ON EMPIRICAL SYSTEM ID, POSSIBLE EXTERNAL ELECTROMAGNETIC/ELECTRONUCLEAR STIMULATION/ACTUATION, AND AUTOMATIC FEEDBACK CONTROL OF COLD FUSION

by

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ABSTRACT

This paper reviews some basic results from modern systems theory, which may prove useful to experimenters researching the cold fusion phenomenon from the point of view of attempting to learn how to stimulate, initiate, regulate, control by command at will, and terminate excess enthalpy, rate of tritium production, neutron count, etc.

Empirical System ID Technology regards an unknown system, to which information-theoretic signals or inputs may be injected, and from which responding outputs may be recorded, as an "arbitrary black box". There are many procedures for performing systematic input-output testing from which the internal dynamics of the unknown processes in the box may be inferred. There are available System ID software packages for processing the data produced by input-output experiments, and then using other software packages in the CACE (Computer Aided Control Engineering) category to design automatic feedback control systems which can be implemented by means of a Controller or Control Computer that converts the system into a closed-loop system by means of processing the output signals to generate appropriate input signals which will regulate the state of the process at a given set-point, or drive it toward a varying state in response to dynamic commands

This procedure can be applied to a Fleischmann-Pons electrochemical cell as follows. Introduce in proximity to the cathode one or more *actuators* selected from the category of all possible external physical stimuli whose effects are to be studied. Such a stimulus might be *electrical* (e.g. additional resistive heating of the electrolyte and/ or electrodes, or an external electrostatic field, or external radiant heating), or *magnetic* (e.g. an external static magnetic field), or *electromagnetic* (e.g. ion or electron cyclotron-resonant heating), or *electro-nuclear* (e.g. high-voltage, fast-switch triggered neutron flashers), etc. The system *inputs* will be the signals controlling such an *actuator suite.*

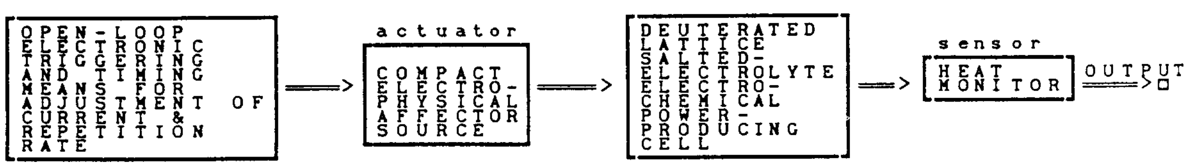
Now install a *sensor suite* comprising one or more measuring instruments selected to monitor the cell's physical properties of interest. Such monitors might include a continuous measurement of excess enthalpy, temperature of either electrodes or electrolyte, rate of tritium production, neutron count, etc. The signals from these sensors constitute the system's *output.*

Suppose that the system is near a steady state ("autonomy"), and that small inputs give small outputs ("linearizability near equilibrium"), and that bounded inputs give bounded outputs ("stability of equilibrium"). Suppose there are l outputs, m inputs, and that in addition to the preceding hypotheses the unknown process dynamic is either "finite dimensional" or adequately so approximable. Then according to the Ho-Kalman Lemma there must exist a finite integer n, and constant matrices F, G, H of dimensions respectively $n{\times}n$, $n{\times}m$, $l{\times}n$ such that the unknown process can be characterized for control purposes by the $l{\times}m$ matrix of scalar transfer functions T_{ij} or *transfer matrix*

$$T(s) = H(sI_n - F)^{-1}G.$$

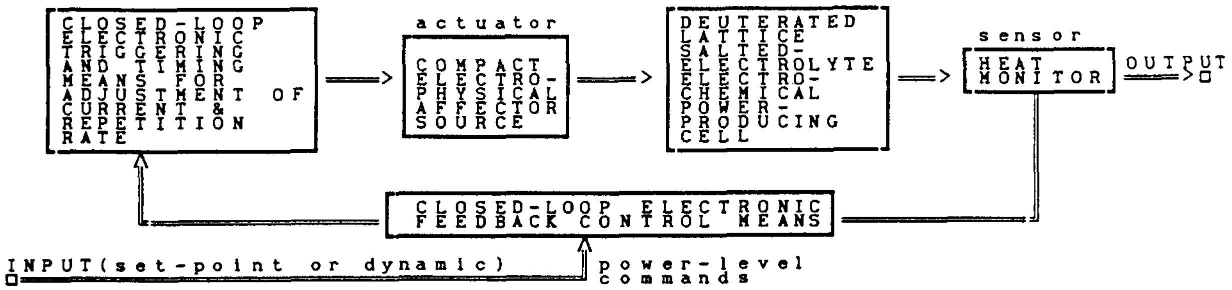
This paper by a systems engineer will outline to experimenters available automatic data-reduction procedures (e.g. the *MATLAB State Space Identification Toolkit*) for determining the matrices (F, G, H) from records of systematic input-output experiments, and available automatic synthesis procedures (e.g. the *MATLAB Robust Control Toolkit*) for designing an optimal *controller* $C(s)$ to close the loop via feedback control.

Figure 1 illustrates *open-loop* control, and Figure 2 depicts *closed-loop* or *feedback* control.



OPEN-LOOP CONTROL SYSTEM FOR STIMULATION, INITIATION & MAINTENANCE

Figure 1



CLOSED-LOOP CONTROL SYSTEM FOR STIMULATION, REGULATION & CONTROL

Figure 2

TEXT

The rather negative report on Cold Fusion by the DOE Advisory Panel contains the statement that "*The claims of cold fusion, however, are unusual in that even the strongest proponents of cold fusion assert that the experiments, FOR UNKNOWN REASONS, are not consistent and reproducible at the present time. ...*". [Emphases added.]

The University of Utah's National Cold Fusion Institute [NCFI] has stated that "*the protocol of the [NCFI] focuses on* THREE *CENTRAL* ISSUES:

- *REPEATABILITY of this ... phenomenon;*
- *Understanding of the* trigger *mechanism which INITIATES [it];*
- *IDENTIFICATION of nuclear by-products*

....". [Emphases added.] As mentioned by Dr. Peter Hagelstein, the third *desideratum* may be subordinated to the first two, for if the phenomenon could be started and stopped at will and maintained reliably for indefinite periods of time, then operation for sufficiently many hours would cause the nuclear "fuel" to disappear and nuclear "ash" to appear in macroscopically measurable quantities, which would then settle definitively the nature of the principal nuclear processes at work.

In other words, it is the presently erratic behavior of the process which needs most to be cured. A Systems Engineer with my background might say that the process appears to lack *controllability* and *observability*.

My own field of specialization is Control Theory. For examples of the use of automatic feedback control in Cold Fusion experiments, see Figure 3.

Control Theory is a a branch of Information Science which analyzes and seeks to synthesize physical systems in terms of the *quantitative characterizations* of *Observability* and *Controllability* introduced in 1960 by R.E. Kalman, who recently received the $350,000 Kyoto Prize for his pioneering work in Mathematical Systems Theory.

To show that these concepts are susceptible to a precise Information-Theoretic definition, I will digress for a moment.

Suppose that the Fleischmann-Pons Effect can be affected *somehow* by any conceivable *external* physical agency. If the secret of mastery of the phenomenon lies in Material Science or Metallurgy, then I myself have not a clue; but if the secret lies in *any known physical affect whatsoever* [e.g. externally imposed electrostatic or magnetostatic fields, or electromagnetic fields, or heat or cold, or particle flux, etc.] then the *completely general* and systematic procedure which I have outlined in the preceding Abstract is certain to discover it, sooner or later. All that one has to do is to arrange for physical *actuators* to affect the process, and physical *sensors* to monitor the results of said actuation, and there is a well-known and frequently employed technique in engineering for doing what is called "*identification of the process dynamics of an unknown arbitrary black box*", about which nothing is known except that input-output 'experiments' can be performed and recorded. (Such *TESTS* should not be called "experiments" because of the Patent Law forbidding patenting of a result which calls for "*UNDUE experimentation*" on the part of the prospective user, but since they are systematic and rational and do not get bogged down in the "*curse of dimensionality*" [too many unknown parameters to be able to do enough 'experiments' to identify them all], I would refer to them as "standardized systematic measurements".)

For examples of possible *input* variables u_i ($i = 1,2,\cdots,m$) and *output* variables y_j ($j = 1,2,\cdots,l$), see Figure 4. The input-output testing is illustrated in Figure 5.

After the input-output measurements have been completed, one processes this multi-channel data by any one of upwards of a hundred different "data reduction packages" available. I use MATLAB (available for less than $5,000 for use on either a 386-based AT-type PC or a Workstation); however, if I were going First Class I would also get MATRIX-X for about $50,000 and run it on a mainframe, from which it can synthesize Control Laws that can be "downloaded" into a proprietary Digital Controller (the S-100) available from Integrated Systems Inc. for about $150,000.

Also there is available NASA's wonderful program "Modified Maximum Likelihood Estimation, release 3" [MMLE3], at no cost (in the public domain) for mainframe computers, and available as a *State Space Identification Toolkit* add-on to MATLAB from The Mathworks Inc.

The results of such a *test-data-reduction* are completely summarized in one easily understood n-vector and five easily understood matrices, generally written in the notation introduced at the Moscow IFAC by Rudolf Kalman in 1960 as (F,G,H,Q,R,b). The matrices are respectively of dimensions $n{\times}n$, $n{\times}m$, $l{\times}n$, $n{\times}n$, $l{\times}l$, where the point to keep in mind is that the dimensions *m and l are known* (because the engineer is using m actuators and l sensors), but the all-important dimension n is *NOT KNOWN IN ADVANCE* (because the insides of the black box or arbitrary process are unknown).

However the engineer can find out n very easily by a one-parameter search (which the patent office cannot call "undue" experimentation), performed not by him but by a computer. The computer simply tries out systematically $n = 1$, $n = 2$, $n = 3$, $\cdots$, until it finds that the residual error in the "fit" to the data has stopped decreasing and started increasing, which is then, *EMPIRICALLY*, the best choice of n. I could go into many technical reasons why I am sure that even as large values as $n = 100$ or $n = 150$ (which is the case for modern aircraft flight control systems and inertial navigation systems for submarines and ICBMs) can be handled effectively by existing software. Having found out n, then the engineer says that the system has been "identified", in the sense that the input-output process dynamics, near equilibrium (and so linearizable), can be represented by a *transfer matrix* [$l{\times}m$ matrix of (lm) scalar transfer functions, or ratios of Laplace transforms of outputs to Laplace transforms of inputs, in terms of the complex Laplace variable s]

$$\Phi = \Phi(s) = H(sI_n - F)^{-1}G, \quad [s = \text{complex frequency}]$$

where now the physical interpretation of the matrices is:

- F = *dynamical* coefficient matrix
- G = *input* distribution matrix
- H = *output* distribution matrix

The important point is that according to the Ho-Kalman Lemma, the *pair* (H,F) must [is guaranteed *a priori* to] satisfy Kalman's condition of *Observability*, and the *pair* (F,G) must satisfy his condition of *Controllability*. See Figure 6.

These conditions are applications of the *Fisher Information Matrix*. (Here by * one denotes the operation of matrix *transposition*.) They are:

$$\textit{Observability}:\ rank(H^*, F^*H^*, (F^*)^2H^*, \cdots, (F^*)^{n-1}H^*) = n$$

$$\textit{Controllability}:\ rank(G, FG, F^2G, \cdots, (F)^{n-1}G) = n$$

If the system is Single-Input, Single-Output (SISO), i.e. if $l = m = 1$, then it has been proved by Kalman that Controllability and Observability are always present, which explains why these concepts were not discovered during the period of Classical Control Theory. The Modern Control Theory era began when Kalman considered Multiple-Input, Multiple-Output (MIMO) systems, in which case one cannot perform Computer Aided Control Engineering (CACE) effectively without first checking the system's observability and controllability. See Figure 8.

To explain the practical importance of Controllability and Observability one must look at one more abstraction. The transfer function formulation conceals the *time*-domain *state-vector* differential equation formulation

$$dx/dt = Fx + Gu + v(t), \qquad (x \in \mathbb{R}^n),$$

$$y = b + Hx + w(t),$$

where now x is the *state vector* of the unknown system's open-loop process dynamics (an element of real Euclidean n-space $\mathbb{R}^n$). Here the zero-mean Gaussian "white noise" processes $v(t)$ and $w(t)$ are, respectively, the system's *process disturbance* and *measurement noise* vectors, respectively; the reason one needs to know Q and R as well as (F, G, H) is that Q is the *covariance matrix* of v and R is the *covariance matrix* of w. Also the l-vector b is the vector of *sensor biases*. In the Sampled Data case, Figures 9 and 10, the preceding differential equations are replaced by the system of difference equations

$$x^{k+1} = \Phi \cdot x^k + \Gamma \cdot u^k,$$

$$y^k = H \cdot x^k,$$

where for simplicity we have neglected sensor noise and process disturbance, and where the *state transition matrix* is given by a matrix exponential

$$\Phi = exp(F \cdot \Delta t),$$

and where Δt is the *sampling interval* and where Γ is given in terms of F and G as in Figure 10.

To recapitulate, you get a tape of MMLE3 or equivalent, you run your input-output "tests" (*not* "experiments") for a time $0 \le t \le T$, and you end up with m-channel recordings of the m inputs $\{u(t) |\ [t,T]\}$ plus l-channel recordings of the l outputs $\{y(t) |\ [t,T]\}$, which data are to be processed by MMLE3.

Then MMLE3 spits out *THE ANSWERS*:

$$(n,\ F,\ G,\ H,\ Q,\ R,\ b),$$

and you have succeeded in *identifying* the unknown arbitrary black box!

The physical significance of Controllability and Observability is that, as Kalman proved at the 1960 Moscow IFAC, if the system is Controllable then there *must exist* at least one control command input policy (or "control law") *which will drive the system's state* vector to *any* prespecified terminal state, *provided* that either $l = n$ and the n sensors are sufficient to measure all n state variables (components of x) or else (the usual case in engineering, where $l = 1$ or 2 or 3, but $n = 30$) the system is also Observable, in which case there exists at least one filtering policy (filter law) which can provide *in real time and on-line* actual *MINIMAL VARIANCE* ("optimal") estimates of all unmeasured state variables, and using these with the theoretically ideal state-feedback control law ("certainty-equivalence principle") is guaranteed *a priori* to succeed (up to minimum irreducible steady-state errors related to the size of Q and R). (His discovery is this "Control/Filter *Separation* Principle.")

An author in the IEEE *Spectrum* has said that Kalman Filtering is the biggest advance in electrical engineering since World War II. Kalman himself once said to me that "the reason that Kalman-Bucy Filtering turned out to be more important than Wiener Filtering is that Newton is more important than Gauss!" (That is, it is more important to know F somewhat accurately than to know Q and R accurately.)

Around 1961 I gave a one-week course at NASA Langley on "Modern Control Theory"; one participant, Dr. E. Armstrong has since devoted more than a decade to numerical analysis and programming of the basic necessities of Optimal Regulation and Control of Linear Systems (ORACLS) and his control synthesis toolkit is now in the public domain as a NASA-supplied minimal-cost alternative to MATRIX-X or MATLAB. (It is also available in a hardback book called ORACLS from Marcel Dekker.) I agree that Q and R are less important than endowing the *closed-loop* successor to F with certain properties called *fidelity* and *robustness*. In my Langley lectures I presented closed-form algorithms for choosing the state-variable feedback gains so as to place the complex frequencies of the resultant controlled system at *any prespecified location* in the complex-frequency plane. Kalman in a chapter of a book on *Mathematical Systems Theory* has called my result "The Fundamental Theorem of Control Theory." Professor Kailath of Stanford on page 298 of his standard text on *Linear Systems* refers to the "Bass-Gura formula" as the most direct route to "pole placement", also called "eigenstructure assignment".

In other words, once the engineer completes the above-summarized process of *EMPIRICAL SYSTEM IDENTIFICATION*, the game is essentially over, for given the *reduced* data (n, F, G, H, Q, R, b), one can input this data to such a program as ORACLS and *instantly* find out the "control/filter law" to embody in an algorithm in a *control computer* which closes the loop by operating upon the system's sensor outputs and feeding the results back into the command signals to the system's actuator inputs. You can then make the closed-loop process "jump through arbitrary hoops" upon command.

If you want to go First Class, you don't have to understand any of the preceding theoretical results. You just go to Integrated Systems Inc. of Palo Alto and purchase MATRIX-X for $50,000 plus their proprietary Control Computer S-100 for $150,000. You then take this equipment to your unknown system (say a full-scale airplane in a wind-tunnel that can be tested but has never flown). You "exercise" all the input-output channels in a systematic way (operating every actuator signal to wiggle every control surface and stimulate output from every gyro, accelerometer, alpha-meter, or other sensor), recording the results on tape. Then have MATRIX-X process the data and *DOWNLOAD* its "optimal" closed-loop control/filter algorithms into their proprietary black-box S-100. You then stick S-100 into the airplane's electronics, take it out of the wind tunnel, and fly off into severe turbulence and return during a thunderstorm and zero-visibility to make a completely automatic landing. In other words, with these *Automatic Synthesis Procedures* (which are the descendent's of the ASP program of Kalman, Englar, and Bucy), you can accomplish in one day what would have previously taken hundreds of man-years by old-fashioned methods.

If what I am sketching above were not more or less true, then we could not have launched the thin-walled, flexible Saturn V booster on automatic pilot through shearing wind gusts, nor landed a man on the moon, nor achieved ICBM CEP's [Circular Error Probable] rumored by Astronomer Jastrow in the popular press to be about 100 feet, nor pressured the Soviets into preferring to end the Cold War rather than compete in an SDI space-arms race.

The above vast theory (of which I have only hinted at the tip of the iceberg) is every bit as rich and powerful as, say , Quantum Mechanics, but today's physicists, complacent over doing their own engineering during the Manhattan project, don't want to acknowledge its existence, nor contemplate the use of engineers other than as subordinates. That is why I am certain that it is easer to apply the above-sketched procedure to control of a Hot Fusion magnetic bottle (say the high-beta toroidal pinch Scyllac, which was canceled for uncontrollable instabilities) than it is to control a soft-landing Lunar Excursion Module (LEM), but the physicists in charge would never listen to a systems engineer and now their entire empire is starting to fall apart.

This is why I am hoping to gain the ears of the people pioneering the new field of Cold Fusion, in case it turns out that the process cannot be operated successfully in a scaled-up version without automatic regulation, because the above is the *SCIENTIFIC* way to go about it. (The above is called Empirical Systems Control; it is better to perform it in parallel with A Priori Modeling Control, as we did on the Saturn V, in which fundamental physics and engineering is used to derive theoretical formulae for (F, G, H) [see Greensite's two-volume book published in the USA in 1970 by Spartan Books and distributed in the UK by Macmillan & Co. Ltd.], because if the empirical tests yield a value of F which is in close agreement with your expectations -- as it was on the Saturn V -- then you can have even greater confidence in the "scientific" validity of your approach; in the case of Saturn V, the input-output tests involved placing the assembled vehicle in a vertical cradle for "shake testing", in which the engines were swiveled and the vibrations 300 feet above at the nose were recorded; on its *first flight*, all 29 state-variables were recorded by special instruments and telemetered back to the ground, and none deviated more than 10% from "nominal".

My UCLA collaborator Dr. Don Wiberg has applied Kalman-type multivariable methods to study the control of Fission Reactors. He submitted a proposal during the early stages of the Three Mile Island project which, he says, if it had been acted upon would have resulted in a more controllable system and prevented their disastrous partial melt-down!

POSTSCRIPT.

Hearing Dr. Stan Pons's impressive empirical identification of half-a dozen coefficients in a nonlinear "black box" input-output model reminded me that I should have said that not only does one want to find (F,G,H,Q,R,b) but *very importantly* one also needs to know the *variances* $(\Delta F,\Delta G,\Delta H,\Delta Q,\Delta R,\Delta b)$ which correspond to the data. His reference to the Levenberg-Marquardt Algorithm for Nonlinear Regression in the book *Numerical Recipes* [Press *et al*, Cambridge U. Press] is a valuable alternative to my references above. (Cf. also J.C. Nash's improved version in his *Compact Numerical Methods* [Wiley] and *Nonlinear Parameter Estimation* [Marcel Dekker].)

EXAMPLES OF AUTOMATIC FEEDBACK CONTROL

1. **Peripheral systems:**
   •Constant-temperature bath [regulator]

2. **Electrochemical cells**
   •D. Gozzi et al (Rome)
   <u>Nuovo Cimento</u>, vol. 103A (1990), No 1, pp. 143-154

"Time, electrode temperature, palladium electrode potential vs. reference and the potential difference between Pt and Pd electrodes, were simultaneously transferred into a computer. The data acquisition system was programmed, for safety reasons, to switch off the applied current when the electrode temperature was over 80 C"

Figure 3

l = # of OUTPUT signals (SENSOR states)

m = # of INPUT signals (ACTUATOR states)

n = # of STATE variables

EXAMPLES of possible OUTPUT variables

y_1 = excess power (watts)
y_2 = cathode temperature (degrees K)
y_3 = anode temperature (degrees K)
y_4 = electrolyte temperature (degrees K)
.
.
.
y_l = ?

EXAMPLES of possible INPUT variables
u_1 = current (amperes)
u_2 = potential (volts)
u_3 = pressure (pascals)
u_4 = heating/cooling (watts)
.
.
.
u_m = ?

SISO = Single-Input Single-Output ($l = m = 1$)
MIMO = Multiple-Input Multiple-Output ($l >$ or $m > 1$)

Figure 4

HO-KALMAN LEMMA

$u \longrightarrow \boxed{\mathcal{L}} \longrightarrow y \qquad (u \in \mathbb{R}^m,\ y \in \mathbb{R}^l)$

there exists a finite integer n and matrices
(F, G, H)
of dimensions $n \times n$, $n \times m$, $l \times n$, respectively
such that
for some initial state vector $x^0 \in \mathbb{R}^n$, & $t \geq 0$

$$\dot{x} = Fx + Gu, \quad x(0) = x^0, \quad (\dot{} = d/dt),$$
$$y = Hx,$$

where the system (F, G, H) is
CONTROLLABLE & OBSERVABLE

Figure 6

ARBITRARY UNKNOWN PROCESS

$u_1 \longrightarrow$, $u_2 \longrightarrow$, …, $u_m \longrightarrow$

UNKNOWN PROCESS assumed

(1) near equilibrium ($u = 0 \Rightarrow y = 0$)
(2) linearizable ($y \cong \mathcal{L}u$, $\mathcal{L}$ linear*)
(3) stable (u bounded $\Rightarrow y$ bounded)
(4) finite-dimensional dynamics

*[proportional & additive]

$\longrightarrow y_1$, $\longrightarrow y_2$, …, $\longrightarrow y_l$

$$\begin{pmatrix} u_1 \\ u_2 \\ \vdots \\ u_m \end{pmatrix} = u \in \mathbb{R}^m, \qquad y = \mathcal{L}u, \qquad \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_l \end{pmatrix} = y \in \mathbb{R}^l$$

can RECORD $u(t)$, $y(t)$ for future time: $0 \leq t < +\infty$

$$y(\cdot) = \mathcal{L}\{u(\cdot)\}$$

Figure 5

CACE =
Computer Aided Control Engineering

SISO systems are always both controllable & observable.

MIMO systems must be checked:
(1) if not controllable, add more or different kinds of actuators;
(2) if controllable, optimize controllability by adjusting actuator parameters (e.g. location, size etc.)
(3) if not observable, add more or different kinds of sensors;
(4) if observable, optimize observability by adjusting sensor parameters (e.g. location, scaling, etc.)

Figure 8

CONTROLLABILITY & OBSERVABILITY

the pair (F,G) is *controllable* if $rank(G) = m$ and

$$det(\mathbb{C}) > 0,$$

$$\mathbb{C} = \mathfrak{C}\cdot(G^{*}G)^{-1}\cdot\mathfrak{C}^{*}, \quad \mathfrak{C} = (G, FG, F^{2}G, \cdots, F^{n-1}G).$$

a quantitative measure of the amount of controllability is

$$\gamma = \|\mathbb{C}^{-1}\|.$$

the pair (F,H) is *observable* if $rank(H) = l$ and (F^{*},H^{*}) is controllable

- CONTROLLABILITY $\Rightarrow \exists$ input $u(\cdot)$ which drives state x to any assigned state
- OBSERVABILILTY $\Rightarrow \exists$ a linear filter which will give an unbiased minimal-variance estimate of the state $x(t)$ from $\{y(\tau) \mid 0 \le \tau < t\}$

Figure 7

y = output vector

u = input vector

x = state vector

F = dynamical coefficient matrix

G = input distribution matrix

H = output distribution matrix

$\Delta\tau$ = sampling interval

$\Phi = e^{F\Delta\tau}$ = state transition matrix

$\Gamma = F^{-1}(\Phi - I_n)\, G$ = discrete-time input distribution matrix

If $\Delta t \ll 1$, then

$\Phi = I_n + F\Delta t + \ldots$

$\Gamma = \Delta tG + \ldots$

Figure 9

SAMPLED-DATA VERSION

$$t_k = k\cdot\Delta t, \quad (k = 1,2,3,\cdots)$$

$$v^k = v(t_k), \quad v \in \mathbb{R}^p$$

$$x^{k+1} = \Phi x^k + \Gamma u^k,$$

$$y^k = Hx^k,$$

$$\Phi = e^{F\Delta t} = \text{state transition matrix},$$

$$\Gamma = F^{-1}(\Phi - I_n)G.$$

Figure 10

IDENTIFIABILITY CANONICAL FORM

$$x^{k+1} = \Phi x^k + \Gamma u^k,$$

$$y^k = Hx^k,$$

$$\Gamma = \begin{pmatrix} 0 \\ I_m \end{pmatrix}, \quad H = (I_l, 0).$$

only Φ is unknown

Figure 11

STATE OF THE ART

EMPIRICAL ID & MULTI-INPUT, MULTI-OUTPUT (MIMO) CONTROL

1. Identify process state-transition matrix using e.g. *MATLAB State-Space Identification Toolbox* with input-output experiments
2. Design process Controller [algorithms for control computer] using e.g. *Matrix-x* software or NASA's (public domain) *ORACLS* software or *MATLAB Robust Control Toolbox.*

Figure 12

CURRENT R&D

INTELLIGENT SYSTEMS TECHNOLOGY

1. Use input-output records of actual process to train a *neural network* to mimic the process. Then the *synaptic weight matrix* of the trained net is just the state transition matrix (in identifiability canonical form).
2. Use *fuzzy-logic* techniques and *AI* techniques (rule-based expert systems) to implement a self-tuning or adaptive controller.

Figure 13