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A CONCEPT FOR A LEARNING ATTITUDE CONTROL SYSTEM FOR LAUNCH VEHICLES

By Juergen K. Baumeister
Astrionics Laboratory

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This paper outlines a rough concept derived from literature studies and computational investigations, of a digitalized adaptive or learning control system for any high performance space launcher, space shuttle, or aircraft. The concept that has been established with special attention given to practical applicability in terms of performance and complexity may serve as a baseline for further investigations and development. Alternative algorithms and procedures for the appropriate subroutines of the system, taken from statistics, digital filtering, and control engineering, are discussed and suggestions for further investigations are made. The proposed system is subdivided into identification, optimization, and online control.

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SUMMARY

This paper outlines a rough concept derived from literature studies and computational investigations of a digitalized adaptive or learning control system for any high performance space launcher, space shuttle, or aircraft. The concept that has been established with special attention given to practical applicability in terms of performance and complexity may serve as a baseline for further investigations and development. Alternative algorithms and procedures for the appropriate subroutines of the system, taken from statistics, digital filtering, and control engineering, are discussed and suggestions for further investigations are made. The proposed system is subdivided into identification, optimization, and online control.

INTRODUCTION

Most existing attitude control systems use conventional static control methods. The use of self-adapting techniques is very limited; the system design is normally based on a compromise for a special range of vehicle performance on its trajectory and must be switched over to another design in structure or adjustment if the first design is no longer satisfactory because of changing environmental conditions. Thus, the system behavior is not optimal in most of the operational points; although a lot of control methods that may promise better results are known, their practical application is too expensive in terms of complexity, volume, and costs or even impossible with respect to feasibility.

Indeed, using analog techniques, the possibilities of the designer in the realization of mathematical equations are limited. He must provide a more or less complicated network that can be used only for the special purpose for which it was designed. Sometimes the equation may introduce undesired dynamical elements. In any case, numerical computation cannot be provided.

Until recently digital technologies for attitude control purposes could not be used because the speed of digital computers was too low to cover the attitude control real-time requirements. In addition, the volume of digital computer elements was so great that the use of a digital computer seemed to be unreasonable.

With the increasing speed of digital computers and the decreasing size of digital computer elements, a new approach to the realization of an attitude control system using special or general purpose digital computers seems to be justified. In fact, some examples of realization already exist. However, with the means to use digital technologies for attitude control, it does not seem reasonable to realize the same control law that was realized using analog technologies. The use of digital technology may open a new approach to the application of modern control theory in the attitude control field. This approach could improve the system behavior by using adapting techniques or even learning control techniques to optimize the system performance over the whole range of vehicle parameter changes caused by extremely changing environmental conditions which the vehicle meets on its trajectory.

The use of digital technologies in attitude control may lead to an improvement of system behavior over the whole range of mission profile, but this may not be the sole advantage.

Using analog technology, the design of a control system is based on networks provided for a special system in a special environmental condition, balanced as a compromise when the environmental conditions along a special trajectory are considered. If anything is changed in the system, e.g., weight, mass distribution, structural flexibility, or environmental conditions because of another trajectory, it must be considered whether the system is able to deal with the new situation. Doing this requires spending a lot of time and money which could cause a serious delay in the time schedule. As a result of such an investigation, it may often be necessary to readjust or redesign the control system.

These disadvantages may possibly be avoided by using a digitalized control system including a digital computer. Such a system, based on learning techniques, may not be affected by changes in vehicle and trajectory data; within limits, it will adapt to new conditions. In most cases, it should be possible to use the same hardware with a new or rearranged computer program. The preparational efforts would reduce software costs and the price for each equipment set would reduce hardware costs because of the possibility of using unchanged equipment for different missions and possibly different vehicles.

However, it could be argued that the costs for a digital control system will exceed those of an analog control system even if the capacities are comparable. This may be true considering single, nonredundant systems; but in almost all applications where such highly advanced systems are used, the extremely high reliability required can only be provided by designing redundant systems. Therefore, to obtain a validity check, analog systems must be triplicated. Because of the other structure of digital computers, the same reliability may be reached by using a redundant set providing inherent checks in each of the duplicated digital computers. It may also be said that digital elements are more reliable than analog elements; thus, the cost of a digital system is not much higher and may even be lower than that of an analog system.

In addition, a digital computer integrated into a control system may be used for other purposes; e.g., preflight check of the system or even purposes not connected directly with the system per se such as navigation.

Summarizing these considerations leads to the assumption that the application of an attitude control system including a digital computer and using learning techniques may result in improvement of performance, mission flexibility, vehicle compatibility, reliability, and overall costs.

The principle of a learning digital attitude control system conceived for the attitude control of a space launcher may be applicable for the attitude control of a reentering space vehicle, perhaps with aerodynamic landing capabilities, as well as for the attitude control of a reapplicable launcher vehicle on its way from launch to aerodynamic landing. It may also be applicable for high performance aircraft.

In establishing a digitalized adaptive or learning control system, it is assumed that the system to be controlled is linear. In limits, this assumption will not affect the practical applicability of the concept; in practice, most all conventional control systems being used for attitude control are based on this assumption. Generally, the concept may be extended to be applicable to nonlinear systems. However, this possiblity will not be considered here.

BASIC REQUIREMENTS

To present an overall idea of the requirements and to show how a system of the envisaged type could be useful or necessary in modern space technology, one of the latest and most ambitious space vehicle projects, the reusable aircraft type space transport vehicle will be used as an example. Some general characteristics of such a vehicle will be used to derive basic requirements for the envisaged adaptive control system.

The system must control the vehicle according to given handling qualities during its operational phases in earth atmosphere; these phases are:

1. Earth orbital launch

2. Separation of stages or boosting vehicles

3. Reentry into earth atmosphere, maneuver for energy management, and homing

4. Aircraft type landing including automatic operation

5. Aircraft type mission in earth atmosphere including cross-country operation

Furthermore, control must be provided during aircraft type operation of the vehicle under circumstances such as the following:

1. Large number of operational flights with alternate missions

2. Last minute decisions on trajectory and loads

3. Different type of loads

4. Minimum turnaround time

5. Autonomous operation during the whole mission

6. Minimization or elimination of ground support

The consequences of the functional and operational requirements for the control system are as follow:

1. Differences in the trajectories to be flown will cause the control system to deal with an enormous spectrum of different environmental conditions.

2. Because of the differences in the mission objectives and the different loading conditions, the control system must cover different mass distributions.

3. The requirement for autonomous operation, minimum turnaround time, and minimization of ground support makes it impossible to provide preflight wind and load check and preflight computation with respect to mass distribution and trajectory. Consequently, it will be impossible to adjust the control system with respect to the envisaged trajectory and the actual mass distribution before launch or reentry.

4. All preflight preparations and preflight checkout still necessary must be performed in the onboard electronic intelligence system with little effort compared to other launch vehicles.

5. Because the vehicle will have an aircraft type fuselage, aerodynamic coupling between different axes and with elastic modes will increase. Thus, the control system will find an extremely complex situation in controlling the vehicle performance.

It will be very difficult to predict the vehicle performance in its complexity for all combinations of mission phase configurations that the control system will meet during vehicle lifetime. Furthermore, covering the whole performance spectrum with a conventional type control system will be extremely difficult.

Summarizing the operational conditions and consequences for the control system results in the following fundamental requirements for the design of the envisaged digitalized learning attitude control system:

1. It is assumed that the system performance can be predicted within acceptable accuracy for all initial trajectory points, such as $t = 0$, and all $t = 0$ after separation of boosting vehicles.

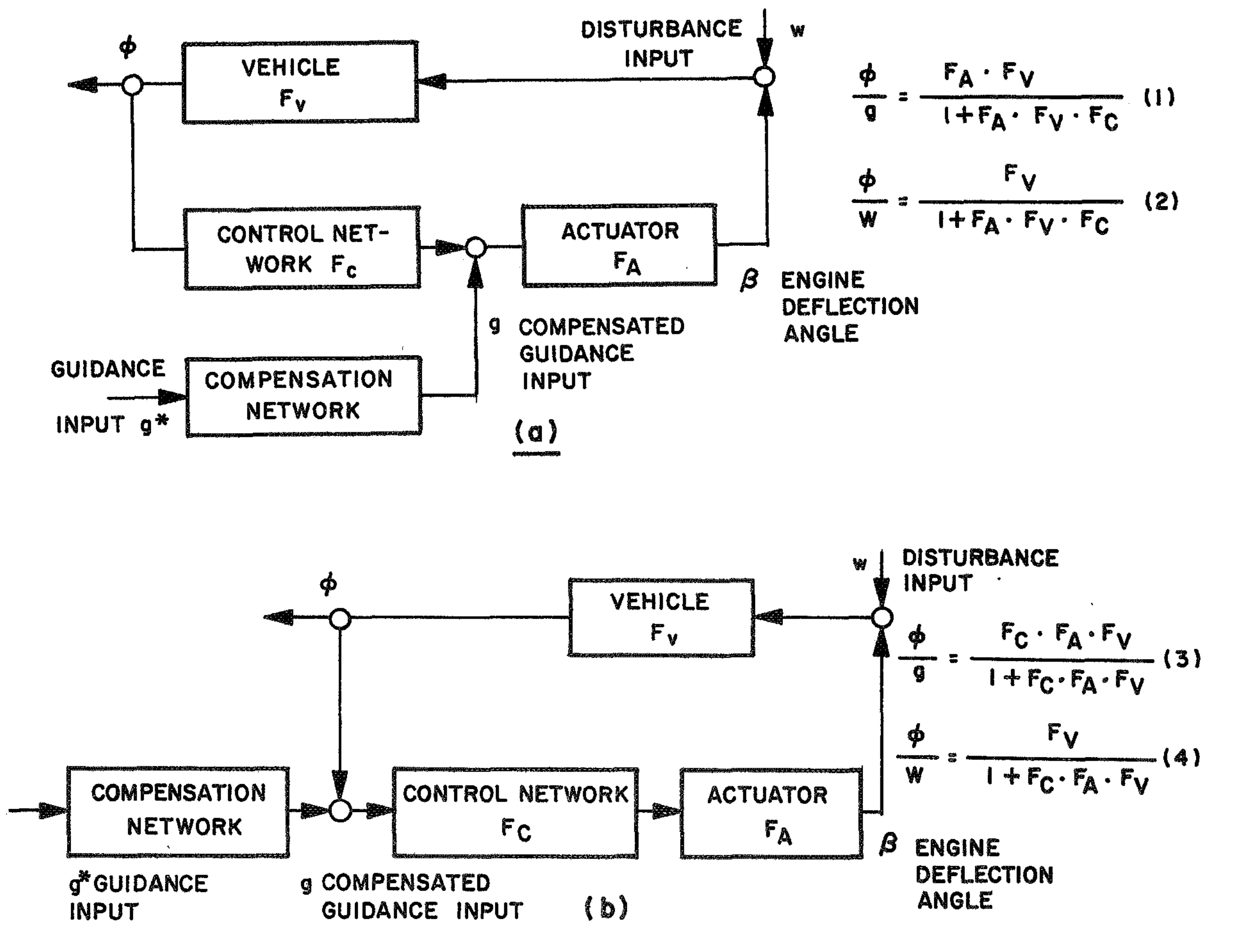
2. It is assumed that the system performance in all other trajectory points is unknown; i.e., the coefficients and order of the transfer function of the vehicle are unknown.

3. The system must identify the performance of the vehicle continuously except for the initial moment of the trajectory as stated in item 1.

4. The system must provide closed-loop performance according to either given handling qualities (region acceptable or better) or according to a desired model performance for all trajectory points, except for the initial moments of the trajectory as stated in item 1.

OVERALL SYSTEM

Most methods and procedures dealing with adaptive control of aircraft and spacecraft consider especially the guidance aspect of the problem; therefore, a special property of attitude control is pointed out. Figures 1a and 1b show simple block diagrams of an attitude control loop, with pitch angle ϕ to be controlled for different locations of guidance input.



$$\frac{\phi}{g} = \frac{F_A \cdot F_V}{1 + F_A \cdot F_V \cdot F_C} \quad (1)$$

$$\frac{\phi}{w} = \frac{F_V}{1 + F_A \cdot F_V \cdot F_C} \quad (2)$$

$$\frac{\phi}{g} = \frac{F_C \cdot F_A \cdot F_V}{1 + F_C \cdot F_A \cdot F_V} \quad (3)$$

$$\frac{\phi}{w} = \frac{F_V}{1 + F_C \cdot F_A \cdot F_V} \quad (4)$$

Figure 1. Block diagram of attitude control loop.

In selecting a control network, there is obviously the choice to optimize the loop performance with respect to its response because of either an arbitrary guidance signal or an arbitrary disturbance signal. Thereby, the disturbances are considered to be winds, wind gusts, or differences in thrust. Presumably, these disturbances enter the loop at the input of the vehicle in terms of momentum and are equal to appropriate engine deflections.

If the choice is taken with respect to the guidance signal response, a response to a disturbance must be accepted that is different from the guidance response. Depending on where the guidance signal enters the loop, this difference is determined at least by the transfer function of the actuator. There is no possibility of influencing this response.

To meet special requirements concerning the responses to disturbance inputs, the loop performance must be optimized with respect to these disturbance inputs. After this, the desired guidance response can easily be provided by an additional compensation network located in the guidance input line [1]. If the control loop is optimized with respect to disturbances, the same loop performance can be provided for guidance inputs, simply by introducing the inverse difference between $\frac{\phi}{g}$ and $\frac{\phi}{W}$ as a compensation network in the guidance input line.

If the hardware implementation is feasible, as it is using digital technology, the optimization can be performed with respect to the guidance signal entering the compensation network. As a result, the loop will respond equally to guidance and disturbance inputs. This is important for the application of all adaptive procedures, which need the loop input as a measurable magnitude.

Remembering the assumption that the vehicle will be unknown except for the initial condition, some kind of statistical open- or closed-loop identification procedure must be chosen.

After a mathematical model of the vehicle is obtained, an optimization procedure must be applied to find the latest optimal control law. According to this control law the digital control filter will be adjusted.

No matter what kind of method may be chosen for each step in this learning and control procedure, the generalized block diagram will be as shown in Figure 2.

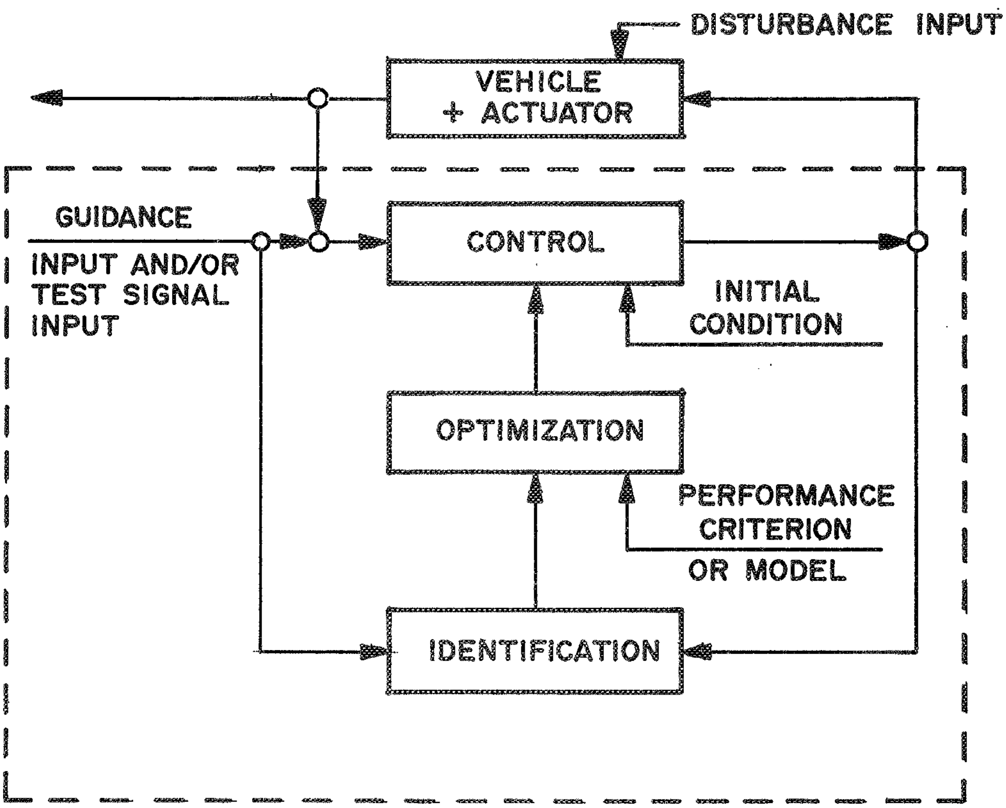


Figure 2. Learning attitude control system.

All reflections made in the following sections and all procedures considered for application in a learning attitude control system, concerning identification, optimization, and control, are based on the assumption that digital technology will be used for implementation.

IDENTIFICATION

Assuming that the loop would not have a disturbance input, the identification of the unknown plant would be very easy. The most straightforward approach to identification would be the application of the convolution integral.

However, in the presence of disturbances affecting the plant, the observed output signal is not only the response to the input signal β, but also a superposition of responses to input signal β and disturbance input w (Fig. 1). The disturbance w cannot be measured; hence, both vehicle performance and disturbance input are unknown. Thus, to identify the plant behavior, the plant output caused by disturbances must be eliminated. Considering this situation results in the identification process being necessarily a statistical one.

To get enough statistical information, the process must be observed over a significant interval of time. Choosing either an open-loop or a closed-loop identification procedure will allow a statistical analysis to be performed or will assure the convergence of the process, respectively. In both cases, this interval must be a multiple of the slowest time constant of frequency modes included in the vehicle transfer function [2]. The value of this multiple depends on the selected identification procedure and the required accuracy.

Using an open-loop identification procedure, it is obvious that the process must be faster than a significant change of plant coefficients, thus assuring that the necessary assumption of a time-invariant system is allowed and the difference between estimated and actual plant is small. Using a closed-loop identification procedure, a time-variant system may be acceptable for a few methods, but convergence must be assured within time constraints to get valid estimates as mentioned previously.

The selection of an identification procedure for application in a learning attitude control system will depend on its capability to deal with the rate of change of vehicle coefficients.

As previously stated, the slowest frequency mode of the vehicle transfer function determines the length of time necessary to perform plant identification. On the other hand, the rate of change of the coefficients of higher frequency is more significant to the control problem. Furthermore, a delay in the identification of a change in these coefficients will be most hazardous to the vehicle. In the presence of very slow modes, the length of requested observation time would become unacceptably long; consequently, these extremely slow modes cannot be included in the identification process. It is therefore suggested to split the frequency band which may show differences between lowest and highest frequency of the order of three (e.g., 0.1 to 20 Hz) into two or more parts and to provide identification in parallel portions. This may be done by feeding the signals under observation to different bandpass filters. In parallel operation the same or different identification methods may then be applied to the filtered signals. Thus, for higher frequencies, identification will take much less time than for identification of the complete frequency band and appropriate adjustments of the control network can be provided more often. Extremely low frequency modes, which cannot be identified with a reasonable interval of time, may be neglected. In this case, control is provided in the outer guidance loop [3]. Figure 3 shows the simplified block diagram for parallel identification. A presumption for application of a statistical identification procedure is that the signal input to the system to be identified is uncorrelated with noise [4, 5]. Thus, either the guidance signal or a defined test signal can be used as an external input to the closed loop.

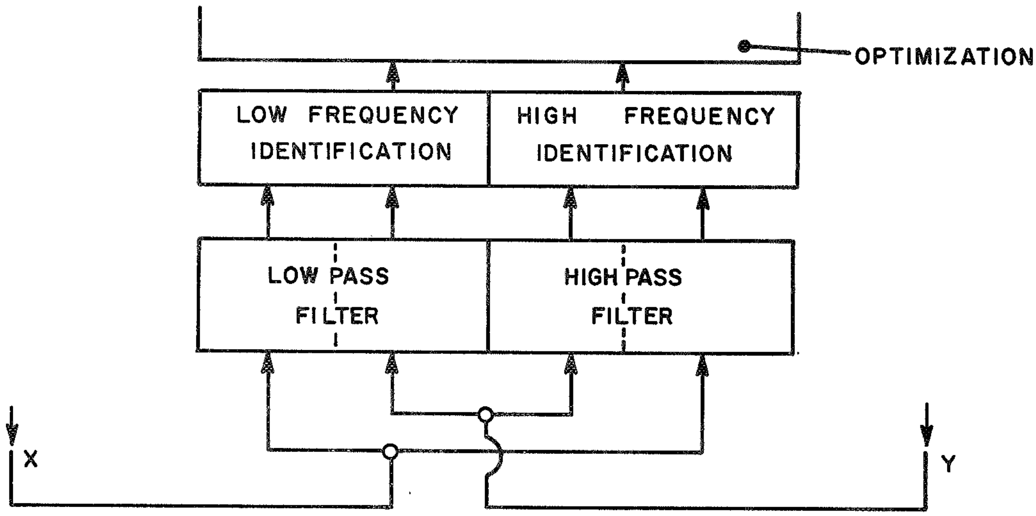


Figure 3. Block diagram for parallel identification.

A number of both open- and closed-loop identification procedures can be found in literature. For practical application to attitude control, this number reduces considerably because of the severe limitations made by the special choice of assumptions with respect to statistical properties of input signals and noise, as well as dynamic properties of the system to be analyzed. These assumptions, such as white noise input, stationary random input, a priori knowledge of statistical signal properties, time-invariant system, and well-damped system weighting function, prevent the practical application of those procedures.

The most straightforward approach to the solution, using an open-loop procedure, would be the application of auto- and cross-power-spectra relationships for calculation of the system transfer function, either by taking the Fourier integral over autocorrelation and cross-correlation functions as proposed by Blackman and Tukey [6] and many others or more directly by the use of Fast Fourier Transform as proposed by Butcher and Cook most recently [7]. However, these methods do not fit the problem because they assume white noise as an input or at least a significant amount of energy over the whole frequency band. If it is acceptable to feed white noise as a test signal to the system, a much simpler procedure can be applied, as will be seen later on.

A more promising way seems to be the application of an auto-cross-correlation convolution, as shown by Levin [8], Reswich [9], and Solodovnikov [4] and many others. Written as a sum, it is

$$R_{xy}(\tau) = \sum_{n=0}^{n} R_{xx}(\tau - n \cdot \tau_0)\, g(\delta) \qquad ,$$

$$\tau = \delta = 0,\ \tau_0,\ 2\tau_0 \ldots\ N\tau_0\,, \qquad (5)$$

where

$g(\delta)$ represents the impulse response by its sample ordinates and τ_0 is the time interval of one sample. Since the autocorrelation function $R_{xx}(\tau)$ of the input signal $x(\tau)$, the cross-correlation function $R_{xy}(\tau)$ of the input signal $x(\tau)$, and the output signal $y(\tau)$ are known, equation (5) can be solved for the impulse response of the system. This method does not explicitly require a special statistical property of the input signal, but the solution of the appropriate matrix system is very sensitive to the signal characteristic.

A possibility for use of this method may exist by the principle of the delay-line-synthesizer described by Reswich and Goodman [9,10]. Figure 4 shows the basic block diagram. The upper part of the block diagram with input $R_{xx}(\tau)$, output $R^*_{xy}(\tau)$, delay line $R_{xx}(\tau - n \cdot \tau_0)$, and weights g_n represents the auto-cross-correlation convolution. Since the impulse response is unknown, the weight must be adjusted such that the error $e(\tau)$ between the estimated cross-correlation function $R^*_{xy}(\tau)$ and the actual one $R_{xy}(\tau)$ is a minimum. $R_{xx}(\tau)$ and $R_{xy}(\tau)$ are synchronously and repeatedly generated and fed to the system. The minimization is facilitated by the fact that there is a direct relation between each weight g_n and a localized point of the error time function.

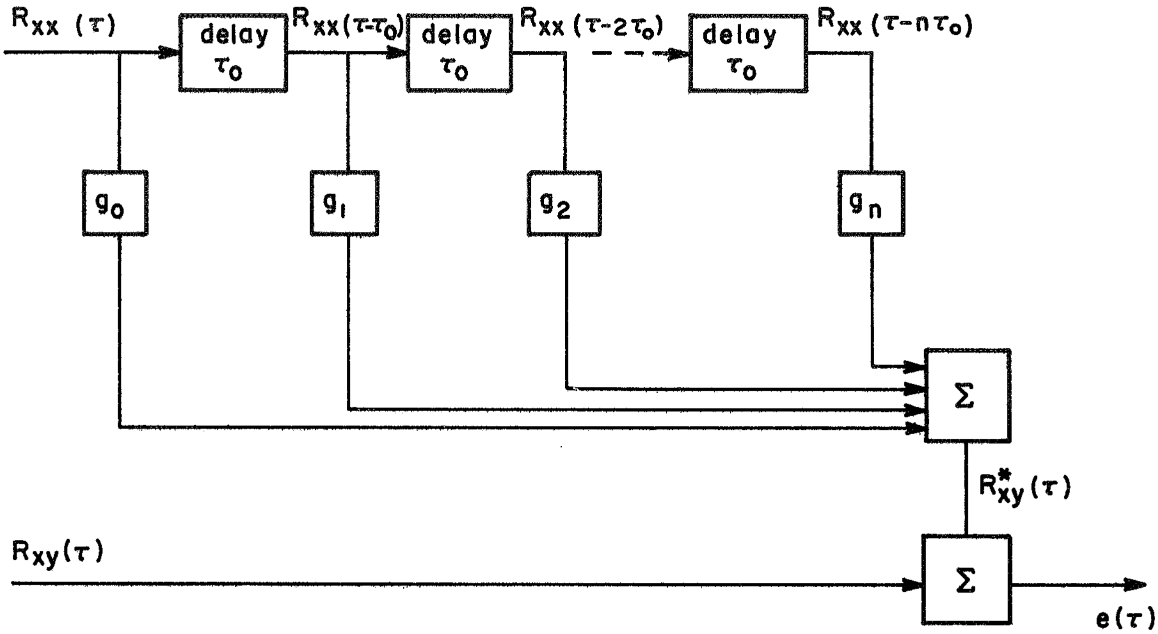


Figure 4. Block diagram of the delay-line-synthesizer.

For the particular case that $x(t)$ is white noise, $R_{xx}(\tau)$ equals a delta function $\delta(\tau)$, and thus equation (5) changes to

$$R_{xx}(\tau) = \alpha \cdot g(\tau) \qquad ,$$

where

$$\alpha = \delta^2$$

and δ is the RMS value of the input signal $x(t)$. Thus, the cross-correlation function is proportional to the impulse response. The evaluation of $g(\tau)$ is extremely simplified in this case. However, the method can only be applied if random noise is fed to the system as a test signal. The guidance signal, assumed to be a stationary random process, will not have the characteristic of white noise, not even over a limited range of the spectrum, while the test signal may be freely chosen within special limits. Binary pseudorandom noise is extremely suitable as a test signal [11]. It is a completely defined periodic binary sequence and has all the statistical properties of white noise over the length of one period.

With regard to a true random signal, pseudorandom noise avoids the disadvantages which are given by the statistical variance of the signal as a result of noninfinite observation time. It has no statistical variance; thus, time of observation can be considerably reduced.

If the time of observation equals the length of one period, the results of one measurement are absolutely repeatable, as long as the parameters of the system do not change. Binary pseudorandom noise can be provided easily by a shift register, a modulo two adder, and a Schmitt trigger as explained in Reference 11.

Considering closed-loop identification procedures, filter techniques proposed by Wiener [12], one of the first to work in this field, will be observed. This technique assumes time-invariant systems. More recently Kalman and Bucy [13] developed a filter technique for time-variant systems. Both Wiener and Kalman-Bucy filter technologies need a priori information on the statistical properties of signals.

An adaptive filter for identification of time-variant systems dealing both with stationary and nonstationary input signals without needing a priori information on statistical signal properties is proposed by Widrow [14, 15]. This adaptive filter uses a tapped delay line, variable weights, and a simplified algorithm for the adjustment of weights based on a gradient technique. The block diagram of the adaptive filter shown in Figure 5 is basically the same as that shown in Figure 4, but the filter inputs are directly the sampled input and output signals of the vehicle.

All identification procedures considered here for practical application describe the system performance in terms of its impulse response.

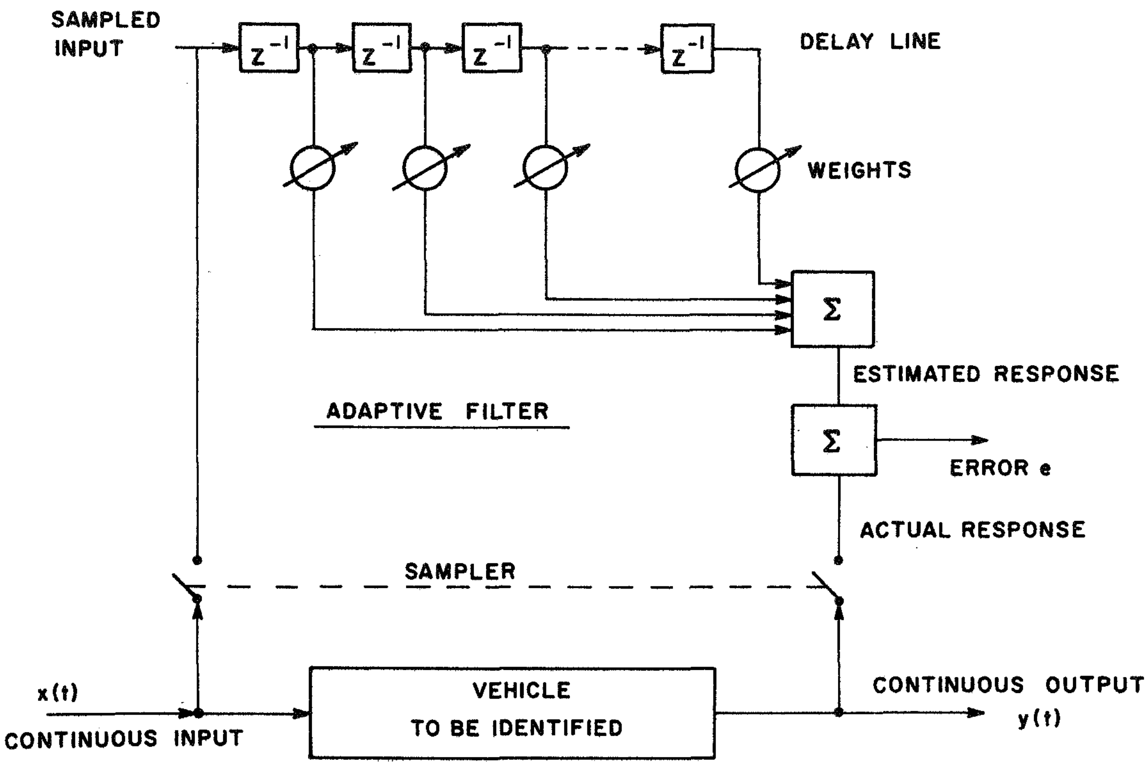


Figure 5. Block diagram of adaptive filter.

OPTIMIZATION

The selection of optimization procedures depends both on control performance requirements and on identification procedures to be used. Very important for the result of optimization and thus for the selection of optimization procedures is the accuracy with which the plant has been identified.

The requirements on control performance are significantly influenced by handling qualities. Specific areas of the complex plane are rated as excellent, good, acceptable, poor, and unacceptable. It is desired that the dominant poles of the closed loop equation lie in the positive rated areas. No pole is allowed to lie in the restricted area. The indicated areas are defined by specific combinations of frequency and damping factors. Figure 6 shows some areas of the p-plane, rated by MIL and Agard Specification [16, 17].

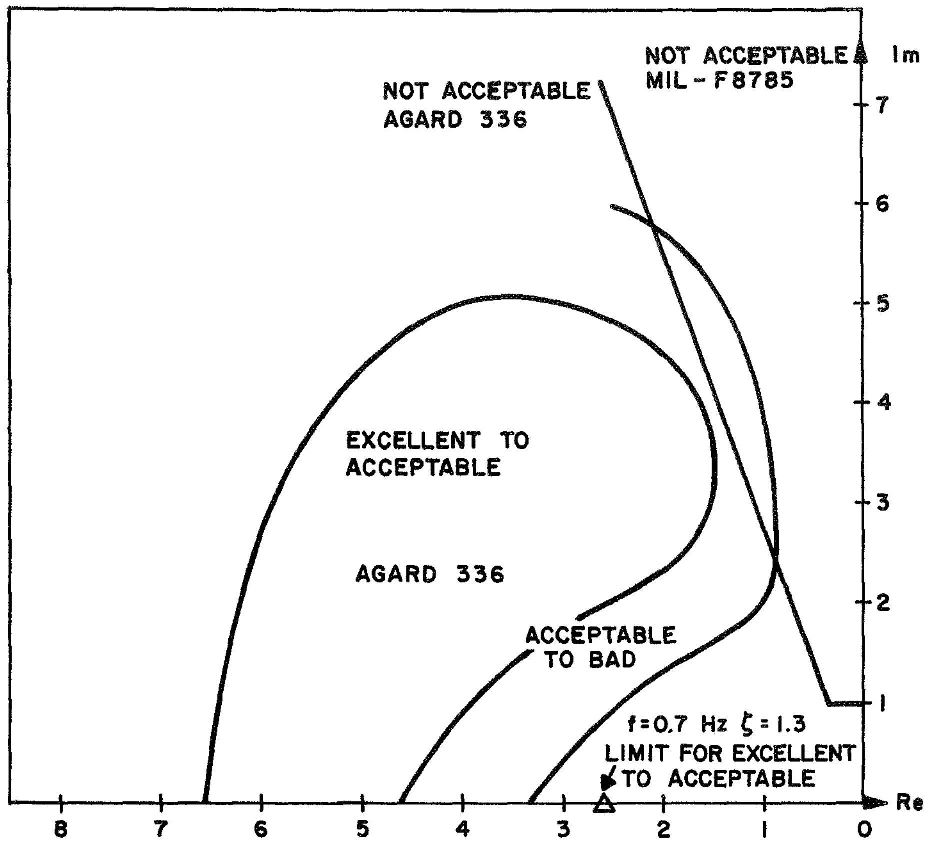


Figure 6. Areas of p-plane.

In some cases of restricted application, the minimization of integral criteria is required. The integral is taken over the absolute or squared error of the system response to a unit step impulse. In some cases, the error is weighted; for example, by time or squared time. The most common integral criteria are: the integral of squared error (ISE), the integral of time times squared error (ITSE), the integral of squared time times squared error (ISTSE), the integral of absolute error (IAE), and the integral of time times absolute error (ITAE) [18]. These criteria can be used to reduce the dynamic response to any input signal, but they cannot be used to define a specific response characteristic. A control system adjusted according to one of these integral criteria usually shows some insignificance in compensating oscillations of higher frequency and low amplitude that are superimposed to the dominant modes.

To cover higher requirements on control performance, better use of integral criteria can be made in a model type closed-loop optimization. For this application a model loop is established using the estimated plant model and a control system model that must be adjusted. The output of this model loop is compared with the output of another model, showing the desired optimal behavior. In adjusting the control system model, the difference between both output signals is minimized by using one of the previously mentioned integral criteria.

For more demanding requirements concerning specific handling qualities, either an analytical or a model type closed-loop optimization should be applied.

The first presumption for the application of any analytical optimization procedure is the necessity for explicit knowledge of plant behavior with significant accuracy, preferably in terms of poles and zeros of the p- or z-transfer function. The analytical approach used by an engineer designing a control system is defined by trial and error procedures as well as logic decisions. It may be possible to simplify this procedure and to develop an automated control system design by applying several methods for analysis and synthesis and a sequence of logic steps and decisions, but it appears to be at least questionable whether all possible combinations of plant configuration can be foreseen and appropriate procedures can be programed.

Thus a method using a more straightforward optimization would be preferable. It would be most desirable to apply a method providing insensitivity against parameter changes, thus dealing with identification errors.

Assuming for a moment that the plant characteristic could be identified with 100 percent accuracy and assuming an unlimited capacity for the implementation of any control network, the most forward solution of the task would be a complete pole-zero compensation. Using this method, all unwanted poles and zeros of the plant would be compensated, and a closed-loop behavior equivalent to that of a chosen model would be provided. Even roots caused by bending or sloshing modes with nearby zeros would be eliminated; these are very difficult to influence if the control poles and zeros are too far away and chosen to deal with all poles and zeros of the plant as a compromise.

The theoretical background for this method is quite simple. Assume that an arbitrary input, a disturbance or a guidance command signal for example, would hit both the actual closed-loop and the appropriate model for desired loop behavior. Summing up the responses of the model and actual loop with different signs results in the error time function that represents the difference between actual and desired response of the actual loop (Fig. 7).

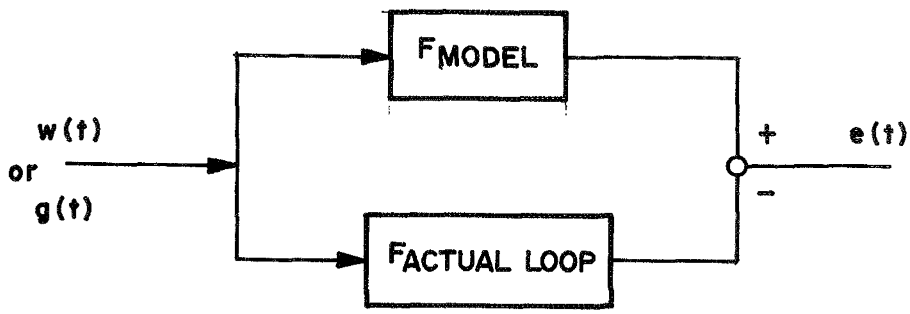


Figure 7. Actual and desired response of the actual loop.

A necessary condition for optimal loop behavior is

$$e(t) = 0 \;;$$

thus,

$$F_M - F_A = 0 \quad . \tag{6}$$

Considering as an example a control loop according to the block diagram in Figure 1a, the closed-loop equation with respect to disturbance input is

$$F_Z = \frac{\phi}{w} = \frac{F_V}{1 + F_A \cdot F_V F_C} \tag{7}$$

Substituting equation (7) into equation (6) and solving for F_C results in the optimal control law

$$F_C = \frac{1}{F_M \cdot F_A} - \frac{1}{F_V \cdot F_A} \tag{8}$$

Then

$$F_C = \frac{F_{M_D} \cdot F_{V_N} \cdot F_{A_D} - F_{V_D} \cdot F_{M_N} \cdot F_{A_D}}{F_{M_N} \cdot F_{V_N} \cdot F_{A_N}} , \qquad (9)$$

where the indices N and D denote numerator and denominator of the appropriate transfer function.

For physical realizability of F_C, the denominator has to be at least of equal order to the numerator. This balance may be enforced by an additional network cascaded to F_C with poles located far left in the complex plane.

The procedure requires a comparatively low computational effort for the implementation of the control network and is extremely simple from the methodological point of view. Storage of the optimization program and the execution of the computation are minimal.

As shown later in this report, it is indeed possible to provide digital control networks of the requested complexity. Hence, the application of this procedure is practicable with respect to optimization and filter implementation.

However, the identification procedure will definitely introduce a significant error. As a result, the poles and zeros of the control network will not exactly compensate the appropriate zeros and poles of the actual plant. This will produce unwanted roots between the appropriate poles and zeros of the plant and the control network. If a large loop gain has been provided, these unwanted roots are forced toward the appropriate zeros, thus resulting in small residues; i.e., the influence on closed-loop behavior is extremely small and can be neglected.

The same philosophy has been used to some extent by Horowitz in his root locus approach to closed-loop sensitivity against parameter changes of the plant [19] and by Truxal for cascade compensation [20]. In fact, the applied method is considered to be insensitive to errors in the identification process.

A limitation for the application of the model-compensation procedure is given if the identified plant has zeros in the right half of the complex plane.

In this case imperfect cancellation will create a root near the right-half plane zero. Even if the residue is extremely small, the unstable mode will affect the loop after an appropriate time.

For a better understanding of this situation, equation (9) is substituted into equation (7) to obtain

$$F_Z = \frac{F_{V_N} F_{A_D} F^*_{V_N} F^*_{A_N} F^*_{M_N}}{F_{V_N} F^*_{A_D} F^*_{V_N} F_{A_N} F^*_{M_D} + F_{V_D} F_{A_D} F^*_{V_N} F^*_{A_N} F^*_{M_N} - F^*_{V_D} F^*_{A_D} F_{V_N} F_{A_N} F^*_{M_N}} \tag{10}$$

All terms marked with an asterisk are out of the control equation. The asteriated terms concerning vehicle and actuator are received from the identification procedure and may be considered to be of small difference to the appropriate ones of the actual systems. Because of these differences in terms of the denominator of equation (10) that are supposed to compensate each other, small amounts are added to the coefficients of the remaining term.

It can easily be seen that the system may become unstable only in case these are zeros with positive real parts in the vehicle transfer function.

For left-half plane zeros near the imaginary axis, appropriate biasing procedures can be provided to assure closed-loop stability.

If the fact that the plant will have rhp-zeros cannot be excluded or avoided by the choice of appropriate feedback loops, the model compensation technique cannot be applied.

In this case, the solution to the problem may be part compensation together with an analytical approach as mentioned previously.

A simplified block diagram of a closed-loop model optimization as previously explained is shown in Figure 8. The minimization of the selected integral criteria can be provided by applying any kind of climbing procedure, as for example the gradient method and pattern search method [21]. It is obvious that this kind of optimization is extremely complex and needs a large amount of computational effort. There again, as in identification, the problem arises to reach convergence in a limited time.

It should be possible to integrate a closed-loop optimization and a closed-loop identification procedure to an adaptive control filter. This would have advantages with respect to performance of adaptation and requested computational effort. An investigation as to whether the method of Widrow [14] can be extended in this sense is suggested. As mentioned previously, the method is proposed as an adaptive filter for identification purposes. The block diagram of such an integrated system would be as shown in Figure 5, but with the plant model replaced by an actual plant and with either a defined test or guidance signal as an input.

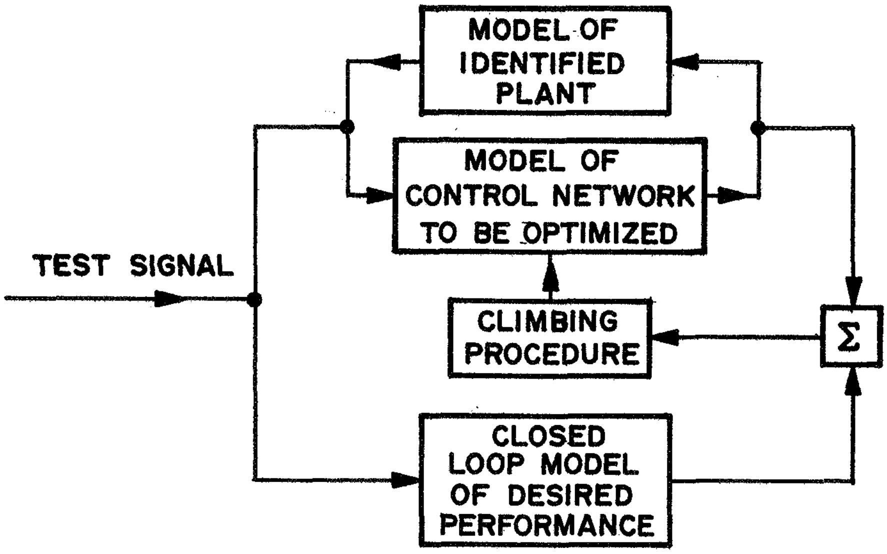


Figure 8. Block diagram of a closed-loop-model optimization.

CONTROL

To provide actual online attitude control and to close the loop using a digital computer, a continuous analog signal or a continuously measurable physical magnitude received from the rate gyro, attitude reference system, or accelerometer must be sampled (analog to digital conversion). After digital execution of the control algorism, it must be reconverted to a continuous signal or a continuously measurable physical magnitude (digital to analog conversion).

As for any digital signal processing, the sampling rate is defined by a multiple of the highest frequency that is included in the control process, according to Shannon's theorem [22]. In most cases, this highest frequency will be given by the highest bending mode or by the servomotor dynamic.

For each input sample, an appropriate output sample must be computed using the control law equation. The different procedures for the implementation of a control law described in the following paragraphs are applicable no matter whether they will be used in an adaptive or fixed coefficient design. The coefficients in an adaptive system are changed continuously or stepwise.

The control law may be defined by the impulse response of the control system or by its transfer function in the p- or z-domain. The transfer function in p describes an analog system, while the transfer function in z stands for an appropriate digitized system.

If the control law is defined by an impulse response, the output samples are reasonably computed by use of the convolution integral formula, expressed by a sum [20]. Thus,

$$y(t) = \sum_{n=0}^{K} g_n \, x(t - n \cdot T) \tag{11}$$

where $x(t)$ is an arbitrary input, g_n represents the impulse response by its sampled ordinates, and T is the time interval of one sample.

If the control law is defined by the transfer function in p, such as

$$F(p) = \frac{A_0 + A_1 p + \ldots A_N p^N}{1 + B_1 p + \ldots B_M p^M} , \tag{12}$$

it is necessary to execute as a first step the frequency transform

$$p \rightarrow \frac{2}{T} \frac{1 - z}{1 + z} , \qquad \text{where } z = e^{-pT} , \tag{13}$$

resulting in the appropriate z-transfer function [23]

$$F(z) = \frac{a_0 + a_1 z + \ldots a_N z^N}{1 + b_1 z + \ldots b_M z^M} \tag{14}$$

This z-transfer function is now transformed into the time domain by use of the following recursive formula [24]:

$$y_K = a_0 \cdot x_K + a_1 \cdot x_{K-1} + \ldots a_n \cdot x_{K-N} - b_1 \cdot y_{k-1} - \ldots b_m \cdot y_{K-M} \tag{15}$$

For each input sample, the appropriate output sample is computed taking into account the previous input and output samples.

For the practical feasibility of this procedure, it is necessary to use some computational aids. For example, it is not possible to provide a digital network of an order higher than three or four using a straightforward approach. Because of the limited word length, the resolution of the z-transfer function coefficients causes problems; therefore, the complete transfer functions must be split in functions of smaller orders, in either partial fractioned or factored form (Fig. 9) [25, 26]. Having done this, the described procedure must be applied separately to the fractioned or factored parts of the transfer function.

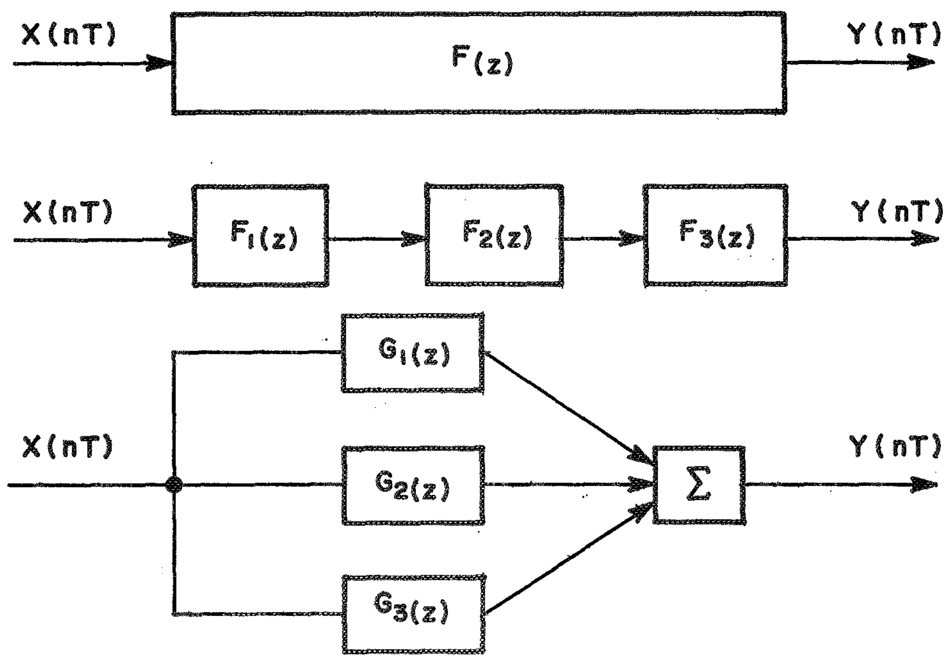


Figure 9. Fractioned or factored parts of transfer functions.

If the digital filter has been properly designed, a significant convergence between the dynamic properties of the continuous and the discrete filter will be reached.

Implementing this method in a digital computer provides much more complicated control laws of higher order than would be possible using analog hardware. Nearly every desired pole-zero combination can be realized. This is because the signal processing in a digital computer is a numerical one and is so far not dependent on physical properties of hardware elements. Different from analog technology, there is an inherent isolation between the digital elements. No dynamic characteristics of digital elements must be considered as in the case using resistances, capacitances, and inductances.

INTERFACE

It has been stated previously that all identification procedures considered for application in a learning attitude control system will describe the vehicle by its impulse response. For optimization and online control implementation, it has been assumed up to now that the input to the appropriate procedure would be available in the most favorable form. This is not true in all cases. Depending on the final choice of optimization procedure, some additional signal processing may be required.

The most favorable optimization procedure, from this point of view, would be a closed-loop model type, based on an adaptive filter which models the optimal impulse response of the control system. Such a system was mentioned previously. In this case, the implementation of online control could be provided directly by application of the convolution equation.

Another favorable closed-loop model type optimization in this respect could be imagined, simulating the vehicle by direct convolution and the control network by recursion (transformation of z-transfer function into time domain). Thus, the optimization could be provided by adjustment of the coefficients in the recursive formula. For implementation of online control, the adjusted recursive formula could be directly applied.

With an analytical method for optimization, the vehicle must be defined by its poles and zeros or by the coefficients of the polynomials in the numerator and denominator of the transfer function. Descriptions in p- or z-domain are both suitable.

Thus a conversion of the system impulse response must be provided.

From theory, different ways of interface signal processing could be chosen, but with respect to practical feasibility and minimal computational effort, it seems to be reasonable to provide optimization in the z-domain. Hence, the complete line of signal processing from system identification to network implementation may be as follows (Fig. 10):

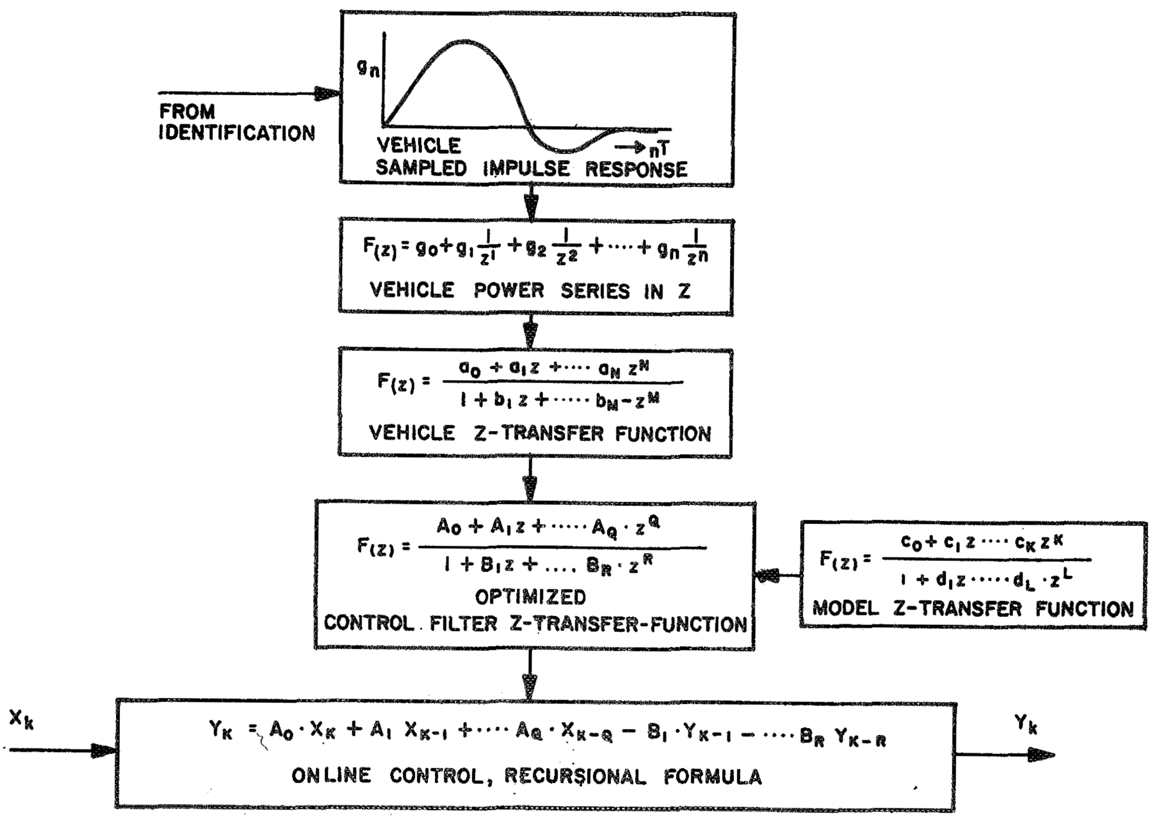


Figure 10. Signal processing.

1. Transformation of vehicle impulse response into a power series in z [27, 23].

2. Evaluation of z-transfer function coefficients.

3. Fractioning or factoring of complete z-transfer function into parts of third or fourth order.

4. Optimization by use of model transfer function in z .

5. Transformation of optimized control transfer function into time domain, using recursional formulas.

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APPROVAL

A CONCEPT FOR A LEARNING ATTITUDE CONTROL SYSTEM FOR LAUNCH VEHICLES

By

Juergen K. Baumeister

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