Serial No. 449,475

Filing Date 25 May 1995

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DEPARTMENT OF THE NAVY
CODE OOCC3
ARLINGTON VA 22217-5660

Navy Case No. 76745

ENHANCED ADAPTIVE STATISTICAL FILTER PROVIDING IMPROVED PERFORMANCE FOR TARGET MOTION ANALYSIS NOISE DISCRIMINATION

STATEMENT OF GOVERNMENT INTEREST

The invention described herein may be manufactured by or for the Government of the United States of America for Governmental purposes without the payment of any royalties thereon or therefor.

CROSS-REFERENCE TO RELATED PATENT APPLICATION

This patent application is co-pending with a related patent application entitled ENHANCED ADAPTIVE STATISTICAL FILTER PROVIDING SPARSE DATA STOCHASTIC MENSURATION FOR RESIDUAL ERRORS TO IMPROVED PERFORMANCE FOR TARGET MOTION ANALYSIS NOISE DISCRIMINATION, Navy Case 76744, of which Francis J. O'Brien, Jr., is the inventor.

BACKGROUND OF THE INVENTION

(1) Field of the Invention

The invention is generally related to the field of signal processing, primarily digital signal processing, and more particularly to the field of systems for performing target motion analysis. The invention provides an improved adaptive statistical decorrelation system for enhancing noise discrimination.

(2) Description of the Prior Art

Relative motion analysis is employed in a number of applications, including target motion analysis and robotics systems, to determine the range, bearing, speed, velocity and direction of motion (velocity) of an object relative to a sensor. In relative motion analysis, either or both of the object and the sensor may be stationary or in motion. Typical relative motion analysis systems include a sensor, a motion analysis processing arrangement and a filter. The sensor, typically a sonar or radar sensor, provides a data stream representing signals emanating from or reflected off the object, as received or observed by the sensor. The data stream includes not only the desired signal, representing information as to the object's position and motion relative to the sensor, but also undesirable random noise, such as that induced by the medium through which the signal travels. The filter is provided to reduce or eliminate the noise, effectively extracting from the data stream the portion representative of the object's position and motion relative to the sensor. The filter provides the extracted portion to the motion analysis processing arrangement, which uses the data stream to generate estimates of the position, and velocity of the object relative to the sensor.

Prior relative motion analysis systems that made use of single fixed-order filters did not provide optimum performance of extracting the desired portion of the data stream. On the other hand, a system including a plurality of filters of diverse orders, and an arrangement for determining the filter whose order provides an optimal performance is disclosed in U. S. Patent No. 5,144,595, issued September 1, 1992, to Marcus L. Graham, et al., entitled Adaptive Statistical Filter Providing Improved Performance For Target Motion Analysis Discrimination, assigned to the assignee of the present application, which patent is hereby incorporated by reference. The system described in the Graham patent provides better performance than prior systems that used only single fixed-order filters. However, the design of the system described in the Graham patent is based on the assumption that the noise component is completely random and that the noise component of the data stream at each point in time is completely uncorrelated to the noise component at successive points in time. This assumption is not necessarily correct. For many known sensors and data gathering techniques there is often a correlation between the portion of the noise component in the data stream at successive points in time.

Typically, for example, the data stream representation at a particular point in time as provided by typical sensors used with a relative motion, or kinematics, analysis system is not just the instantaneous value of the signal as detected by the sensor at that point in time. Indeed, the value D_n that is provided for a particular point in time T_n is essentially taken over a window, termed the sample integration time, that the sensor requires to actually determine a value. In that technique, the sensor will receive a continuous stream of data d_T, and, for each time t_T for which it provides a value D_T, it will report the value as effectively the normalized sum of the value d_T actually detected by the sensor at time t_T, and weighted values detected at selected previous points in time in the window defining the sample integration time. Otherwise stated, for each time t_T

$$D_T = A\left[d_t + \sum_{k=1}^{K} c_k d_{T-k} \right] \qquad (1).$$

In equation, Eqn. 1, each "c_k" represents a weighting coefficient, and "A" represents a normalization factor. Typically, the weighting coefficients c_k will be positive, but will decrease toward zero as "k" increases, so that the contribution of components d_{T-k} to the data value D_T as provided by the sensor will decrease as their displacement from time t_T increases. Otherwise stated, the values d_{T-k} as detected by the sensor which are detected by the sensor closer to the time t_T at which the sensor will provide a data value D_T will provide a greater contribution to the value of D_T.

The particular function selected for the weighting coefficients c_k will be selected based on a number of factors; in the typical case, the weighting coefficients may be, for example, an exponential function, in which case the coefficients will decrease exponentially. In any case, it will be apparent from equation Eqn. 1, since that D_T, the value of the data stream at each point in time as provided by the sensors, includes some components from values d_{T-K} to d_T as detected by the sensor, and since these values include a noise component as detected by the sensor at the respective points in time in the window, if, as is generally the case, there is an overlap in windows for successive points in time t_T, there will be a correlation between the noise component of values D_T provided at successive points in time.

U. S. Patent Application Ser. No. 08/127,145, filed 22 September 1993, (Navy Case 74980) in the name of Francis J. O'Brien, et al., entitled "Enhanced Adaptive Statistical Filter Providing Improved Performance for Target Motion Analysis Noise Discrimination," assigned to the assignee of the present application, discloses a system that incorporates a pre-whitener which pre-whitens the signal from the sensors in relation to noise correlation induced by the sensor's sampling and integration methodology. The pre-whitening serves to reduce correlation of the noise components which might be introduced by the sensor.

SUMMARY OF THE INVENTION

An Object of the invention is to provide a new and improved adaptive statistical decorrelator providing improved performance for target motion analysis noise discrimination, in particular an improvement in the system disclosed in the aforementioned U. S. Patent Application Ser. No. 08/127,145, which further reduces correlation of noise components in a relative motion analysis system.

In brief summary, the relative motion analysis system includes an adaptive statistical filter system for receiving data streams comprising a series of data values from a sensor associated with successive points in time. Each data value includes a data component representative of the motion of a target and a noise component, with the noise components of data values associated with proximate points in time being correlated. The adaptive statistical filter system includes a prewhitener module, a plurality of statistical filters of different orders, a correlation mensuration and decorrelation module and a selection module. The prewhitener module receives the data stream from the sensor and generates a corrected data stream comprising a series of corrected data values each associated with a data value of the data stream, each including a data component and a noise component with the noise components of data values associated with proximate points in time being decorrelated. The plural statistical filters are coupled to receive the corrected data stream in parallel from the prewhitener. Each statistical filter generates coefficient values to fit the corrected data stream to a polynomial of corresponding order and fit values representative of the degree of fit of the corrected data stream to the polynomial. The correlation mensuration and decorrelation module performs a hypothesis test to determine whether the degree of correlation in the data stream is statistically significant. If the degree of correlation is statistically significant, the correlation mensuration and decorrelation module further generates decorrelated fit values using an autoregressive moving average methodology which assesses the noise components of the statistical filter. The selection module receives the decorrelated fit values and coefficient values from the plural statistical filters and selects coefficient values from one of the filters in response to the decorrelated fit values. The coefficient values are coupled to a target motion analysis module which determines position and velocity of the target.

BRIEF DESCRIPTION OF THE DRAWINGS

This invention is pointed out with particularity in the appended claims. The above and further advantages of this invention may be better understood by referring to the following description taken in conjunction with the accompanying drawing, in which:

FIG. 1 is a functional block diagram of a relative motion analysis system as constructed in accordance with the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. 1 is a functional block diagram of a relative motion analysis system 10 as constructed in accordance with the invention. With reference to FIG. 1, system 10 includes a sensor 11, a prewhitener 12, a filter module 13 and a target motion analysis module 17. The sensor 11 generates, at successive points in time t_T a measurement data stream D_T, which includes data regarding a target (not shown), plus noise introduced by the communication channel between the target and the sensor 11, and provides the data stream D_T to the prewhitener 12. The measurement data stream provided by the sensor generally comprises data values representative of the kinematics associated with the relative positions of the target and the sensor, for example, the angle of arrival of a sonar or radar signal detected by the sensor 11 at each point in time. Each data value provided by the sensor effectively reflects the value of the detected signal at a particular point of time as well as the values of the detected signal at proximate points of time over a predetermined time window which precedes time t_T, with the contribution provided by the values diminishing with increasing time interval from the particular point in time with which the data value is associated. In one particular embodiment, the contribution to the data value D_T generated by the sensor at each time t_T provided by values of the detected signal from the sensor 11 prior to time t_T decreases in accordance with an exponential weighting function, as described above in connection with equation Eqn. 1.

Since the data value D_T provided by the sensor 11 associated with each point in time t_T reflects the values of signals, including the desired signal and the noise, as detected at previous points in time, there is a degree of correlation of noise in the data values associated with proximate points in time. The prewhitener 12 receives the data values from the sensor 11, and generates corrected data values in which the noise is effectively de-correlated, effectively "whitening" the noise element in the corrected data stream that is provided to the filter module 13. The operation of the prewhitener 12 will be described below.

The filter module 13 receives the corrected data stream and processes it to generate values representing a fit of the corrected data stream to a curve defined by a polynomial of one of a selected series of orders, which are transmitted to the target motion analysis module 17. For details of the basic operational groundwork performed by filter module 13 and for details of target motion analysis module 17, see the aforementioned U. S. Patent No. 5,144,595, issued September 1, 1992, to Graham, et al. Generally, the filter module includes a plurality of Kalman filters 14(0) through 14(2) [generally identified by reference numeral 14(i)], where index "i" identifies the model order of the regression curve used in the respective filter 14(i). Thus, Kalman filter 14(0) uses a zeroth order Kalman filter, Kalman filter 14(1) uses a first order regression model, and Kalman filter 14(2) uses a second order regression model. Each Kalman filter 14(i), as is typical, receives an input data stream from the prewhitener 12 and generates an output comprised of data values that represent coefficients of a fit of the input data stream to a curve defined by a polynomial of the same order "i", using an adaptive least-squares fit technique.

Thus, the Kalman filter 14(0) generates values reflecting a fit of the data stream input to it to a curve defined by a zeroth order polynomial, Kalman filter 14(1) generates values reflecting a fit of the data stream input to it to a curve defined by a first order polynomial, and Kalman filter 14(2) generates values reflecting a fit of the data stream input to it to a curve defined by a second order polynomial. In addition, each Kalman filter 14(i) generates an error value $E_i(t)$ reflecting the difference between the curve defined by the values generated by it to the actual data values input to it, effectively constituting residual error values reflecting the goodness of the fit to the curve of the respective order "i."

Each Kalman filter 14(i) provides the data values to a correlation mensuration and decorrelation module 15 over a line 20(i), and the error values $E_i(t_T)$ to the module 15 over a line 21(i). The correlation mensuration and decorrelation module 15 transfers the data values to a sequential comparator module 16 for processing as described below, and processes the error values in connection with an autoregressive moving average methodology, as will be described below in more detail, to generate decorrelated residual error values $E_i{*}(t_T)$ that are substantially completely decorrelated.

The sequential comparator module 16 receives the data values and the decorrelated residual error values $E_i{*}(t_T)$ for each time

"t_T" from the correlation mensuration and decorrelation module 15 and performs a pair-wise F-test operation, which is described in detail in the aforementioned Graham, et al., patent, between pairs of adjacent-order decorrelated error values $E_0*(t_T)$ and $E_1*(t_T)$, $E_1*(t_T)$ and $E_2*(t_T)$, generated by the correlation mensuration and decorrelation module 15 from residual error values $E_i(t_T)$ provided by the Kalman filters 14(i), and in response selects the highest-ordered Kalman filter 14(i) for which the F-test operation provides a result above a predetermined threshold value. Thus, the sequential comparator module 16 initially performs the F-test operation using the decorrelated error values $E_2*(t_T)$ and $E_1*(t_T)$, to generate an F-statistic value, which is also described in detail in the aforementioned Graham, et al., patent. If the F-statistic is above a predetermined threshold value, the sequential comparator module 16 selects the Kalman filter 14(2).

However, if the sequential comparator module 16 determines that the F-statistic value is not above the predetermined threshold value, it performs the F-test operation using decorrelated error values $E_1*(t_T)$ and $E_0*(t_T)$, and generates a second F-statistic value. Again, if the F-statistic value is above a predetermined threshold value [which may be different from the threshold value used for the F-statistic value generated using decorrelated error values generated from the error values provided by the Kalman filters 14(2) and 14(1)], the sequential comparator module 16 selects the Kalman filter 14(1). On the other hand, if the F-statistic value generated using the decorrelated error values $E_1*(t_T)$ and $E_0*(t_T)$ is not above the threshold value predetermined for that F-test operation, the sequential comparator module 16 selects the low-order Kalman filter 14(0).

The sequential comparator module 16 couples the data values from the correlation mensuration and decorrelation module 15 and the identification "i" of the selected Kalman filter to an optimum model order and parameter estimate selection module 17. In response, the module 17 couples the data values from the selected Kalman filter 14(i) to the target motion analysis module 18. The target motion analysis module 18 uses the data values to determine range and bearing of the target in a known manner.

It will be appreciated that the Kalman filters 14(i), correlation mensuration and decorrelation module 15, sequential comparator module 16 and the optimum model order and parameter selection module 17 will perform the above-described operations iteratively, as successive values are received from the prewhitener 12 for successive points in time. Accordingly, the data values and error values provided by the Kalman filters 14(i) may be continuously updated at successive points in time, representing modification of the fits of the data input thereto to curves of the respective polynomial orders, as well as updating of the residual error values. In addition, the selection of Kalman filter 14(i) made by the sequential comparator module 16 may be continuously updated at successive points in time.

It will further be appreciated that the orders of Kalman filters need not be limited to zero through two. Thus, Kalman filters 14(i) of orders three and above may be provided in the filter module 13. If such higher-ordered Kalman filters 14(i) are provided, sequential comparator module 16 will perform a pair wise F-test operation between error values from adjacent-ordered filters as described above.

As noted above, the prewhitener 12 is provided to provide an initial decorrelation of the contribution of noise between data values D_T it receives from the sensor 11 for proximate points in time. The prewhitener 12 uses an autoregression arrangement, in one embodiment a first order autoregression arrangement in which the correlation between noise components of a current and prior data measurement is

$$E_T = p\,E_{T-1} + n \qquad (2)$$

where "E_T" and "E_{T-1}" represent the composite error term for the noise components of the data measurement for the current t_T and previous t_{T-1} times, as provided by the sensor 11 and "p" is a factor that represents the degree of correlation between the current and previous data measurement. The value of "n" represents the error term for the noise component of the current data measurement for the un-correlated portion, and effectively represents the degree of contribution of signals in the portion of the time window that the sensor 11 uses in generating the data value D_T associated with time t_T that does not overlap with the time window that the sensor uses in generating the data value D_{T-1} associated with time t_{T-1}. The prewhitener 12 subtracts the quantity "p" times the value D_{T-1} from the value D_T to generate a value $D*_T$ in the corrected data stream for that time "t_T" for which the noise component has been de-correlated from the noise components of values in the corrected data stream at adjacent time; that is,

$$D*_T = D_T - pD_{T-1} \quad (3)$$

It will be appreciated that the prewhitener 12 will not correct the first data value D_0 it receives from the sensor 11 associated with the initial time t_0, since there is no previous data value for which the noise component will be correlated.

While the prewhitener 12 in one embodiment is being described in terms of a first-order autoregression model, it will be appreciated that other models may be used for the prewhitener, including autoregression models of second and higher order and polynomial models.

The factor "p" in equations Eqn. 2 and Eqn. 3 will be determined by the particular mechanism used by the sensor 11 to correlate signal values received by it to generate data values that it provides to the prewhitener 12, which mechanism, it will be appreciated, will also result in correlation of the noise. Using the previously-described example of an exponentially-weighted mechanism, the factor "p" will be determined from a knowledge of the effective integration time "τ" (effectively the period of the time window) and the measurement sampling period "T" (that is, the time between successive measurements by the sensor 11), and is specifically given by

$$p = e^{-\left(\frac{T}{\tau}\right)} \tag{4}$$

were "e" is the mathematical constant (approximately 2.71828). It will be appreciated that the exponential function represented by equation Eqn. 4 is selected for the herein-described embodiment of prewhitener 12 since it reflects the exponential weighting function used by the sensor 11 in generating the successive data values D_T.

Using the factor "p" from equation Eqn. 4, the prewhitener 12 generates for each time t_T the values of the data stream D_T that it receives from the sensor 11 in accordance with equation Eqn. 3 to generate the corrected values D^*_T for the corrected data stream, for each time t_T after time t_0.

While the prewhitener 12 has been described as using a first-order autoregression model to generate corrected values $D*_T$, it will be appreciated by those skilled in the art that other models may be used, including second- and higher-order autoregression models and polynomial models. In addition, it will be appreciated that the particular exponential form of factor "p" defined in equation Eqn. 4 is defined in accordance with the particular model implemented by the sensor 11 to generate data values. Accordingly, factor "p" for a prewhitener 12 used in a system in which the sensor implements a different model may be determined in accordance with the particular model implemented by the sensor.

As described above, the correlation mensuration and decorrelation module 15 processes the error values it receives from the Kalman filters 14(i) in connection with an autoregressive moving average methodology to generate residual error values that are substantially completely decorrelated. In accordance with the autoregressive moving average methodology, the residual error term, $E_i(t_T)$, provided by an "i-th" order Kalman filter 14(i), for each time "t_T"=0,...,n may be expressed by

$$E_i(t_T) = \kappa_i E_i(t_T - 1) + \varepsilon_i(t_T) \qquad (5),$$

where "κ_i" represents a factor summarizing the amount of inter-residual correlation, and "$\varepsilon_i(t_T)$" represents a purely random, uncorrelated value for the error term. Generally, the value of

κ_i is given by

$$\kappa_i = \frac{\sum_{t_T=1}^{n} E_i(t_T)\, E_i(t_T-1)}{\sum_{t_T=0}^{n} E_i(t_T)^2} \qquad (6).$$

Accordingly, the correlation mensuration and decorrelation module 15, upon receiving a residual error value $E_i\ (t_T)$ from a particular Kalman filter 14(i), generates a value for κ_i in accordance with equation 6. Thereafter, the correlation mensuration and decorrelation module 15 performs a conventional statistical hypothesis test, using a conventional Durbin-Watson "d" statistic, to determine whether the value of "κ_i " represents a statistically-significant magnitude. If it determines that the value of "κ_i " represents a statistically-significant magnitude, the correlation mensuration and decorrelation module 15 generates a first-order approximation to an orthogonal error structure $E_i{*}(t_T)$ in accordance with

$$E_i{*}(t_T) = E_i(t_T) - \kappa_i E_i(t_T-1) \qquad (7).$$

The values for $E_i{*}(t_T)$ are then substituted for values $E_i\ (t_T)$ in equation 5, and the correlation mensuration and decorrelation module 15 generates new value of κ_i in accordance with equation

6, and applies the statistical significance test to determines whether the new value of κ_i is also statistically significant. If so, the correlation mensuration and decorrelation module 15 repeats the approximation in accordance with equation 7, and again generates a new value for κ_i. The correlation mensuration and decorrelation module 15 repeats these operations through a series of iterations until it determines that it has generated a value for κ_i that is statistically insignificant. At that point, as indicated in connection with equation 5, the value for $E_i{*}(t_T)$ generated in accordance with equation 7 corresponds to the value for $\varepsilon_i(t)$, the purely random,uncorrelated residual error value, which the correlation mensuration and decorrelation module 15 passes to the sequential comparator module 16 for use in connection with the F-test as described above. It will be appreciated that the correlation mensuration and decorrelation module 15 will perform these operations for each of the residual error values $E_i(t_T)$ that it receives from each of the Kalman filters 14(i) at each time "t_T," so as to provide a time series of uncorrelated residual error values $\varepsilon_i(t_T)$ for each "i-th" order Kalman filter 14(i).

The invention provides a number of advantages. In particular, the relative motion analysis system 10 constructed in accordance with the invention will provide for improved accuracy and an enhanced noise filtration without significant loss of information in the presence of correlated noise.

In light of the above, it is therefore understood that the invention may be practiced otherwise than as specifically described.

Navy Case No. 76745

ENHANCED ADAPTIVE STATISTICAL FILTER PROVIDING IMPROVED PERFORMANCE FOR TARGET MOTION ANALYSIS NOISE DISCRIMINATION

ABSTRACT OF THE DISCLOSURE

An adaptive statistical filter system for receiving a data stream comprising a series of data values from a sensor associated with successive points in time. Each data value includes a data component representative of the motion of a target and a noise component, with the noise components of data values associated with proximate points in time being correlated. The adaptive statistical filter system includes a prewhitener, a plurality of statistical filters of different orders, correlation mensuration and decorrelator module and a selector. The prewhitener generates a corrected data stream comprising corrected data values, each including a data component and a time-correlated noise component. The plural statistical filters receive the corrected data stream and generate coefficient values to fit the corrected data stream to a polynomial of corresponding order and fit values representative of the degree of fit of corrected data stream to the polynomial. The correlation mensuration and decorrelation module performs a hypothesis test to determine whether the degree of correlation is statistically significant, and, if it is, generates decorrelated fit values using an autoregressive moving average methodology which assesses

the noise components of the statistical filter. The selector receives the decorrelated fit values and coefficient values from the plural statistical filters and selects coefficient values from one of the filters in response to the decorrelated fit values. The coefficient values are coupled to a target motion analysis module which determines position and velocity of a target.

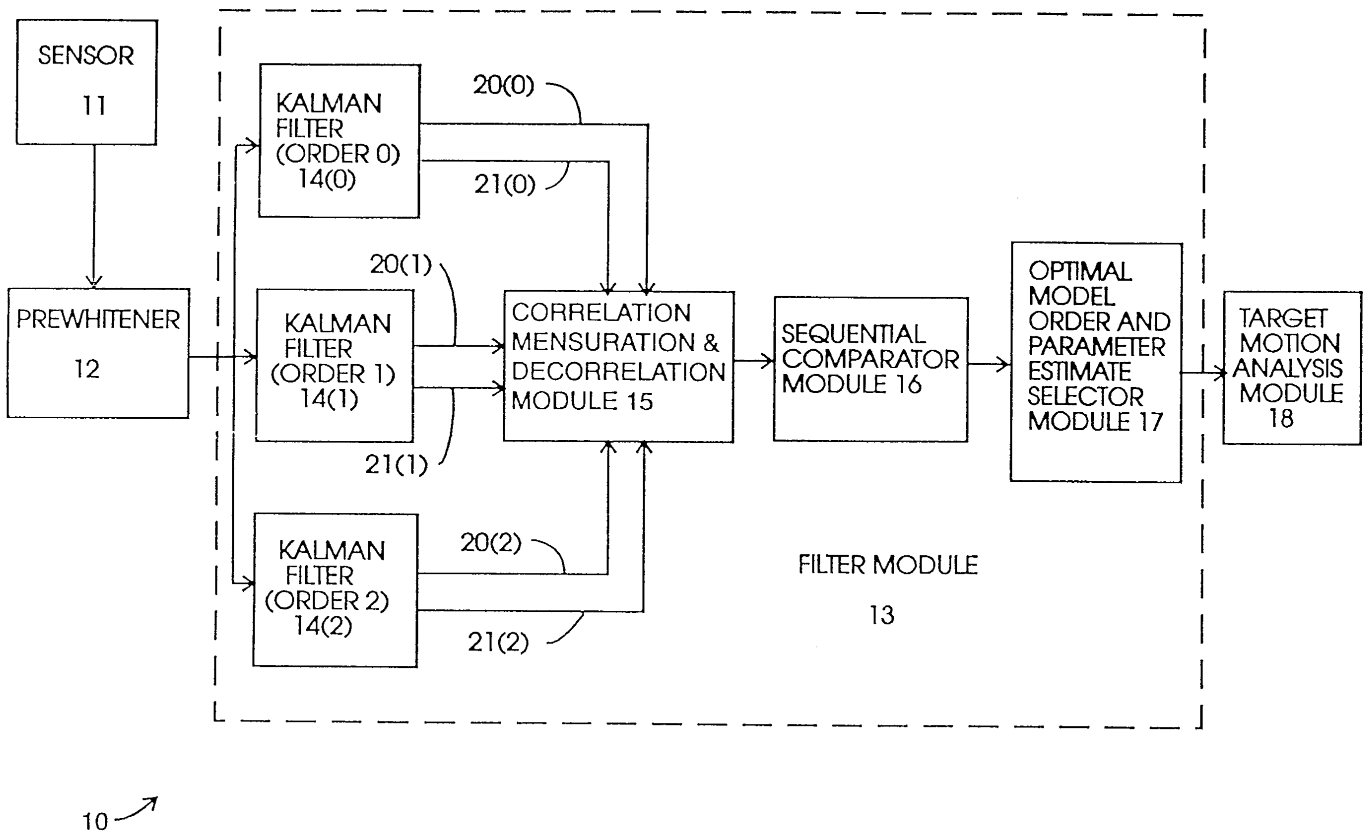
SENSOR
11
PREWHITENER
12
KALMAN FILTER (ORDER 0) 14(0)
KALMAN FILTER (ORDER 1) 14(1)
KALMAN FILTER (ORDER 2) 14(2)
20(0)
21(0)
20(1)
21(1)
20(2)
21(2)
CORRELATION MENSURATION & DECORRELATION MODULE 15
SEQUENTIAL COMPARATOR MODULE 16
OPTIMAL MODEL ORDER AND PARAMETER ESTIMATE SELECTOR MODULE 17
TARGET MOTION ANALYSIS MODULE 18
FILTER MODULE
13
10

FIG. 1