

Description**Technical Field**

6 This invention relates generally to sensor signal processing and more particularly to the calibration and standardization of sensor outputs using multiple sensor systems.

Background Art

10 Electrically controlled systems often respond, at least in part, to external events. Sensors of various kinds are typically utilized to allow such a system to monitor the desired external events. Such sensors provide predictable electrical responses to specific environmental stimuli. Sensors are comprised of one or more components, and such components are usually only accurate within some degree of tolerance. As a result, sensors are calibrated prior to installation and use.

15 However, such calibration techniques are relatively costly. Instead, a data base can be empirically prepared for each sensor to relate that sensor's output to known environmental influences. Such an apparatus and method for calibrating a sensor was recently patented (PCT/US86/00908; see WO 87/00267 of January 15, 1987). However, such a complete empirical data base may still be much too expensive to prepare and update in real-time for every sensor of a large sensor system.

20 Fortunately, it has turned out that there seldom is an absolute need for such an empirical data base if the sensor system only has some data-redundancy or overdetermination in it (see Antti A. Lange, 1986: "A High-pass Filter for Optimum Calibration of Observing Systems with Applications"; pages 311-327 of *Simulation and Optimization of Large Systems*, edited by Andrzej J. Osladacz and published by Clarendon Press/Oxford University Press, Oxford, UK, 1986).

25 It has for a much longer time been known how the calibration of relatively small sensor systems can be maintained in real-time by using various computational methods under the general title of Kalman Filtering (Kalman, 1960; and Kalman and Bucy, 1961). However, certain *stability* conditions must be satisfied otherwise all the estimated calibration and other desired parameters may start to diverge towards false solutions when continuously updated again and again.

30 Fortunately, certain *observability* and *controllability* conditions guarantee the stability of an *optimal* Kalman Filter. These conditions together with a strict optimality usually require that a full measurement cycle or even several cycles of an entire multiple sensor system should be able to be processed and analysed at one time. However, this has not been possible in large real-time applications. Instead, much faster suboptimal Kalman Filters using only a few measurements at a time are exploited in the real-time applications of navigation technology and process control.

35 Unfortunately, the prior art real-time calibration techniques either yield the severe computation loads of optimal Kalman Filtering or their stability is more or less uncertain as it is the situation with suboptimal Kalman Filtering and Lange's High-pass Filter. A fast Kalman Estimation algorithm has been reported but it only applies to a restricted problem area (Falconer and Ljung, 1978: "Application of Fast Kalman Estimation to Adaptive Equalization", IEEE Transactions on Communications, Vol. COM-26, No. 10, October 1978, pages 1439-1446).

40 There exists a need for a calibration apparatus and method for large sensor systems that offers broad application and equal or better computational speed, reliability, accuracy, and cost benefits.

Summary of the Invention

45 These needs are substantially met by provision of the apparatus and method for calibrating a sensor system in real-time or in near real-time as described in this specification. Through use of this apparatus and method, unreliable trim points and most expensive internal calibration techniques can be eliminated from the sensors. Instead, a data base is created from more or less scratch and updated in real-time for the entire multiple sensor system. In addition, to aid convergence and accuracy of the measuring process, entirely uncalibrated but otherwise predictable sensors can be included in the sensor system.

50 Pursuant to the apparatus of the invention, a microcomputer or other element capable of performing in real-time or near real-time the specified logic functions receives output from a system of several sensor units, accesses a data base, and determines readings of the sensor units in view of the data base information to yield standardized calibrated outputs and updates the data base information; and, pursuant to the method of invention, the logic functions are based on such a revision of Lange's High-pass Filter for Optimum Calibration of Observing Systems that transforms the filter into a Kalman Filter.

Brief Description of the Drawings

These and other attributes of the invention will become more clear upon making a thorough review and study of the following description of the best mode for carrying out the invention, particularly when reviewed in conjunction with the drawings, wherein:

Fig. 1 comprises a block diagram depiction of a prior art sensor and calibration unit;

Fig. 2 comprises a block diagram depiction of a prior art apparatus and method for calibrating a large sensor system (based on so-called decentralized Kalman Filtering);

Fig. 3 comprises a block diagram of the apparatus of the invention (based on so-called centralized Kalman Filtering); and

Fig. 4 comprises a schematic diagram of an example of a preferred embodiment of the apparatus of the invention.

Best Mode for Carrying out the Invention

Prior to explaining the invention, it will be helpful to first understand the prior art calibration technique of Fig. 1. A typical prior art sensor and calibration unit includes a logic unit (11) and a data base unit (12). The sensor signal from a sensor unit (13) proceeds directly through an amplifier/transmission (16) unit to an output/interface unit (18). Based upon this input and upon the information contained in the data base unit (12), the logic unit (11) then provides a calibrated sensor reading for use as desired.

Referring now to Fig. 3, the apparatus of the invention has been outlined. It includes generally a logic unit (1) and a data base unit (2) that operate in conjunction with a centralized multiple sensor system (3). The data base unit (2) provides storage for all information on most recent control and performance aspects of the sensors including, if any, test point sensor output values and the corresponding empirically determined external event values. The logic unit (1) receives sensor outputs from the sensor system (3), and accesses the data base unit (2). Based on these inputs, the logic unit (1) provides the outputs (5) that comprise updated calibration data, sensor readings and monitoring information on the desired external events. Prior to explaining the invented Fast Kalman Filtering (FKF) method pursuant to the way in which the logic unit (1) is used, it will be helpful to first understand some fundamentals of Kalman Filtering.

An optimal recursive filter is one for which there is no need to store all past measurements for the purpose of computing present estimates of the *state* parameters. This is the *Markov property* of a stochastic process and fundamental to *optimal* Kalman Filtering. For the wind-tracking apparatus of Fig. 4 the position coordinates of the weather balloon - and, as we shall soon see, all more or less unknown calibration parameters of the tracking sensors as well - are referred to as the *state* of the system.

The process is described by the equations from (1) to (3). The first equation tells how a *measurement* vector y_t depends on the *state* vector s_t at timepoint t , ($t=0,1,2,\dots$). This is the linearized *Measurement* (or *observation*) equation:

$$y_t = H_t s_t + e_t \quad (1)$$

The design matrix H_t is typically composed of the partial derivatives of the actual Measurement equations. The second equation describes the time evolution of e.g. a weather balloon flight and is the *System* (or *state*) equation:

$$s_t = s_{t-1} + u_{t-1} + a_t \quad (2)$$

(or, $s_t = A s_{t-1} + B u_{t-1} + a_t$ more generally)

which tells how the balloon position is composed of its previous position s_{t-1} as well as of increments u_{t-1} and a_t . These increments are typically caused by a known *uniform motion* and an unknown random *acceleration*, respectively.

The measurement errors, the acceleration term and the previous position usually are mutually uncorrelated and are briefly described here by the following covariances matrices:

$$R_{e_t} = \text{Cov}(e_t) = E(e_t e_t')$$

$$R_{a_t} = \text{Cov}(a_t) = E(a_t a_t')$$

and

$$P_{t-1} = \text{Cov}(\hat{s}_{t-1}) = E\{(\hat{s}_{t-1} - s_{t-1})(\hat{s}_{t-1} - s_{t-1})'\}$$

(3)

The Kalman forward recursion formulae give us the best linear unbiased estimates of the present state

$$\hat{s}_t = \hat{s}_{t-1} + u_{t-1} + K_t \{y_t - H_t(\hat{s}_{t-1} + u_{t-1})\} \quad (4)$$

and its covariance matrix

$$P_t = \text{Cov}(\hat{s}_t) = P_{t-1} - K_t H_t P_{t-1} \quad (5)$$

where the Kalman gain matrix K_t is defined by

$$K_t = (P_{t-1} + R_a) H_t' \{H_t (P_{t-1} + R_a) H_t' + R_c\}^{-1} \quad (6)$$

Let us now partition the estimated state vector $\hat{s}_t$ and its covariance matrix P_t as follows:

$$\hat{s}_t = \begin{bmatrix} \hat{b}_t \\ \hat{c}_t \end{bmatrix}, \quad P_t = \text{Cov}(\hat{s}_t) = \begin{bmatrix} P_{b_t} & \text{Cov}(\hat{b}_t, \hat{c}_t) \\ \text{Cov}(\hat{c}_t, \hat{b}_t) & P_{c_t} \end{bmatrix} \quad (7)$$

where $\hat{b}_t$ tells us the estimated balloon position; and,
 $\hat{c}_t$ the estimated calibration parameters.

The respective partitioning of the other quantities will then be as follows:

$$H_t = [H_{b_t} \ H_{c_t}] = [X_t \ G_t], \quad u_t = \begin{bmatrix} u_{b_t} \\ u_{c_t} \end{bmatrix}, \quad a_t = \begin{bmatrix} a_{b_t} \\ a_{c_t} \end{bmatrix},$$

and,

$$R_a = \begin{bmatrix} R_{a_{b_t}} & \text{Cov}(a_{b_t}, a_{c_t}) \\ \text{Cov}(a_{c_t}, a_{b_t}) & R_{a_{c_t}} \end{bmatrix} \quad (8)$$

The recursion formulae from (4) to (6) gives us now a filtered (based on updated calibration parameters) position vector

$$\hat{b}_t = \hat{b}_{t-1} + u_{b_{t-1}} + K_{b_t} \{y_t - H_t(\hat{s}_{t-1} + u_{t-1})\} \quad (9)$$

and the updated calibration parameter vector

$$\hat{c}_t = \hat{c}_{t-1} + u_{c_{t-1}} + K_{c_t} \{y_t - H_t(\hat{s}_{t-1} + u_{t-1})\} \quad (10)$$

The Kalman gain matrices are respectively

$$K_{b_t} = (P_{b_{t-1}} + R_{a_{b_t}}) H_{b_t}' \left\{ H_{b_t} (P_{b_{t-1}} + R_{a_{b_t}}) H_{b_t}' + R_{e_t} \right\}^{-1} + \dots$$

and

(11)

$$K_{c_t} = (P_{c_{t-1}} + R_{a_{c_t}}) H_{c_t}' \left\{ H_{c_t} (P_{c_{t-1}} + R_{a_{c_t}}) H_{c_t}' + R_{e_t} \right\}^{-1} + \dots$$

Equation (9) specifies a high-pass filter because it suppresses from the position coordinates all those "noise" effects that stem from constant or slow-varying calibration errors of the tracking sensors. Its frequency responses depend on the calibration stability of each sensor and optimal tuning takes place automatically. However, one must use accurate estimates for the covariance matrices $P_{t=0}$, R_{a_t} and R_{e_t} as well as to keep track of recalibration or adjustments $u_{a_{t-1}}$ of the sensors at all timepoints $t, t=1, 2, \dots$. Equation (10) specifies a low-pass filter because it suppresses the random noise a_{c_t} from the calibration parameters and it can be used for updating the calibration parameter vector. It resembles an *exponential smoothing filter* where the weights of the moving averaging come from (11).

Because the calibration parameters are very closely related to the *measurements* a design matrix H_t usually has linearly dependent column vectors. This will cause numerical problems unless adequate precautions are taken. Firstly, an *initialization* is needed for adequate initial guesses of the position vector $b_{t=0}$ and the calibration vector $c_{t=0}$. Lange's High-pass Filter (Lange, 1988a) can extract this information from all available data sources e.g. instrument calibration, laboratory tests, intercomparisons and archived *measurements*. Secondly, the well-known *stability* conditions of Kalman Filtering should also be satisfied otherwise truncation and round-off errors may gradually contaminate the filtering results (see e.g. Gelb 1974: "Applied Optimal Estimation", MIT Press, page 132).

The *stability* of a Kalman Filter refers to the behaviour of estimated parameters when measurements are suppressed. The calibration parameters typically are unobservable dig many external events. In fact, the number of *measurements* must always be greater than that of entirely unknown *state* parameters. This is a matter of great practical importance for all observing systems with many calibration parameters to be estimated. The very necessary *observability* condition can usually be satisfied by processing the incoming sensor signals in large data batches or, alternatively, employing tests for "whiteness" on long time series of the residuals e and making the corrective actions when established. In fact, for a truly *optimal* Kalman Filter, not only the Kalman Gain matrices (11) but the volume of a data batch also depend on the *state* and model parameters in dynamic fashion. Prior art methods use the Kalman Recursions (4) to (6) for estimating these parameters.

Now, we introduce the following modified form of the *State equation*

$$\hat{s}_{t-1} + u_{t-1} = I s_t + (\hat{s}_{t-1} - s_{t-1}) - a_t \quad (12)$$

where $\hat{s}$ represents an estimated value of a *state* vector s . We combine it with the *Measurement equation* (1) in order to obtain so-called *Augmented Model*:

$$\begin{bmatrix} y_t \\ \hat{s}_{t-1} + u_{t-1} \end{bmatrix} = \begin{bmatrix} H_t \\ I \end{bmatrix} s_t + \begin{bmatrix} e_t \\ (\hat{s}_{t-1} - s_{t-1}) - a_t \end{bmatrix} \quad (13)$$

i.e. $z_t = Z_t s_t + \varepsilon_t$

The *state* parameters can now be computed by using the well-known solution of a Regression Analysis problem given below. We use it for *Updating*:

$$\hat{s}_t = (Z_t' V_t^{-1} Z_t)^{-1} Z_t' V_t^{-1} z_t \quad (14)$$

The result is algebraically equivalent to use of the Kalman Recursions but not numerically (see e.g. Harvey, 1981: "Time Series Models", Philip Allan Publishers Ltd, Oxford, UK, pp. 101-119). For the balloon tracking problem with a large number sensors with slipping calibration the matrix to be inverted in equations (6) or (11) is larger than that in formula (14).

The *initialization* of the large optimal Kalman Filter for solving the calibration problem of the balloon tracking sensors is done by Lange's High-pass Filter. It exploits an analytical sparse-matrix inversion formula (Lange, 1988a) for solving regression models with the following so-called Canonical Block-angular matrix structure:

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_K \end{bmatrix} = \begin{bmatrix} X_1 & & & G_1 \\ & X_2 & & G_2 \\ & & \ddots & \vdots \\ & & & X_K G_K \end{bmatrix} \begin{bmatrix} b_1 \\ \vdots \\ b_K \\ c_K \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_K \end{bmatrix} \quad (15)$$

This is a matrix representation of the *Measurement equation* of an entire windfinding intercomparison experiment or one balloon flight. The vectors $b_1, b_2, \dots, b_K$ typically refer to consecutive position coordinates of a weather balloon but may also contain those calibration parameters that have a significant time or space variation. The vector c refers to the other calibration parameters that are constant over the sampling period.

Updating of the *state* parameters including the calibration drifts in particular, is based on optimal Kalman filtering. However, the Kalman Recursions would now require the inversions of the very large matrices in equations (6) or (11) because *measurements* must be processed in large data batches in order to create observability for the calibration parameters. A data batch usually is a new balloon flight.

Fortunately, the Regression Analytical approach leads almost to the same block-angular matrix structure as in equation (15). The optimal estimates ($\hat{\cdot}$) of $b_1, b_2, \dots, b_K$ and c are obtained by making the following logical insertions into formula (15) for each timepoint $t, t = 1, 2, \dots$:

$$\begin{aligned} y_k &:= \begin{bmatrix} y_{t,k} \\ \hat{b}_{t-1,k} + u_{b_{t-1,k}} \end{bmatrix}; \quad X_k := \begin{bmatrix} X_{t,k} \\ -I \end{bmatrix}; \\ G_k &:= \begin{bmatrix} G_{t,k} \\ -I \end{bmatrix}; \quad b_k := b_{t,k}; \text{ and,} \\ e_k &:= \begin{bmatrix} e_{t,k} \\ (\hat{b}_{t-1,k} - b_{t-1,k}) - a_{b_{t,k}} \end{bmatrix}; \quad \text{for } k=1, \dots, K; \\ &\text{and,} \\ y_{K+1} &:= \hat{c}_{t-1} + u_{c_{t-1}}; \quad X_{K+1} := [\text{empty}]; \\ G_{K+1} &:= [I]; \quad c := c_t; \text{ and, } e_{K+1} := (\hat{c}_{t-1} - c_{t-1}) - a_{c_t} \end{aligned} \quad (16)$$

These insertions conclude the specification of the Fast Kalman Filter (FKF) algorithm for the embodiment of the invention for calibrating the upper-air wind tracking system of Fig. 4.

Another preferred mode for carrying out the invention is the Global Observing System of the World Weather Watch. Here, the vector y_k contains various observed inconsistencies and systematic errors of weather reports (e.g. mean day-night differences of pressure values which should be about zero) from a radiosonde system k or from a homogeneous cluster k of radiosonde stations of a country (Lange, 1988a/b). The calibration drift vector b_k will then tell us what is wrong and to what extent. The calibration drift vector c refers to errors of a global nature or which are more or less common to all observing systems (e.g. biases in satellite radiances and in their vertical weighting functions or some atmospheric tide effects).

For all large multiple sensor systems their design matrices H typically are sparse. Thus, one can usually perform

Partitioning:

$$s_t = \begin{bmatrix} b_{t,1} \\ \vdots \\ b_{t,K} \\ c_t \end{bmatrix} \quad y_t = \begin{bmatrix} y_{t,1} \\ y_{t,2} \\ \vdots \\ y_{t,K} \end{bmatrix} \quad H_t = \begin{bmatrix} x_{t,1} & x_{t,2} & \dots & x_{t,K} & G_{t,1} \\ & & & & G_{t,2} \\ & & & & \vdots \\ & & & & G_{t,K} \end{bmatrix} \quad (17)$$

where

c_t typically represents calibration parameters at time t ; and,
 $b_{t,k}$ all other state parameters in the time and/or space volume.

If the partitioning is not obvious one may try to do it automatically by using a specific algorithm that converts every sparse linear system into the above Canonical Blocpo-angular Form (Weil and Kettler, 1971: "Rearranging Matrices to Block-angular Form for Decomposition (and other) Algorithms", Management Science, Vol. 18, No. 1, September 1971, pages 98-107).

Augmented model for a space volume case: see equations (15) and (16).

Augmented Model for a moving time volume (length L):

$$\begin{bmatrix} \hat{s}_{t-1} + u_{t-1} \\ \hat{s}_{t-2} + u_{t-2} \\ \vdots \\ \hat{s}_{t-L} + u_{t-L} \\ \hat{c}_{t-1} + u_{c,t-1} \end{bmatrix} = \begin{bmatrix} H_t & F_t \\ I & \\ & H_{t-1} & F_{t-1} \\ & I & \\ & & \ddots \\ & & H_{t-L+1} & F_{t-L+1} \\ & & I & \end{bmatrix} \begin{bmatrix} s_t \\ s_{t-1} \\ \vdots \\ s_{t-L+1} \\ c_t \end{bmatrix} + \begin{bmatrix} e_t \\ (\hat{s}_{t-1} - s_{t-1}) - a_t \\ e_{t-1} \\ (\hat{s}_{t-2} - s_{t-2}) - a_{t-1} \\ \vdots \\ e_{t-L+1} \\ (\hat{s}_{t-L} - s_{t-L}) - a_{t-L+1} \\ (\hat{c}_{t-1} - c_{t-1}) - a_{c,t} \end{bmatrix} \quad (18)$$

$$\text{i.e. } Z_t = Z_t s_t + e_t$$

and where vector C_t represents all those calibration parameters that are constants in the moving volume. As previously, we proceed with

Updating:

$$\hat{s}_t = \{Z_t' V_t^{-1} Z_t\}^{-1} Z_t' V_t^{-1} Z_t \quad (19)$$

Please observe, that the gigantic matrix Z takes a *nested* block-angular form when adding the space domain. Lange's High-pass Filter can be revised to cope with all such sparsities of **Augmented Models**.

The Fast Kalman Filter (FKF) formulae for the recursion step at any timepoint t are as follows:

$$\begin{aligned} \hat{s}_{t-l} &= \{X_{t-l}' V_{t-l}^{-1} X_{t-l}\}^{-1} X_{t-l}' V_{t-l}^{-1} (y_{t-l} - G_{t-l} \hat{c}_t) \quad \text{for } l=0,1,2,\dots,L-1 \\ \hat{c}_t &= \left\{ \sum_{l=0}^L G_{t-l}' R_{t-l} G_{t-l} \right\}^{-1} \sum_{l=0}^L G_{t-l}' R_{t-l} y_{t-l} \end{aligned} \quad (20)$$

where, for $t=0,1,2,\dots,L-1$,

$$R_{t-l} = V_{t-l}^{-1} \left\{ I - X_{t-l} \left[X_{t-l}' V_{t-l}^{-1} X_{t-l} \right]^{-1} X_{t-l}' V_{t-l}^{-1} \right\}$$

$$V_{t-l} = \begin{bmatrix} \text{Cov}(e_{t-l}) & \\ & \text{Cov}\{A(\hat{s}_{t-l-1} - s_{t-l-1}) - a_{t-l}\} \end{bmatrix}$$

$$y_{t-l} = \begin{bmatrix} \hat{A} s_{t-l-1} + B u_{t-l-1} \\ y_{t-l} \end{bmatrix}$$

$$X_{t-l} = \begin{bmatrix} H_{t-l} \\ I \end{bmatrix}$$

$$G_{t-l} = \begin{bmatrix} F_{t-l} \\ \end{bmatrix}$$

and, i.e. for $t=L$,

$$R_{t-L} = V_{t-L}^{-1}$$

$$V_{t-L} = \text{Cov}\{A(\hat{C}_{t-1} - C_{t-1}) - a_{c_t}\}$$

$$y_{t-L} = A \hat{C}_{t-1} + B u_{t-1}$$

$$G_{t-L} = I.$$

When the *state* vectors are also *decoupled* in the *space* domain those subsystems are indicated by equations (17), (16) and (15). In fact, Lange's revised High-pass Filter algorithm as specified by the formulae (20) will do the whole job in one go if only the detailed substructures are permuted to conform with the overall block-angular form of equation (18).

For a Continuous Kalman Filter: $u_t = F(t) \Delta t b_t$ (Gelb 1974, pp.122-124).

Referring now to Fig. 2, a specific embodiment of a prior art navigation system using a decentralized Kalman Filtering technique will be explained. As suggested by the block diagram, Federated Filtering (Neal A. Carlson, 1988: "Federated Filter for Fault-Tolerant Integrated Navigation Systems", Proceedings of the IEEE 1988 PLANS, IEEE AES Society, see figure 1 on page 111) is a two-stage data processing technique in which the outputs of local, sensor-related filters are subsequently processed and combined by a larger master filter. Each local filter is dedicated to a separate subsystem of sensors. One or more local filters may also use data from a common reference system, e.g., an inertial navigation system (INS). The advantages over an prior art centralized Kalman filtering technique are an increased total system throughput by parallel operation of local filters and a further increase of system throughput by using the local filters for data compression. Approaches of this kind have been absolutely necessary for large multi-sensor navigation systems because of high-speed computing requirements. From the viewpoint of a prior art centralized Kalman Filter of a large sensor system, these approaches for speeding up the computations fall into the two general categories of approximative methods i.e. *decoupling states* and *prefiltering for data compression* (see e.g. Gelb, 1974: "Applied Optimal Estimation", MIT Press, pages 289-291). The disadvantages are that an approximative Kalman Filter never is strictly optimal and, consequently, its stability becomes more or less uncertain. In any case, the stability is more difficult to establish in a theoretically rigorous way.

Referring now to Fig. 3, a block diagram of the apparatus of the invention that makes use of a theoretically

sound yet practical centralized Kalman an Filtering method will be described.

As can be seen by comparing Figs. 1 and 3, the logic unit (1) of the invention has a two-way communication link to the data base unit (2) whereas the prior art logic unit (11) can only read from its data base unit (12). In order the prior art sensor and calibration unit to operate properly, the data base unit (12) must have an appropriate collection of data regarding sensor (13) performance. Such information must be empirically established, and often needs to be re-established at adequate intervals, for each individual sensor (13) by sequentially exposing each sensor (13) to a number of known external events of known magnitudes. This is not possible in many cases of practical importance; consider e.g. a radiometric sensor of an orbiting weather satellite. In contrast, the logic unit (1) of the invention has a capability of stretching and updating the calibration information collected in its data base (2) assuming only that a certain observability condition of Kalman Filtering is satisfied.

As can be seen by comparing Figs. 2 and 3, the Federated Kalman Filter solution is the same as that of a single, centralized Kalman Filter only if the information fusion and division operations are performed after every local filter measurement update cycle (and when the master filter should be able to cope with the large Kalman Filtering problem without any help from *decoupling states*). Thus, the prior art solution of Fig. 2 is theoretically inferior because it is a full centralized Kalman Filter solution of Fig. 3 that yields optimal results as shown by Kalman in 1960 or, in fact, by Gauss and Markov already in the early 1800. However, the computation load of a prior art centralized Kalman Filter is proportional to n^3 where n is the number of the *state* parameters i.e. the number of all unknown quantities that need to be solved for an update of the process parameter estimates.

Pursuant to use of this apparatus and method, simple and inexpensive sensors can be fully exploited without too much regard for their internal calibration provisions and the speed of logic units. Despite use of entirely uncalibrated but predictable sensors, accurate results can be obtained in real-time applications through use of the calibration and standardization method and apparatus disclosed herein.

The invented Fast Kalman Filtering (FKF) method is based on the general principle of *decoupling states*. The use of Lange's analytical sparse-matrix inversion method is pursuant to the invention (see e.g. Lange, 1988a). Because the solution is straightforward and exact the optimality of a large centralized Kalman Filter can be achieved with a hard-to-beat computational efficiency.

Those skilled in the art will appreciate that many variations could be practiced with respect to the above described invention without departing from the invention as claimed. Therefore, it should be understood that the scope of the invention should not be considered as limited to the specific embodiment described, except in so far as the claims may specifically include such limitations.

References

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- (4) Lange, A. A. (1988a): "A high-pass filter for optimum calibration of observing systems with applications". Simulation and Optimization of Large Systems, edited by A. J. Osadacz, Oxford University Press/Clarendon Press, Oxford, 1988, 311-327.
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Claims

1. A method for calibrating readings of a multiple sensor system, the sensors providing output signals in response to external events, the method comprising the steps of:
 - a) providing data base means for storing information on:
 - a plurality of test point sensor output signal values for some of said sensors and a plurality of values for said external events corresponding to said test point sensor output values wherein the improvement comprises minimal requirements for the amount and quality of said test point data and that uncalibrated sensors can be added;
 - said calibrated sensor readings or, alternatively, said readings accompanied with their calibration parameters and values for said external events corresponding to a situation; and,



sound yet practical centralized Kalman an Filtering method will be described.

As can be seen by comparing Figs. 1 and 3, the logic unit (1) of the invention has a two-way communication link to the data base unit (2) whereas the prior art logic unit (11) can only read from its data base unit (12). In order the prior art sensor and calibration unit to operate properly, the data base unit (12) must have an appropriate collection of data regarding sensor (13) performance. Such information must be empirically established, and often needs to be re-established at adequate intervals, for each individual sensor (13) by sequentially exposing each sensor (13) to a number of known external events of known magnitudes. This is not possible in many cases of practical importance; consider e.g. a radiometric sensor of an orbiting weather satellite. In contrast, the logic unit (1) of the invention has a capability of stretching and updating the calibration information collected in its data base (2) assuming only that a certain observability condition of Kalman Filtering is satisfied.

As can be seen by comparing Figs. 2 and 3, the Federated Kalman Filter solution is the same as that of a single, centralized Kalman Filter only if the information fusion and division operations are performed after every local filter measurement update cycle (and when the master filter should be able to cope with the large Kalman Filtering problem without any help from *decoupling states*). Thus, the prior art solution of Fig. 2 is theoretically inferior because it is a full centralized Kalman Filter solution of Fig. 3 that yields optimal results as shown by Kalman in 1960 or, in fact, by Gauss and Markov already in the early 1800. However, the computation load of a prior art centralized Kalman Filter is proportional to n^3 where n is the number of the *state* parameters i.e. the number of all unknown quantities that need to be solved for an update of the process parameter estimates.

Pursuant to use of this apparatus and method, simple and inexpensive sensors can be fully exploited without too much regard for their internal calibration provisions and the speed of logic units. Despite use of entirely uncalibrated but predictable sensors, accurate results can be obtained in real-time applications through use of the calibration and standardization method and apparatus disclosed herein.

The invented Fast Kalman Filtering (FKF) method is based on the general principle of *decoupling states*. The use of Lange's analytical sparse-matrix inversion method is pursuant to the invention (see e.g. Lange, 1988a). Because the solution is straightforward and exact the optimality of a large centralized Kalman Filter can be achieved with a hard-to-beat computational efficiency.

Those skilled in the art will appreciate that many variations could be practiced with respect to the above described invention without departing from the invention as claimed. Therefore, it should be understood that the scope of the invention should not be considered as limited to the specific embodiment described, except in so far as the claims may specifically include such limitations.

References

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- (3) Lange, A. A. (1984): "Integration, calibration and intercomparison of windfinding devices". WMO Instruments and Observing Methods Report No. 15.
- (4) Lange, A. A. (1988a): "A high-pass filter for optimum calibration of observing systems with applications". Simulation and Optimization of Large Systems, edited by A. J. Osiadacz, Oxford University Press/Clarendon Press, Oxford, 1988, 311-327.
- (5) Lange, A. A. (1988b): "Determination of the radiosonde biases by using satellite radiance measurements". WMO Instruments and Observing Methods Report No. 33, 201-206.

Claims

1. A method for calibrating readings of a multiple sensor system, the sensors providing output signals in response to external events, the method comprising the steps of:
 - a) providing data base means for storing information on:
 - a plurality of test point sensor output signal values for some of said sensors and a plurality of values for said external events corresponding to said test point sensor output values wherein the improvement comprises minimal requirements for the amount and quality of said test point data and that uncalibrated sensors can be added;
 - said calibrated sensor readings or, alternatively, said readings accompanied with their calibration parameters and values for said external events corresponding to a situation; and,



- controls of or changes in, if any, said sensors or said external events corresponding to a new situation;
- b) providing logic means for accessing said calibrated readings or, alternatively, said readings accompanied with their calibration parameters, wherein the improvement comprises both read and write so that said logic means has a two-way communications link to said data base means;
- c) providing said sensor output signals from said sensors to said logic means;
- d) providing information, if any, on said controls or changes to said data base means;
- e) updating by a Kalman recursion wherein the improvement comprises the use of an algorithm obtained from the Fast Kalman Filter (FKF) formulae (20) of the description, in said logic means (1), values of both said external events and said calibration parameters corresponding to said new situation; and,
- f) providing updated values of said calibrated readings and/or said values of said external events, as desired.
2. The method of claim 1 wherein said logic means (1) operates in a decentralized or cascaded fashion but exploits in one way or another Kalman altering wherein the improvement comprises the use of an algorithm obtained from the Fast Kalman Filter (FKF) formulae (20) of the description.
3. A calibration apparatus for use with a multiple sensor system that provides substantially predictable sensor outputs in response to a monitored event, the apparatus comprising:
- a) data base means for storing information on a plurality of sensor output values for each sensor with which the calibration apparatus will be used and a plurality of values for said external event corresponding to a situation and to some test points wherein the improvement comprises minimal requirements for the amount and quality of said test point data and that uncalibrated sensors can be added; and,
- b) logic means (1), based on Kalman filtering wherein the improvement comprises the use of an algorithm obtained from the Fast Kalman Filter (FKF) formulae (20) of the description, operably connected to said multiple sensor system for receiving said sensor outputs and further being operably connected to said data base means for accessing and updating said information on said plurality of sensor output values and said plurality of values for said external event, for providing an output that comprises calibrated readings for said multiple sensor system and/or, as desired, current values of said external event that may all be substantially standardized to preselected standards.
4. The apparatus of claim 3 wherein said logic means (1) operates in a decentralized or cascaded fashion but exploits in one way or another Kalman filtering wherein the improvement comprises the use of an algorithm obtained from the Fast Kalman Filter (FKF) formulae (20) of the description.
5. The method of claim 1 including the step of:
- a) adapting by using Kalman filtering wherein the improvement comprises the use of an algorithm obtained from the Fast Kalman Filter (FKF) formulae (20) of the description, in said logic means (1), said information on said controls of or changes in said sensors or said external events as far as their true magnitudes are unknown.
6. The method of claim 2 including the step of:
- a) adapting by using Kalman filtering wherein the improvement comprises the use of an algorithm obtained from the Fast Kalman Filter (FKF) formulae (20) of the description, in said logic means (1), said information on said controls of or changes in said sensors or said external events as far as their true magnitudes are unknown.
7. A data-assimilation apparatus for use with an observing system and a dynamical prediction system that provides substantially predictable outputs in response to a monitored event, the apparatus comprising:
- a) data base means for storing information on a plurality of sensor output values for each sensor system with which the apparatus will be used and a plurality of values including their changes predicted by said dynamical system for said external event and for some test points wherein the improvement comprises minimal requirements for the amount and quality of said test point data and that uncalibrated sensors can be added; and,
- b) logic means (1), based on Kalman filtering wherein the improvement comprises the use of an algorithm obtained from the Fast Kalman Filter (FKF) formulae (20) of the description, operably connected to said observing and prediction systems for receiving said sensor outputs and further being operably connected to said data base means for accessing and updating said information on said plurality of sensor output values and said plurality of values and predicted changes for said external event, for pro-



viding an output that comprises calibrated readings for said observing system and/or, as desired, current values of said external event.

- 5 8. A prediction apparatus for use with an observing system and a dynamical prediction system that provides substantially predictable outputs ahead of monitored events, the apparatus comprising:
 - a) data base means for storing information on a plurality of sensor output values for each sensor system with which the apparatus will be used and a plurality of values including their changes predicted by said dynamical system for said external events and for some test points wherein the improvement comprises minimal requirements for the amount and quality of said test point data and that uncalibrated sensors can be added; and,
 - 10 b) logic means (1), based on Kalman filtering wherein the improvement comprises the use of an algorithm obtained from the Fast Kalman Filter (FKF) formulae (20) of the description, operably connected to said observing and prediction systems for receiving said sensor outputs and further being operably connected to said data base means for accessing and updating said information on said plurality of sensor output values and said plurality of values and predicted changes for said external events, for providing an output that comprises predicted readings for said observing system and/or, as desired, predicted values of said external events.
- 15 9. A control apparatus for use with a sensor system and a dynamic system that provides substantially predictable state parameters of said dynamic system, the apparatus comprising:
 - 20 a) data base means for storing information on a plurality of sensor output values for said sensor system with which the apparatus will be used and a plurality of values, controls and changes predicted by a model of said dynamic system for said state parameters and for some test points wherein the improvement comprises minimal requirements for the amount and quality of said test point data and that uncalibrated sensors can be added; and,
 - 25 b) logic means (1), based on Kalman altering wherein the improvement comprises the use of an algorithm obtained from the Fast Kalman Filter (FKF) formulae (20) of the description, operably connected to said sensor and dynamic systems for receiving said sensor outputs and said controls and further being operably connected to said data base means for accessing and updating said information on said plurality of sensor output values and said plurality of values, controls and predicted changes for said state parameters, for providing an output that comprises calibrated/predicted readings for said sensor system and/or current/predicted values of said state parameters, as desired.
- 30 10. Apparatus of claim 7, 8 or 9 wherein said logic means (1) operates in a decentralized or cascaded fashion but exploits in one way or another Kalman altering wherein the improvement comprises the use of an algorithm obtained from the Fast Kalman Filter (FKF) formulae (20) of the description.
- 35 11. Apparatus of claim 3, 7, 8, or 9 wherein information on controls or changes in said sensors or said external events as far as their true magnitudes are unknown is adapted by using Kalman altering wherein the improvement comprises the use of an algorithm obtained from the Fast Kalman Filter (FKF) formulae (20) of the description.
- 40 12. Apparatus of claim 4 or 10 wherein information on controls or changes in said sensors or said external events as far as their true magnitudes are unknown is adapted by using Kalman altering wherein the improvement comprises the use of an algorithm obtained from the Fast Kalman Filter (FKF) formulae (20) of the description.
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Patentansprüche

- 50 1. Eine Methode, um Lesungen eines Multisensorsystems fein zu messen; die Sensoren geben Ausgabesignale in Reaktion auf äussere Ereignisse; die Methode enthält folgende Schritte:
 - a) Versorgung von Datenbasismitteln für die Aufspeicherung von Information über:
 - eine Vielzahl von Testpunktsensorausgabesignalwerten für einige der besagten Sensoren und
 - 55 eine Vielzahl von Werten für die besagten äusseren Ereignisse, die den besagten Testpunktsensorausgabewerten entsprechen, wobei die Verbesserung in minimalen Anforderungen für die Menge und Qualität der besagten Testpunktdaten besteht und darin, dass ungemessene Sensoren hinzugefügt werden können;



- die besagten fein gemessenen Sensorenlesungen oder, als Alternative, die besagten Lesungen zusammen mit ihren Messungsparametern und Werten für die besagten äusseren Ereignisse, die einer Situation entsprechen; und,
- Kontrollen von oder Veränderungen in, wenn vorhanden, besagten Sensoren oder besagten äusseren Ereignissen, die einer neuen Situation entsprechen;
- b) Versorgung von Logischen Mitteln, um die besagten feingemessenen Lesungen oder, als Alternative, die besagten Lesungen zusammen mit ihren Messungsparametern zu erhalten, wobei die Verbesserung sowohl Lesen als auch Schreiben beinhaltet, so dass die besagten Logischen Mittel eine zweigleisige Kommunikationsverbindung zu den besagten Datenbasismitteln haben;
- c) Ermöglichung der besagten Sensorenausgabesignale von den besagten Sensoren zu den besagten Logischen Mitteln;
- d) Versorgung von Information, wenn vorhanden, über besagte Kontrollen oder Veränderungen zu den besagten Datenbasismitteln;
- e) Auf den neuesten Stand bringen durch eine Kalman Rekursion, wobei die Verbesserung in dem Gebrauch eines Algorithmuses besteht, der durch die Fast Kalman Filter (FKF) Formel (20) der Beschreibung erhalten wird, in besagten Logischen Mitteln, von Werten von sowohl besagten äusseren Ereignissen als auch von besagten fein gemessenen Parametern entsprechend der besagten neuen Situation; und,
- f) Auf Verlangen, Versorgung von auf den neuesten Stand gebrachten Werten der besagten fein gemessenen Lesungen und/oder von den besagten Werten der besagten äusseren Ereignisse.
2. Die Methode von Anspruch 1, wobei die besagten Logischen Mittel (1) in einer dezentralisierten oder kaskadenartigen Form wirken, aber in der einen oder der anderen Weise die Kalman Filterung ausnutzen, wobei die Verbesserung in dem Gebrauch eines Algorithmuses besteht, der von der Fast Kalman Filter (FKF) Formel (20) der Beschreibung erhalten wird.
3. Ein Feinmessungsgerät für den Gebrauch mit einem Multisensorsystem, das wesentlich voraussagbare Sensorenausgaben in Reaktion auf ein untersuchtes Ereignis gibt; das Gerät besteht aus:
- a) Datenbasismitteln zur Speicherung von Information über eine Vielzahl von Sensorenausgabewerten für jeden Sensor, mit dem das Feinmessungsgerät benutzt werden wird, und über eine Vielzahl von Werten für besagtes äusseres Ereignis in Bezug auf eine Situation und auf einige Testpunkte, wobei die Verbesserung in minimalen Anforderungen für die Menge und Qualität der besagten Testpunktdaten besteht und darin, dass ungemessene Sensoren hinzugefügt werden können; und,
- b) Logischen Mitteln, die auf der Kalman Filterung basieren, wobei die Verbesserung in dem Gebrauch eines Algorithmuses besteht, der von der Fast Kalman Filter (FKF) Formel (20) der Beschreibung erhalten wird, die wirksam mit dem besagten Multisensorsystem verbunden sind, um besagte Sensorenausgaben zu empfangen, und die weiter wirksam mit den besagten Datenbasismitteln verbunden sind, um Zugang zu besagter Information über die besagte Vielzahl von Sensorenausgabewerten und über die besagte Vielzahl von Werten für eine besagtes äusseres Ereignis zu geben, und um sie auf den neuesten Stand zu bringen, um eine Ausgabe zu gewährleisten, die fein gemessene Lesungen für besagtes Multisensorsystem und/oder, wie verlangt, aktuelle Werte des besagten äusseren Ereignisses umfasst, die alle wesentlich nach den vorherdefinierten Mustern genormt werden können.
4. Das Gerät des Anspruches 3, wobei die besagten Logischen Mittel (1) in einer dezentralisierten oder kaskadenartigen Form arbeiten, aber in der einen oder anderen Weise die Kalman Filterung ausnutzen, wobei die Verbesserung in dem Gebrauch eines Algorithmuses besteht, der von der Fast Kalman Filter (FKF) Formel (20) der Beschreibung erhalten wird.
5. Die Methode des Anspruches 1 beinhaltet den Schritt:
- a) der Anpassung durch den Gebrauch der Kalman Filterung, wobei die Verbesserung in dem Gebrauch eines Algorithmuses besteht, der von der Fast Kalman Filter (FKF) Formel (20) der Beschreibung erhalten wird, in besagten Logischen Mitteln, von besagter Information über besagte Kontrollen von oder Veränderungen in besagten Sensoren oder besagten äusseren Ereignissen so weit wie ihre wahren Grössen unbekannt sind.
6. Die Methode des Anspruches 2 beinhaltet den Schritt:
- a) der Anpassung durch den Gebrauch der Kalman Filterung, wobei die Verbesserung in dem Gebrauch eines Algorithmuses besteht, der von der Fast Kalman Filter (FKF) Formel (20) der Beschreibung



erhalten wird, in besagten Logischen Mitteln, von besagter Information über besagte Kontrollen von oder Veränderungen in besagten Sensoren oder besagten äusseren Ereignissen so weit wie ihre wahren Grössen unbekannt sind.

- 5 7. Ein Datenaufnahmegerät zum Gebrauch mit einem Beobachtungssystem und einem dynamischen Prognosesystem, das wesentlich voraussagbare Ausgaben in Bezug auf ein untersuchtes Ereignis gibt; das Gerät besteht aus:
- 10 a) Datenbasismitteln zur Aufspeicherung von Information über eine Vielzahl von Sensorenausgabewerten für jedes Sensorensystem, mit dem das Gerät gebraucht werden wird, und über eine Vielzahl von Werten einschliesslich ihrer Veränderungen, die durch das besagte dynamische System für besagte äussere Ereignisse und für einige Testpunkte vorausgesagt werden, wobei die Verbesserung in minimalen Anforderungen für die Menge und Qualität der besagten Testpunktdaten besteht und darin, dass ungemessene Sensoren hinzugefügt werden können; und,
- 15 b) Logischen Mitteln (1), die auf der Kalman Filterung basiert sind, wobei die Verbesserung in dem Gebrauch eines Algorithmuses besteht, der von der Fast Kalman Filter (FKF) Formel (20) der Beschreibung erhalten wird, die wirksam mit den besagten Beobachtungs- und Prognosesystemen verbunden sind, um besagte Sensorenausgaben zu empfangen, und die weiter wirksam mit dem besagten Datenbasismitteln verbunden sind, um Zugang zu besagter Information über die besagte Vielzahl von Sensorenausgabewerten und über die besagte Vielzahl von Werten und vorausgesagten Veränderungen für ein besagtes äusseres Ereignis zu geben, und um sie auf den neuesten Stand zu bringen, um eine Ausgabe zu gewährleisten, die fein gemessene Lesungen für besagtes Beobachtungssystem und/oder, wie verlangt, aktuelle Werte des besagten äusseren Ereignisses umfasst.
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8. Ein Prognosegerät für den Gebrauch mit einem Beobachtungssystem und einem dynamischen Prognosesystem, das wesentlich voraussagbare Ausgaben im voraus zu untersuchten Ereignissen gibt; das Gerät beinhaltet:
- 25 a) Datenbasismittel zur Aufspeicherung von Information über eine Vielzahl von Sensorenausgabewerten für jedes Sensorensystem, mit dem das Gerät gebraucht werden wird, und über eine Vielzahl von Werten einschliesslich ihrer Veränderungen, die durch das besagte dynamische System für besagte äussere Ereignisse und für einige Testpunkte vorausgesagt werden, wobei die Verbesserung in minimalen Anforderungen für die Menge und Qualität der besagten Testpunktdaten besteht und darin, dass ungemessene Sensoren hinzugefügt werden können; und,
- 30 b) Logische Mittel (1), die auf der Kalman Filterung basiert sind, wobei die Verbesserung in dem Gebrauch eines Algorithmuses besteht, der von der Fast Kalman Filter (FKF) Formel (20) der Beschreibung erhalten wird, die wirksam mit den besagten Beobachtungs- und Prognosesystemen verbunden sind, um besagte Sensorenausgaben zu empfangen, und die weiter wirksam mit den besagten Datenbasismitteln verbunden sind, um Zugang zu besagter Information über die besagte Vielzahl von Sensorenausgabewerten und über die besagte Vielzahl von Werten und vorausgesagten Veränderungen für besagte äussere Ereignisse zu geben, und um sie auf den neuesten Stand zu bringen, um eine Ausgabe zu gewährleisten, die vorausgesagte Lesungen für das besagte Beobachtungssystem und/oder, wie verlangt, vorausgesagte Werte von besagten äusseren Ereignissen umfasst.
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9. Ein Kontrollgerät für den Gebrauch mit einem Sensorensystem und einem dynamischen System, das wesentlich voraussagbare Zustandsparameter des besagten dynamischen Systems ermöglicht; das Gerät besteht aus:
- 40 a) Datenbasismitteln zur Aufspeicherung von Information über eine Vielzahl von Sensorenausgabewerten für besagtes Sensorensystem, mit dem das Gerät gebraucht werden wird, und über eine Vielzahl von Werten, Kontrollen und Veränderungen, die durch ein Modell des besagten dynamischen Systems für besagte Zustandsparameter und für einige Testpunkte vorhergesagt werden, wobei die Verbesserung in minimalen Anforderungen für die Menge und Qualität der besagten Testpunktdaten besteht und darin, dass ungemessene Sensoren hinzugefügt werden können; und,
- 45 b) Logischen Mitteln (1), die auf der Kalman Filterung basieren, wobei die Verbesserung in dem Gebrauch eines Algorithmuses besteht, der von der Fast Kalman Filter (FKF) Formel (20) der Beschreibung erhalten wird, die wirksam mit den besagten Sensoren- und dynamischen Systemen verbunden sind, um besagte Sensorenausgaben und besagte Kontrollen zu empfangen, und die weiter wirksam mit den besagten Datenbasismitteln verbunden sind, um Zugang zu besagter Information über die besagte Vielzahl von Sensorenausgabewerten und über die besagte Vielzahl von Werten, Kontrollen und vorausgesagten Veränderungen für besagte Zustandsparameter zu geben, und um sie auf den neu-
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esten Stand zu bringen, um eine Ausgabe zu gewährleisten, die feingemessene/vorausgesagte Lesungen für das besagte Sensorensystem und/oder, wie verlangt, aktuelle/vorausgesagte Werte der besagten Zustandsparameter umfasst.

- 5 10. Das Gerät der Ansprüche 7,8 oder 9, wobei die besagten Logischen Mittel in einer dezentralisierten oder kaskadenartigen Form wirken, aber in der einen oder der anderen Weise die Kalman Filterung ausnutzen, wobei die Verbesserung in dem Gebrauch eines Algorithmus besteht, der von der Fast Kalman Filter (FKF) Formel (20) der Beschreibung erhalten wird.
- 10 11. Das Gerät der Ansprüche 3,7,8 oder 9, wobei die Information über Kontrollen oder Veränderungen in besagten Sensoren oder besagten äusseren Ereignissen, so weit wie ihre wahren Grössen unbekannt sind, durch den Gebrauch der Kalman Filterung angepasst ist, wobei die Verbesserung in dem Gebrauch eines Algorithmus besteht, der von der Fast Kalman Filter (FKF) Formel (20) der Beschreibung erhalten wird.
- 15 12. Das Gerät der Ansprüche 4 oder 10, wobei die Information über Kontrollen oder Veränderungen in besagten Sensoren oder besagten äusseren Ereignissen, so weit wie ihre wahren Grössen unbekannt sind, durch den Gebrauch der Kalman Filterung angepasst ist, wobei die Verbesserung in dem Gebrauch eines Algorithmus besteht, der von der Fast Kalman Filter (FKF) Formel (20) der Beschreibung erhalten wird.

20 Revendications

- 25 1. Une méthode pour calibrer les lectures d'un système multi-senseurs, les senseurs pourvoyant des signaux de sortie en réponse à des événements externes, la méthode comprenant les étapes suivantes:
 - a) pourvoir des moyens de base de données afin d'enregistrer des informations sur:
 - une pluralité de valeurs du signal de sortie du point de test du senseur pour certains desdits senseurs et une pluralité de valeurs pour lesdits événements externes qui correspondent aux dites valeurs de sortie du point de test du senseur là où l'amélioration comprend des exigences minimales quant à la quantité et la qualité desdites données du point de test et que des senseurs non calibrés peuvent être ajoutés;
 - lesdites lectures calibrées des senseurs ou, alternativement, lesdites lectures accompagnées de leurs paramètres de calibrage et des valeurs desdits événements externes qui correspondent à une situation; et,
 - des contrôles ou des changements, s'il y a lieu, desdits senseurs ou desdits événements externes qui correspondent à une nouvelle situation;
 - 35 b) pourvoir des moyens logiques pour accéder aux dites lectures calibrées ou, alternativement, aux dites lectures accompagnées de leurs paramètres de calibrage, là où l'amélioration comprend des lectures et des écritures, de manière que lesdits moyens logiques ont un lien de communication dans les deux sens avec lesdits moyens de base de données;
 - 40 c) pourvoir lesdits signaux de sortie du senseur, desdits senseurs aux dits moyens logiques;
 - d) pourvoir des informations, s'il y a lieu, desdits contrôles ou changements aux dits moyens de base de données;
 - 45 e) actualisation par l'usage d'une récurrence Kalman là où l'amélioration comprend l'utilisation d'un algorithme obtenu de la formule (20) Fast Kalman Filter (FKF) de la description, dans lesdits moyens logiques (1), des valeurs desdits événements externes et desdits paramètres de calibrage correspondant à la nouvelle situation; et,
 - f) pourvoir des valeurs actualisées desdites lectures calibrées et/ou desdites valeurs desdits événements externes, comme désiré.
- 50 2. La méthode de la revendication 1 là où lesdits moyens, logiques (1) opèrent de manière décentralisée ou en cascade mais exploitent d'une manière ou d'une autre la filtration Kalman là où l'amélioration comprend l'utilisation d'un algorithme obtenu de la formule (20) Fast Kalman Filter (FKF) de la description.
- 55 3. Un appareil de calibration qui soit utilisé avec un système multi-senseur qui pourvoit des signaux de sortie des senseurs substantiellement prévisibles en réponse à un événement examiné; l'appareil comprenant:
 - a) des moyens de bases de données pour l'enregistrement d'information d'une pluralité de valeurs de sortie du senseur pour chaque senseur avec lesquels l'appareil de calibration sera utilisé et une pluralité de valeurs pour lesdits événements externes correspondant à une situation et à quelques points test



là où l'amélioration comprend des exigences minimales quant à la quantité et la qualité desdites données des points test et que des senseurs non calibrés peuvent être ajoutés; et

b) des moyens logiques (1), basés sur la filtration Kalman là où l'amélioration comprend l'utilisation d'un algorithme obtenu de la formule (20) Fast Kalman Filter (FKF) de la description, connectés de manière opérationnelle au dit système multi-senseur afin de recevoir lesdites sorties des senseurs et plus loin étant connectés de manière opérationnelle aux dits moyens de base de données afin d'accéder et d'actualiser ladite information sur ladite pluralité de valeurs de sortie du senseur et ladite pluralité de valeurs dudit événement externe, afin de pourvoir une sortie qui comprend des lectures calibrées pour ledit système multi-senseur et/ou, comme désiré, des valeurs actuelles dudit événement externe qui peuvent toutes être substantiellement standardisées à des standards prédéfinis.

4. L'appareil de la revendication 3 là où lesdits moyens logiques (1) opèrent d'une manière décentralisée ou en cascade mais exploitent d'une manière ou d'une autre la filtration Kalman là où l'amélioration comprend l'utilisation d'un algorithme obtenu de la formule (20) Fast Kalman Filter (FKF) de la description.

5. La méthode de la revendication 1 incluant l'étape d':

a) adapter en utilisant la filtration Kalman là où l'amélioration comprend l'utilisation d'un algorithme obtenu de la formule (20) Fast Kalman Filter (FKF) de la description, dans lesdits moyens logiques (1), ladite information desdits contrôles, ou changements desdits senseurs ou lesdits événements externes tant que leurs vraies magnitudes sont inconnues.

6. La méthode de la revendication 2 incluant l'étape d':

a) adapter en utilisant la filtration Kalman là où l'amélioration comprend l'utilisation d'un algorithme obtenu de la formule (20) Fast Kalman Filter (FKF) de la description, dans lesdits moyens logiques (1), ladite information desdits contrôles, ou changements desdits senseurs ou lesdits événements externes tant que leurs vraies magnitudes sont inconnues.

7. Un appareil d'assimilation d'information qui soit utilisé avec un système d'observation et un système de prédiction dynamique qui pourvoit des sorties substantiellement prévisibles en réponse à un événement examiné, l'appareil comprenant:

a) des moyens de base de données afin d'enregistrer des informations sur une pluralité de valeurs de sortie du senseur pour chaque système de senseurs avec lesquels l'appareil sera utilisé et une pluralité de valeurs incluant leurs changements prédits par ledit système dynamique pour ledit événement externe et pour quelques points de test là où l'amélioration comprend des exigences minimales en ce qui concerne la quantité et la qualité desdites données du point de test et que des senseurs non calibrés peuvent être ajoutés; et,

b) des moyens logiques (1), basés sur la filtration Kalman là où l'amélioration comprend l'utilisation d'un algorithme obtenu de la formule (20) Fast Kalman Filter (FKF) de la description, connectés de manière opérationnelle au dit système d'observation et de prédiction afin que ceux-ci reçoivent lesdites sorties des senseurs et plus loin étant connectés de manière opérationnelle aux dits moyens de base de données afin d'accéder et d'actualiser ladite information sur ladite pluralité de valeurs de sortie des senseurs et ladite pluralité de valeurs et des changements prédits pour ledit événement externe, afin de pourvoir une sortie qui comprend des lectures calibrées pour ledit système d'observation et/ou, comme désiré, les valeurs actuelles dudit événement externe.

8. Un appareil de prédiction qui soit utilisé avec un système d'observation et un système de prédiction dynamique qui pourvoit des sorties substantiellement prévisibles avant les événements examinés, l'appareil comprenant:

a) des moyens de base de données pour enregistrer des informations sur une pluralité de valeurs de sortie du senseur pour chaque système de senseurs avec lesquels l'appareil sera utilisé et une pluralité de valeurs incluant leurs changements prédits par ledit système dynamique pour lesdits événements externes et pour quelques points de test là où l'amélioration comprend des exigences minimales en ce qui concerne la quantité et la qualité desdites données du point de test et que des senseurs non calibrés peuvent être ajoutés; et,

b) des moyens logiques (1), basés sur la filtration Kalman là où l'amélioration comprend l'utilisation d'un algorithme obtenu de la formule (20) Fast Kalman Filter (FKF) de la description, connectés de manière opérationnelle au dit système d'observation et de prédiction afin que ceux-ci reçoivent lesdites sorties des senseurs et plus loin étant connectés de manière opérationnelle aux dits moyens de base de don-



nées afin d'accéder et d'actualiser ladite information sur ladite pluralité de valeurs de sortie des senseurs et ladite pluralité de valeurs et des changements prévus pour lesdits événements externes, afin de pourvoir une sortie qui comprend des lectures prédites pour ledit système d'observation et/ou, comme désiré, les valeurs prédites desdits événements externes.

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9. Un appareil de contrôle qui soit utilisé avec un système de senseurs et un système dynamique qui pourvoit des paramètres d'état substantiellement prévisibles dudit système dynamique, l'appareil comprenant:

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a) des moyens de base de données pour enregistrer des informations sur une pluralité de valeurs de sortie du senseur pour ledit système de senseurs avec lequel l'appareil sera utilisé ainsi qu'une pluralité de valeurs, contrôles et changements prédits par un model dudit système dynamique pour lesdits paramètres d'état et pour quelques points test là où l'amélioration comprend des exigences minimales quant à la quantité et la qualité desdites données du point test et que des senseurs non calibrés peuvent être ajoutés; et,

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b) des moyens logiques (1), basés sur la filtration Kalman là où l'amélioration comprend l'utilisation d'un algorithme obtenu de la formule (20) Fast Kalman Filter (FKF) de la description, connectés de manière opérationnelle aux dits système de senseurs et systèmes dynamiques afin de recevoir les valeurs de sortie dudit senseur et lesdits contrôles et plus loin étant connectés de manière opérationnelle aux dits moyens de base de données afin d'accéder et d'actualiser ladite information sur ladite pluralité de valeurs de sortie des senseurs et ladite pluralité de valeurs, contrôles et changements prédits pour lesdits paramètres d'état, afin de pourvoir, une sortie qui comprend des lectures calibrées/prédites pour ledit système de senseurs et/ou des valeurs actuelles/prédites desdits paramètres d'état, comme désiré.

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10. Appareil des revendications 7, 8 ou 9 là où lesdits moyens logiques (1) opèrent de façon décentralisée ou en cascade mais exploitent d'une manière ou d'une autre la filtration Kalman là où l'amélioration comprend l'utilisation d'un algorithme obtenu de la formule (20) Fast Kalman Filter (FKF) de la description.

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11. Appareil des revendications 3, 7, 8 ou 9 là où l'information des contrôles ou des changements desdits senseurs ou desdits événements externes tant que leurs vraies magnitudes sont inconnues est adaptée en utilisant la filtration Kalman là où l'amélioration comprend l'utilisation d'un algorithme obtenu de la formule (20) Fast Kalman Filter (FKF) de la description.

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12. Appareil des revendications 4 ou 10 là où l'information des contrôles ou changements dans lesdits senseurs ou lesdits événements externes tant que leurs vraies magnitudes sont inconnues est adaptée en utilisant la filtration Kalman là où l'amélioration comprend l'utilisation d'un algorithme obtenu de la formule (20) Fast Kalman Filter (FKF) de la description.

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