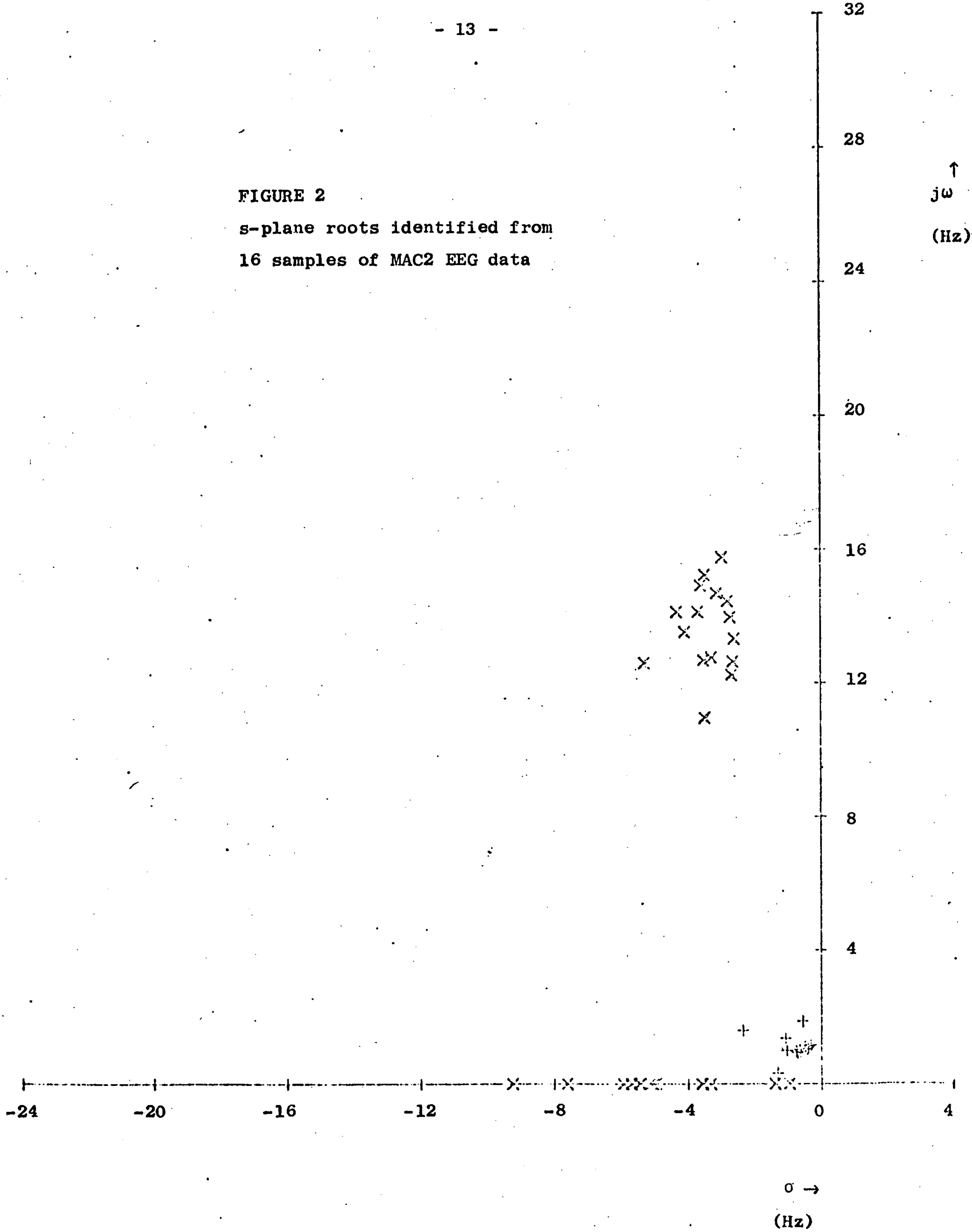


FIGURE 2
s-plane roots identified from
16 samples of MAC2 EEG data



2. Identification and Modelling of Discrete, Stochastic Linear Systems (D. S. Spain)

This research was completed in 1971 and published with the above title as SEL Technical Report No. 6302-10. The basic problem dealt with is the identification of stochastic, discrete, multivariable linear systems from input-output data. The problem definition includes the possibility of both deterministic and stochastic inputs, although all the noise sources are restricted to be gaussian and white. Using an innovations formulation of the maximum likelihood criterion, probability one convergence of the impulse response matrices to their true values can be obtained. From these matrices, a canonical form is developed for multivariable linear systems which requires no structural information or other prior knowledge of the system (although the results are derived in such a way that such knowledge can certainly be used if it is available). This canonical form is also useful in the least squares identification of multivariable systems. Two very satisfactory methods of identifying the dimension of a system are presented, one based on the whiteness of the resulting error process, and the other based on the relative decrease of the cost function as the dimension of the model increases. Conditions are also given which the deterministic input must satisfy to guarantee the probability one convergence of the impulse response matrices, and easy methods are pointed out of constructing input sequences which satisfy these conditions. Finally, both a working program to perform the identification, and suggestions, based on computational experience, for possible improvements, are presented.

3. Equicontrollability and the Model-Following Problem (R. T. Curran)

This research was completed in 1971 and published as SEL Technical Report No. 6303-2 under the title listed above. It introduces the idea of equicontrollability and studies its application to the linear time-invariant model-following problem. The problem is presented in the form of two systems: generically called the plant and the model. The requirement is to find a controller to apply to the plant so that the resultant compensated plant behaves, in an input-output sense, the same as the model. All systems are assumed to be linear and time-invariant.

The basic approach used is to find suitable equicontrollable realizations of the plant and model and to utilize feedback so as to produce a controller of minimal state dimension. The concept of equicontrollability (introduced here) is a generalization of control canonical (phase variable) form applied to multivariable systems. It allows one to visualize clearly the effects of feedback and to pinpoint the parameters of a multivariable system which are invariant under feedback.

The basic contributions contained in this work are: (1) the development of equicontrollable form, (2) solution of the model-following problem in an entirely algorithmic way, suitable for computer programming, and (3) resolution of some questions on system decoupling, along with the application of the above algorithm to accomplish decoupling.