DOCTOR OF PHILOSOPHY

Performance enhancement of complex systems and processes through high dynamic precision adaptive control and sensor fusion

Vershinin, Yuri

Award date:
2019

Awarding institution:
Coventry University

Performance enhancement of complex systems and processes through high dynamic precision adaptive control and sensor fusion

By
Yuri Vershinin

June 2018

Coventry University

A thesis submitted in partial fulfilment of the University's requirements for the degree of Doctor of Philosophy

Contents

Acknowledgments

The material in this thesis is based on upon work undertaken by the author in the Mechancial, Automotive and Aeropsace Engineering Department, with support from the Fluid and Complex Systems Faculty Research Centre, Coventry University. In particual the author acknowledges the support of Professor Andrew Hunt and Dr Phil Costen from the Centre and Professor Mike Blundell from the Department, respectively, for their continued support and guidance throughout its creation.

The author also wishes to acknowlege the input of Professor Lotfy A. Zadeh, University of California, Berkeley, in regard to adaptive control systems for transport applications, that are included in this portfolio of work.

The author is also indebted to Professor Olivier Sparangano, Associate Pro-Vice-Chancellor (Research), Coventry University for encouragement in developing strong links with European researchers culminating in the FP7 supported "DIONICOS" project, a project coordinated by Coventry university and involving twelve partner countries. Special thanks is also expressed to Dr Martin Weigel and Dr Christian Von Ferber from the former Advanced Mathematics Research Centre, now part of FCS, for their support throughout the four year "DIONICOS" project.

1. Introduction

The work presented in this thesis combines together the research results obtained by the author for the solution of practical tasks in science and engineering. They are related to the enhancement of the performance of complex and multivariable processes and systems.

The author of this thesis has designed a new sensor fusion algorithm which allows information to be fused from several sensors on the local processing units in order to obtain reliable information, which is required in many tracking and surveillance systems. For example, several sensors (maybe of a different nature, such as a video camera, a laser-based object detection sensor (LIDAR) and an ultrasonic sensor) can be installed on a car or autonomous vehicle in order to obtain information for the vehicle's navigation. Very often, a video camera does not provide good quality information during the night. The laser sensor is very sensitive to environmental conditions (the intensity of the laser beam is considerably reduced during rain, fog, smoke or snow); the ultrasonic sensor works well, but its accuracy cannot be sufficient for long distance measurement. This new navigation system, based on the designed sensor fusion techniques, allows improved reliability of navigation in different conditions. Moreover, the navigation system will continue to function even when some sensors malfunction or connections are broken. The new navigation system developed by the author is based on the Information Fusion technique, which is incorporated in the continuous-time Kalman filter algorithm. Additionally, this system will reduce the input and output noise, which almost always exists in the real environment. The practical simulation of the above sensor fusion algorithm has been tested on the model of the industrial-type system with three channels. The simulation results have proved that the overall system performs well even in the case of sensor failure in two out of three channels.

The High Dynamic Precision Adaptive Control (HDPAC) algorithm has been developed in order to provide the desirable behaviour of a system when its parameters change or a fault occurs. Very often it is required to control individual channels of a complex system according to the reference model of the each channel. It is well known that the response of a MIMO system (a system with Many Inputs and Many Outputs) may not follow the system's reference model due to interaction between the channels though the system's dynamics. The developed HDPAC algorithm allows this problem to be solved and the behaviour of the MIMO system to be improved. The HDPAC system is based on the simultaneous identification and adaptation of the system's parameters and provides the desirable response of each channel following the required dynamics of a reference model of that channel.

The developed algorithms have been tested for the solution of a practical task; to improve the performance of an aircraft's motion by the decoupling motion of an aircraft on the roll and sideslip. The case where the parameters of the system (aerodynamic coefficients of the aircraft) are time variable has also been considered. The simulation results demonstrated that the HDPAC system allows the changes of six parameters to be tracked simultaneously (aerodynamic coefficients) in two channels (the roll and sideslip channels). The described algorithms can also be employed to control other types of systems and processes. For example, autonomous vehicles, automotive engines, robotics, chemical industrial processes or other systems and processes with time variable parameters can be controlled with the required dynamic precision. Moreover, the control system will provide the desirable performance of the overall system even in cases where the parameters change or when faults occur.

There are 165 references in this thesis. The author's publications are cited in 36 references, which are given in Appendix – 1. The Portfolio Outputs of the author are referenced in Appendix – 2.

2. Autobiographical context

The author has worked on the development of new ideas and methods for the enhancement of the performance of complex systems and processes since 2001. The author received an invitation from the industrial organisation Samsung Heavy Industries (the shipyard near Pusan City, South Korea) to give a presentation about his research work in the area of control engineering. This included discussing the possibility of applying advanced control algorithms to a robot-manipulator in order to improve the quality of the welding process of metal sheets used in ship building.

The author also prepared a project proposal for an EPSRS (Engineering and Physical Sciences Research Council, UK) grant on a relevant topic. This project proposal was approved by the EPSRC and the author visited the above company in South Korea. (It is interesting to note that the company administration arranged the author's transport by special helicopter from Pusan City to the company, which is located on a separate island from the mainland). The company manufactures 'super-big' oil-tankers to deliver oil around the world. The managers and engineers organised a tour and demonstrated the industrial processes of building such ships. During the meeting, the engineers demonstrated the working process of welding metal sheets using a robot-manipulator. They requested that the author help improve the control of the robot-manipulator in order to improve the quality of the seam between two metal sheets which are used to make the body of a ship. In particular, small air gaps appear inside the seam between the two metal sheets during the welding process. They believed that by the implementing a more accurate control of the welding head's motion (which is located on the robot-arm), the quality of the welding would be considerably improved.

The author suggested incorporating the predictive algorithm based on the Kalman filter for the robot-manipulator. The additional advantage of the Kalman filter is that this algorithm can reduce the input-output noise which almost always exists in an industrial environment. However, the Kalman filter algorithm requires a mathematical model of the process. This model is not provided by industrial organisations in most cases. The author then developed a procedure to obtain the mathematical model of the process by experiment and to incorporate this model into the adaptive control algorithm. This was in order to obtain the desirable behaviour of the system, even in a case when the system's parameters change due to the environmental conditions or a fault in the system.

Later, the author presented an extended case for a system with many inputs and many outputs (a MIMO system). This was at the DoCoMo Telecommunications Company in Japan (in Sapporo City, Hokkaido Island), following the company's invitation to the author.

While working as a lecturer at Coventry University, the author was the teacher and module leader for the Flight Dynamics and Control and Avionics modules. Coventry University purchased a Flight Simulator (Merlin Ltd.) in order to support the students' practical experience in Aerospace Systems and Avionics courses. However, the company which had provided this Flight Simulator did not provide mathematical models of the dynamics motion on two axes (the pitch-axis and roll-axis). In order to solve this problem, the author applied the system's identification method based on Markov parameters (impulse response), the Hankel matrix approximation method and the model-order reduction technique. Several practical experiments were completed by the author on the Flight Simulator. Step impulses were applied by using the control stick for the pitch channel and roll channel and the impulse responses from the each channel were recorded using the 3-axis solid-state accelerometer (British Aerospace Ltd), the vibration-type gyroscope (British Aerospace Ltd) and the Data-Acquisition device (National Instruments Ltd.). The author then implemented the above techniques in the Matlab software code and obtained the required mathematical models of the pitch channel and the roll channel. Having these models, students and researchers could design advanced control algorithms for the autopilot. The author presented these results at the First User Groups Conference of Flight Simulators among UK Universities, in Liverpool. The Director of the Merlin Flight Simulator Company said at this Conference that the author had achieved very useful practical results. The Company managers did not believe that a dynamic model of their Flight Simulator could have been obtained, presumably because they wished to keep a monopoly on development. It is not difficult to understand that if a dynamic model of an aircraft or missile could be obtained from a test experiment, then control algorithms could be designed to predict the position of this plant and to intersect it. Arguably this is an interesting and useful task for students' projects and for the research and development of defence organisations in the future. The control from the joystick was implemented onto the aircraft model via the Avionics Data-Bus MIL-STD-1553 using the C programming language. The transmitting and receiving modules of the Avionics Data-Bus MIL-STD-1553 were purchased for education in avionics courses.

A high dynamic precision control method of the separation of an aircraft's motion on a roll and sideslip has also been designed by the author. The significance of this new control method is that a pilot can change the motion of an aircraft on each axis independently from the motion on other axes. This manoeuvre can therefore be very useful when a pilot needs to quickly avoid a collision with another aircraft. A case is described in the open sources where one aircraft went directly head-to-head onto another aircraft. In order to escape the collision, the pilot of the second aircraft tried to rapidly change its motion to a vertical direction. However, due to the extreme aerodynamic forces, the aircraft cracked apart and disintegrated. The crew in the second aircraft all died. This form of attack can moreover be deliberately planned if the pilot of an unfriendly aircraft can calculate the applied forces and the limit of the structure of another aircraft. However, if another aircraft has the ability to change the direction of its motion on each axis independently from other axes, then the aircraft would survive. Another application of the separation of an aircraft's motion on each axis is that the crew could keep the orientation of a gun on an unfriendly aircraft and at the same time, move sideways out of its line-of-sight. This would give an aircraft with such capabilities a significant advantage in the air. The beauty of the designed method is that it is not required to install any additional control surfaces (actuators) on the aircraft. For example, there are military aircraft with additional control surfaces under the aircraft body or with small front wings. The suggested control algorithm for the decoupled motion of an aircraft however can be implemented on any standard aircraft, civilian or military. Thus, no any additional hardware is required as it is based only on specially designed software algorithms. The author published a paper describing this method in the international journal *Aircraft Engineering and Aerospace Technology*. The computer simulation results demonstrated that the system performs well even in the case when an aircraft's parameters change due to environmental conditions or the flight regime. This method can be applied for future

6th generation aircraft. For example, the MIG-31 aircraft is the fastest in the world, but it does not possess the best manoeuvrability for a modern aircraft today. On the other hand, the SU-57 (5th generation aircraft) has 3 axes engine vector control, which allows the best manoeuvrability currently achievable. However, the price is a heavier engine and a more complicated actuation system for the 3 axes engine vector control. The application of the High Dynamic Precision Adaptive Control (HDPAC) method for the decoupled motion of an aircraft is perhaps an alternative way to achieve high manoeuvrability. No additional installation of special control surfaces and actuators would be required on the aircraft and the standard, cheaper engine without vector control could be used.

Later, while working in the Department of Mechanical, Automotive and Aerospace Engineering, the author formed the Applied Research Group (ARG) 'Intelligent Transport Systems and Telematics' (ITS&T). The author designed control algorithms that can be used to control autonomous vehicles. They could be used for controlling city traffic, for the cooperative control of a fleet of cars, for adaptive cruise control, for a car's active suspension systems and for many other applications in the field of transportation and Smart Cities. The author presented his results as the Keynote Speech at the University of California at Berkley (USA). Also, the author personally discussed the application of the adaptive control method for an automotive engine with Professor Lofty Zadeh, the inventor of the Fuzzy-Logic Control Systems, in his office at UC Berkeley. Additionally, the author organised the Special Session 'Intelligent Transport Systems and their Applications' for the IEEE Intelligent Transport Systems Conference, ITSC-2014, (Quindao City, China), in which 6 papers were presented. Moreover, the author conducted the presentation of the suggested control algorithms in the Nissan Automotive Company, UK.

3. Description of the portfolio of evidence

The portfolio consists of samples of three journal papers, one book chapter, one conference papers and one presentation to the Nissan Automotive Company.

3.1 High Dynamic Precision Control System

The results of Output-1 are related to the development of a high precision adaptive control system for multivariable systems or processes. It is a well-known fact that the desirable behaviour of local sub-systems in a multivariable system is difficult to obtain due to the interconnections between the channels. The method presented in this output allows the decoupling of the channels and the adjustment of the overall system's desirable performance, according to reference models of the local sub-systems. The stability of the overall system is guaranteed following the stability criteria based on the Lyapunov function.

3.1.1. Introduction

Many industrial processes and systems include several inputs and several outputs. A mathematical model of such a process or system can be represented in the form of a MIMO system (Many-Inputs-Many-Outputs) (Sinha 1984; Nise 2015); for example a chemical batch reactor with several inputs and outputs. Another example is an aircraft, where the pitch, roll and yaw angles can be controlled by a pilot. Yet another example is a robot manipulator where the motion of each joint can be controlled independently. Due to the interconnection between channels via the system's dynamics, the response of the system may not follow for the desirable trajectory of the applied input. In order to solve this problem, the use of decoupled control algorithms is suggested. However, parameters of real systems can change due to changes in environmental conditions, for example, temperature. Therefore, the outputs of real systems will also change. This paper suggests the employment of adaptive control algorithms in order to provide the system's behaviour according to the reference model for each channel. It is admitted that the dynamics of different channels can also be different. Therefore, the relevant reference models for each channel can be employed in the multivariable system. The stability of the overall multivariable system is guaranteed according to the obtained adaptive control algorithms based on the Lyapunov stability criterion.

3.1.2. The task formulation

A multivariable plant is described by the system of matrix differential equations (Nise 2015):

$$
\begin{aligned}
&\dot{X}_1 = A_{11}X_1 + A_{12}X_2 + \ldots + A_{1n}X_n + U_1,\\
&\dot{X}_2 = A_{21}X_1 + A_{22}X_2 + \ldots + A_{2n}X_n + U_2,\\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\
&\dot{X}_n = A_{n1}X_1 + A_{n2}X_2 + \ldots + A_{nn}X_n + U_n,
\end{aligned}
\tag{1}
$$

where

$$X_1 = [x_{11}, x_{12}, ..., x_{1m}]^T,$$
$$X_2 = [x_{21}, x_{22}, ..., x_{2v}]^T,$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$X_n = [x_{n1}, x_{n2}, ..., x_{nk}]^T.$$

$X_1,\ X_2,\ ...\ X_n$ - are vectors of states of the plant,

$A_{11} = A_{11}(t),\ A_{12} = A_{12}(t),\ A_{nn} = A_{nn}(t)$ - are matrices of variable parameters of the plant,

$U_1,\ U_1,\ ...\ U_n$ - are control vectors.

It is required to find such feedback laws that autonomous motion of plant's co-ordinates at each channel will be provided according to the following reference model:

$$\begin{aligned} \dot{X}_1^m &= A_{11}^m X_1^m + G_1, \\ \dot{X}_2^m &= A_{22}^m X_2^m + G_2, \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \dot{X}_n^m &= A_{nn}^m X_n^m + G_{n,} \end{aligned} \qquad (2)$$

where

$$X_1^m = [x_{11}^m, x_{12}^m, ..., x_{1m}^m]^T,$$
$$X_2^m = [x_{21}^m, x_{22}^m, ..., x_{2v}^m]^T,$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$X_n^m = [x_{n1}^m, x_{n2}^m, ..., x_{nk}^m]^T.$$

$X_1^m,\ X_2^m,\ \dots\ X_n^m$ - are vectors of states of the reference model,

$A_{11}^m,\ A_{22}^m,\ \dots,\ A_{nn}^m$ - are matrices of parameters of the reference model,

$G_1,\ G_2,\ \dots\ G_n$ - are inputs.

3.1.3. Synthesis of the basic loop structure

The feedback controls can be chosen as follows:

$$\begin{aligned} U_1 &= G_1 + K_{11}X_1 + K_{12}X_2 + \dots + K_{1n}X_n, \\ U_2 &= G_2 + K_{21}X_1 + K_{22}X_2 + \dots + K_{2n}X_n, \\ &\dots\dots\dots\dots\dots\dots \\ U_n &= G_n + K_{n1}X_1 + K_{n2}X_2 + \dots + K_{nn}X_n, \end{aligned} \tag{3}$$

where

$K_{11} = K_{11}(t),\ K_{12} = K_{12}(t),\ \dots,\ K_{nn} = K_{nn}(t)$ - are matrices of the feedback variable gains.

According to the equations (1) and (3), the closed loop system can be represented as follows:

$$\begin{aligned} \dot{X}_1 &= (A_{11} + K_{11})X_1 + (A_{12} + K_{12})X_2 + \dots + (A_{1n} + K_{1n})X_n + G_1, \\ \dot{X}_2 &= (A_{21} + K_{21})X_1 + (A_{22} + K_{22})X_2 + \dots + (A_{2n} + K_{2n})X_n + G_2, \\ &\dots\dots\dots\dots\dots\dots \\ \dot{X}_n &= (A_{n1} + K_{n1})X_1 + (A_{n2} + K_{n2})X_2 + \dots + (A_{nn} + K_{nn})X_n + G_n, \end{aligned} \tag{4}$$

It can be seen from (4) that the system "plant + controller" will be dynamically decoupled on each channel if the following conditions are achieved:

$$A_{ij} + K_{ij} = 0, \qquad (\mathrm{i,j} = 1,...\mathrm{n}, \quad \mathrm{i} \neq \mathrm{j}) \tag{5}$$

In order to guarantee the desirable motion of the system according to the reference trajectories (2), it requires to provide the following relation:

$$A_{ii} + K_{ii} = A_{ii}^{m} \tag{6}$$

Thus, for accomplishment of (5) and (6) the following should be provided:

$$\begin{aligned}
&a_{12,0} + k_{12,0} = 0,\\
&a_{12,1} + k_{12,1} = 0,\\
&\dots\dots\dots\dots\\
&a_{12,m-1} + k_{12,m-1} = 0,\\
&\dots\dots\dots\dots\\
&a_{nn-1,k-1} + k_{nn-1,k-1} = 0,
\end{aligned} \tag{7}$$

$$\begin{aligned}
&(a_{11,0} + k_{11,0}) = a_{11,0}^{m},\\
&(a_{11,1} + k_{11,1}) = a_{11,1}^{m},\\
&\dots\dots\dots\dots\\
&(a_{11,m-1} + k_{11,m-1}) = a_{11,m-1}^{m},\\
&\dots\dots\dots\dots\\
&(a_{nn,m-1} + k_{nn,k-1}) = a_{nn,k-1}^{m},
\end{aligned}$$

where

$a_{11,0} = a_{11,0}(t),\ a_{11,1} = a_{11,1}(t),\ ...,\ a_{nn,k-1} = a_{nn,k-1}(t)$ - are variable scalar coefficients of the plant (1),

$a^m_{11,0},\ a^m_{11,1},\ ...,\ a^m_{nn,k-1}$ - are constant scalar coefficients of the model (2),

$k_{11,0} = k_{11,0}(t),\ k_{11,1} = k_{11,1}(t),\ ...,\ k_{nn,k-1} = k_{nn,k-1}(t)$ - are variable scalar gains of the controller (3).

3.1.4. Synthesis of the adaptive control algorithms

The variable parameters of the plant (1) can be represented as follows:

$$A_{11} = A^0_{11} + \Delta A_{11},$$
$$A_{12} = A^0_{12} + \Delta A_{12},$$
....
$$A_{nn} = A^0_{nn} + \Delta A_{nn},$$

where

$A^0_{ij} = const$, (i, j = 1,…, n), A^0_{ij} are the constant matrices whose coefficients correspond to the nominal operation mode of the plant,

$\Delta A_{ij} = \Delta A_{ij}(t)$, ΔA_{ij} - are deviation of the plant parameters from their nominal operation mode.

The controller parameters can be represented analogous:

$$K_{11} = K_{11}^0 + \Delta K_{11},$$
$$K_{12} = K_{12}^0 + \Delta K_{12},$$
....
$$K_{nn} = K_{nn}^0 + \Delta K_{nn},$$

where

K_{ij}^0 = $const$, (i, j = 1,…, n), K_{ij}^0 are matrices of constant coefficients of the controller,

ΔK_{ij} = $\Delta K_{ij}(t)$, ΔK_{ij} - are matrices of adjusting coefficients of the controller.

Thus, the motion of plant co-ordinates on a non-nominal operation mode can be represented as follows:

$$\dot{X}_i = \sum_{j=1}^{n} (A_{ij}^0 + \Delta A_{ij}(t)) X_j + U_{i,} \quad (i = 1,...,n). \tag{8}$$

The feedback control is:

$$U_i = G_i + \sum_{j=1}^{n} (K_{ij}^0 + \Delta K_{ij}(t)) X_j, \quad (i = 1,...,n). \tag{9}$$

Substituting the equation (9) into (8) we can obtain the equation of motion of the system "the plant + the controller" on each channel:

$$\dot{X}_i = \sum_{j=1}^{n} (A_{ij}^0 + \Delta A_{ij}(t)) X_j + \sum_{j=1}^{n} (K_{ij}^0 + \Delta K_{ij}(t)) X_j + G_i. \qquad (10)$$

The model motion equation on each channel can be chosen as follows:

$$\dot{X}_i^m = A_{ii}^m X_i^m + \sum_{\substack{j=1 \\ j \neq i}}^{n} (A_{ij}^0 + K_{ij}^0) X_j + G_i. \qquad (11)$$

Comparing (10) and (11) and taking into account that $A_{ii}^0 + K_{ii}^0 = A_{ii}^m$, the following can obtain:

$$\dot{E}_i = A_{ii}^m E_i + (\Delta A_{ii}(t) + \Delta K_{ii}(t)) X_i + (\sum_{\substack{j=1 \\ j \neq i}}^{n} \Delta A_{ij}(t) + \sum_{\substack{j=1 \\ j \neq i}}^{n} \Delta K_{ij}(t)) X_j \qquad (12)$$

where

$$E_i = X_i - X_i^m \qquad (13)$$

Introduce the following notation:

$$\begin{aligned} Y_{ii} &= Y_{ii}(t) = \Delta A_{ii}(t) + \Delta K_{ii}(t), \\ Y_{ij} &= Y_{ij}(t) = \Delta A_{ij}(t) + \Delta K_{ij}(t), \quad (i \neq j). \end{aligned} \qquad (14)$$

Thus, the error equation (12) can be represented as:

$$\dot{E}_i = A_{ii}^m E_i + Y_{ii} X_i + \sum_{\substack{j=1 \\ j \neq i}}^{n} Y_{ij} X_j \tag{15}$$

Algorithms of adaptation can be specified in the following form:

$$\frac{d}{dt} \Delta K = \Psi \tag{16}$$

Admit that parameters' deviation $\Delta A = \Delta A(t)$ are differentiable in time:

$$\frac{d}{dt} \Delta A(t) = R(t) \tag{17}$$

Therefore, according to (13) – (17) the following is obtained obtain:

$$\begin{aligned} \dot{E} &= A^m E + YX, \\ \dot{Y} &= \Psi + R. \end{aligned} \tag{18}$$

where $R = R(t)$.

The equations (18) with equation (2) describe the dynamic motion of the adaptive control system with the reference model.

Admit that the matrix Ψ is a function of error deviation E and time t, and $\Psi(E,t) = 0$ at $t = 0$.

In this case the state and parametric error motion

$$E \equiv 0, \quad Y \equiv 0 \tag{19}$$

with admission that $R(t) \equiv 0$ according to the hypothesis of quasi - stationarity, is the solution of the system (18).

It is suggested to use the second method of Lyapunov in order to obtain the adaptation algorithms Ψ from the condition of stability of zero solution (19) of the system (18) (Sastry and Bodson 2011; Kokotovic 1991; Egard 2014; Watanaba 1992).

The quadratic function V can be chosen as follows:

$$V = \gamma E^T PE + tr(YY^T), \tag{20}$$

where

$\gamma = const$
$P - is\ simmetric\ matrix,$
$Q - is\ negative\ definite\ matrix.$

A time derivative for the function V is obtained as follows:

$$\dot{V} = \gamma \dot{E}^T PE + \gamma E^T P\dot{E} + tr(\dot{Y}Y^T + Y\dot{Y}^T) = \gamma (A^m E + YX)^T PE + \gamma E^T P(A^m E + YX) + tr(\dot{Y}Y^T + Y\dot{Y}^T) =$$
$$\gamma [(A^m E)^T + (YX)^T]PE + \gamma E^T P(A^m E + YX) + tr(\dot{Y}Y^T + Y\dot{Y}^T) =$$
$$\gamma [E^T (A^m)^T + X^T Y^T]PE + \gamma E^T PA^m E + \gamma E^T PYX + tr(\dot{Y}Y^T + Y\dot{Y}^T) =$$
$$\gamma E^T (A^m)^T PE + \gamma X^T Y^T PE + \gamma E^T PA^m E + \gamma E^T PYX + tr(\dot{Y}Y^T + Y\dot{Y}^T) =$$
$$\gamma E^T ((A^m)^T P + PA^m)E + \gamma X^T Y^T PE + \gamma E^T PYX + tr(\dot{Y}Y^T + Y\dot{Y}^T)$$

(21)

After some intermediate matrix manipulations the following can be obtained:

$$\Psi = -\gamma PEX^T \qquad (22)$$

The derivative of the Lyapunov function is represented as:

$$\dot{V} = \gamma E^T QE \qquad (23)$$

Taking into account that A^T is Hurvitch matrix, the following is obtained:

$$\dot{V} \le 0 \qquad (24)$$

Therefore, according to (18), (16) and using conditions of quasi-stationarity of the system it is straightforward to obtain the adaptation algorithms as:

$$\Delta \dot{K} = -\gamma PEX^T \qquad (25)$$

It follows from the above that motion of the system (16) with the algorithms (25) is stable and conditions (5) and (6) are satisfied.

The complete derivation of algorithms is given in Appendix 3.1.4.

3.1.5 Summary

The control algorithms developed in this output allow the improved performance of a multivariable process or system. This is due to the decoupling of the process or system channels from the interaction via the dynamics of the process or system. The desirable performance of the process or system can be obtained using the relevant reference models for each channel. Adaptive control algorithms allow the adjustment of the overall system's response in the case of parameters changing. The stability of the overall system is guaranteed according to the Lyapunov stability criterion.

3.2 A Data Fusion Algorithm for Multisensor Systems

Output - 2, developed by the author of this thesis, is related to the design of a data fusion algorithm for multisensory systems.

Data fusion techniques are used in many tracking and surveillance systems as well as in applications where reliability is a main concern. One solution for the design of such systems is to employ a number of sensors (maybe of different types) and to fuse the information obtained from all these sensors on a central processor. Past attempts to solve this problem required the organisation of a feedback from the central processor to local processor units (each of which includes a sensor and a local processor). Local estimations were then generated from the global estimation obtained from the previous step (Willner, Chang and Dunn 1976). However, this caused computational bottleneck problems when data was transmitted. This problem was later solved in Speyer (1979) for both cases: decentralised estimation and decentralised LQG control. The algorithms based on the parallelisation of the Kalman filter equations, as proposed in Hashemipour, Roy and Laub (1988), extended the previous results allowing the global estimation to be obtained using only local estimates without the transmission of information between the sensors. Another method for data fusion is based on the so-called Federated Filter, the square-root version of which is given in Carlson (1990). The Bayesian method based and linear sensor fusion algorithms were developed in Chong, Mori and Chang (1990) for the following configurations: the first configuration is with a feedback from the central processor to local processing units and the second configuration is without such a feedback.

Information fusion can be obtained from the combination of state estimates and their error covariances using the Bayesian estimation theory (Wall, Willsky and Sandell 1981; Schweppe 1973). The two-filter method based on forward and backward solutions of Kalman filter or Bellmans's dynamic programming equations is another common method for data fusion (Mayne 1966). A scattering framework (Levy, Castanon, Verghese and Willsky 1983) and decomposition of the information form of the Kalman filter (Kerr 1996) are also popular methods for designing data fusion systems.

All the methods described above require the use of a central processor in order to fuse information obtained by the sensors. The main disadvantage of this approach is that in the case of a central processing failure, the overall system will also fail. The method given in Rao and Durrant-Whyte (1991) is based on internodal communications between local processor units without the need of any central processor. However, the decentralised Kalman filter algorithms are obtained only for a discrete time domain. In practice, continuous time implementations of a sensor fusion system are also required. A new data fusion algorithm based on the continuous time decentralised Kalman filter is proposed in this paper. In addition to the capability of combining information from different sensors, the system allows the graceful degradation of the overall performance if some local units fail or interconnections are broken.

The simulation results of data fusion for three subsystems show that the performance of the overall system degrades gracefully even if the sensors of some subsystems are malfunctioning. Furthermore, local Kalman filters can effectively reduce subsystems and measurement noises.

3.2.1 A data fusion algorithm

The dynamics of subsystems of a complex system can be represented in the following form:

$$\dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) + w_i(t),$$
$$y_i(t) = C_i x_i(t) + v_i(t), \qquad (i = 1,\ 2, ..., n) \qquad (1)$$

where

n – is the number of subsystems,

$x_i(t)$ - is the state of the i-th subsystem,

$u_i(t)$ - is the control signal on the *i*-th subsystem,

$y_i(t)$ - is the output of the *i*-th subsystem,

$w_i(t)$ - is the *i*-th subsystem noise,

$v_i(t)$ - is the measured noise of the *i*-th subsystem.

It is assumed that the subsystem noise $w_i(t)$ and the measured noise $v_i(t)$ are zero-mean Gaussian white noise processes with the following statistical properties:

$$E\{x_i(0)\} = E\{w_i(0)\} = E\{v_i(0)\} = 0\,,$$

$$E\{w_i(t)w_i^T(\tau)\} = Q_i(t)\delta(t-\tau)\,,$$

$$E\{v_i(t)v_i^T(\tau)\} = R_i(t)\delta(t-\tau)\,,$$

$$E\{x_i(0)w_i^T(t)\} = E\{x_i(0)v_i^T(t)\} = E\{w_i(t)v_i^T(\tau)\} = 0$$

and $\mathrm{Q_i(t)} \geq 0,\ R_i(t) > 0.$

State estimates are computed on each subsystem by local Kalman filters as:

$$\dot{\hat{x}}_i(t) = A_i\hat{x}_i(t) + B_i u_i(t) + K_i[y_i(t) - C_i\hat{x}_i(t)]. \qquad (2)$$

The error covariance propagation in the information form is calculated accordingly:

$$\frac{d}{dt}(P_i^{-1}) = -P_i^{-1}A_i - A_i^T P_i^{-1} - P_i^{-1}Q_i P_i^{-1} + C_i^T R_i^{-1} C_i. \quad (3)$$

(Hereafter in the text the time notation index t is dropped for simplification of notations).

The Kalman gain matrix is calculated as:

$$K_i = P_i C_i^T R_i^{-1}, \quad (4)$$

where R_i^{-1} exist.

It is well known (Wall, Willsky and Sandell 1981; Schweppe 1973) that the optimum combination of independent estimates can be accomplished in the form:

$$\hat{x}(t) = P[P_1^{-1}\hat{x}_1 + P_2^{-1}\hat{x}_2 + ... + P_n^{-1}\hat{x}_n], \quad (5)$$

$$P = (P_1^{-1} + P_2^{-1} + ... + P_n^{-1})^{-1}. \quad (6)$$

Decentralizing algorithms (5) and (6) between the subsystems, one can obtain:

$$\hat{x}_k(t) = P_k[P_1^{-1}\hat{x}_1 + P_2^{-1}\hat{x}_2 + ... + P_n^{-1}\hat{x}_n], \quad (7)$$

$$P_k = (P_1^{-1} + P_2^{-1} + ... + P_n^{-1})^{-1}, \quad (i = 1,2,\ldots,k,\ldots,n). \quad (8)$$

Differentiating equations (7) and (8), the following fusion algorithm on the k-th subsystem is obtained:

$$\dot{\hat{x}}_k(t) = \dot{P}_k[\sum_{i=1}^{n} P_i^{-1}\hat{x}_i] + P_k[\sum_{i=1}^{n}\frac{d}{dt}(P_i^{-1})\hat{x}_i + \sum_{i=1}^{n} P_i^{-1}\dot{\hat{x}}_i], \tag{9}$$

$$\frac{d}{dt}(P_k^{-1}) = \sum_{i=1}^{n} P_i^{-1}A_i - \sum_{i=1}^{n} A_i P_i^{-1} + \sum_{i=1}^{n} P_i^{-1}Q_i P_i^{-1} + \sum_{i=1}^{n} C_i^T R_i^{-1} C_i. \tag{10}$$

3.2.2 The model of the plant

The mathematical model of a conveyer driven by three DC electric motors can be obtained from the Newton's second law:

$$\begin{aligned}
J_1\ddot{\theta}_1 &= \tau_1 - k_w[(r_1\theta_1 - r_2\theta_2)/l_{12} + (r_1\theta_1 - r_3\theta_3)/l_{31}], \\
J_2\ddot{\theta}_2 &= \tau_2 - k_w[(r_2\theta_2 - r_1\theta_1)/l_{12} + (r_2\theta_2 - r_3\theta_3)/l_{23}], \\
J_3\ddot{\theta}_3 &= \tau_3 - k_w[(r_3\theta_3 - r_1\theta_1)/l_{31} + (r_3\theta_3 - r_2\theta_2)/l_{23}],
\end{aligned} \tag{11}$$

where

θ_i is angular position of a motor, (i =1,2,3)

J_i is motor inertia,

τ_i is motor torque,

r_i is roll radius,

l_{ij} is distance between rolls, (i, j =1,2,3)

k_w is web constant.

Taking into account that $\tau_i = k_{mi} i_i$, where k_{mi} is the $i-th$ motor constant and i_i is armature current, system (1) can be written in the following form:

$$\ddot{\theta}_1 = (-k_w r_1 / l_{12} J_1 - k_w r_1 / l_{31} J_1)\theta_1 + (k_w r_2 / l_{12} J_1)\theta_2 + (k_w r_3 / l_{31} J_1)\theta_3 + (k_{m1} / J_1) i_1 ,$$
$$\ddot{\theta}_2 = (k_w r_1 / l_{12} J_2)\theta_1 + (-k_w r_2 / l_{12} J_2 - k_w r_2 /_{23} J_2)\theta_2 + (k_w r_3 / l_{23} J_2)\theta_3 + (k_{m2} / J_2) i_2 , \quad (12)$$
$$\ddot{\theta}_3 = (k_w r_1 / l_{31} J_3)\theta_1 + (k_w r_2 / l_{23} J_3)\theta_2 + (-k_w r_3 / l_{31} J_3 - k_w r_3 / l_{23} J_3)\theta_3 + (k_{m3} / J_3) i_3 .$$

Introduce new variables as follows:

$$\begin{aligned} x_1 &= \theta_1 \\ x_2 &= \dot{\theta}_1 \\ x_3 &= \theta_2 \\ x_4 &= \dot{\theta}_2 \\ x_5 &= \theta_3 \\ x_6 &= \dot{\theta}_3 \end{aligned} \quad (13)$$

Using the representation (3) and the fact that $u_i = R_i i_i$, where u_i is the $i-th$ control input, R_i is the armature resistance, the system (2) can be written in the state-space form:

$$
\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ a_{21} & 0 & a_{23} & 0 & a_{25} & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ a_{41} & 0 & a_{43} & 0 & a_{45} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ a_{61} & 0 & a_{63} & 0 & a_{65} & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ b_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & b_2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & b_3 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \tag{14}
$$

where

$$
\begin{aligned}
a_{21} &= -k_w r_1 / l_{12} J_1 - k_w r_1 / l_{31} J_1 \\
a_{23} &= k_w r_2 / l_{12} J_1 \\
a_{25} &= k_w r_3 / l_{31} J_1 \\
a_{41} &= k_w r_1 / l_{12} J_2 \\
a_{43} &= -k_w r_2 / l_{12} J_2 - k_w r_2 /_{23} J_2 \\
a_{45} &= k_w r_3 / l_{23} J_2 \\
a_{61} &= k_w r_1 / l_{31} J_3 \\
a_{63} &= k_w r_2 / l_{23} J_3 \\
a_{65} &= -k_w r_3 / l_{31} J_3 - k_w r_3 / l_{23} J_3
\end{aligned} \tag{15}
$$

$$
\begin{aligned}
b_1 &= k_{m1} / J_1 R_1 \\
b_2 &= k_{m2} / J_2 R_2 \\
b_3 &= k_{m3} / J_3 R_3
\end{aligned}
$$

The observation model can be represented as

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix} \tag{16}$$

3.2.3 Experimental results

The simulation results of data fusion for three subsystems are shown in Figures 1 – 3. It is assumed that all subsystems are identical. The inputs to the subsystems are sinusoidal signals with noise.

Fig.1 shows the case when all sensors are functioning.

Fig.2 shows the case when sensor 2 is malfunctioning.

Fig.3 shows the case when sensor 3 is malfunctioning.

According to the simulation results given in Figure 2, the data fusion algorithm allows the second subsystem to continue to work with minimal degradation of performance. Figure 3 shows that the third subsystem continues to work with graceful degradation of performance even though its sensor is malfunctioning.

3.2.4 Summary

The new data fusion algorithm presented in this paper allows the combination of information from different sensors in continuous time. Continuous-time decentralised Kalman filters (DKF) are used as data fusion devices on local subsystems. Such a structure gives the flexibility for the reconfiguration of a control system. New subsystems can easily be added without needing any redesign of the whole system. The system does not require a central processor. Therefore, in the case of the failure of some local subsystems (each of which includes a local processor, sensors and actuators), the overall system will continue to work.

The simulation results show that the performance of the overall system degrades gracefully even if the sensors of some subsystems fail or interconnections are broken. Furthermore, local Kalman filters can effectively reduce subsystems and measurement noises.

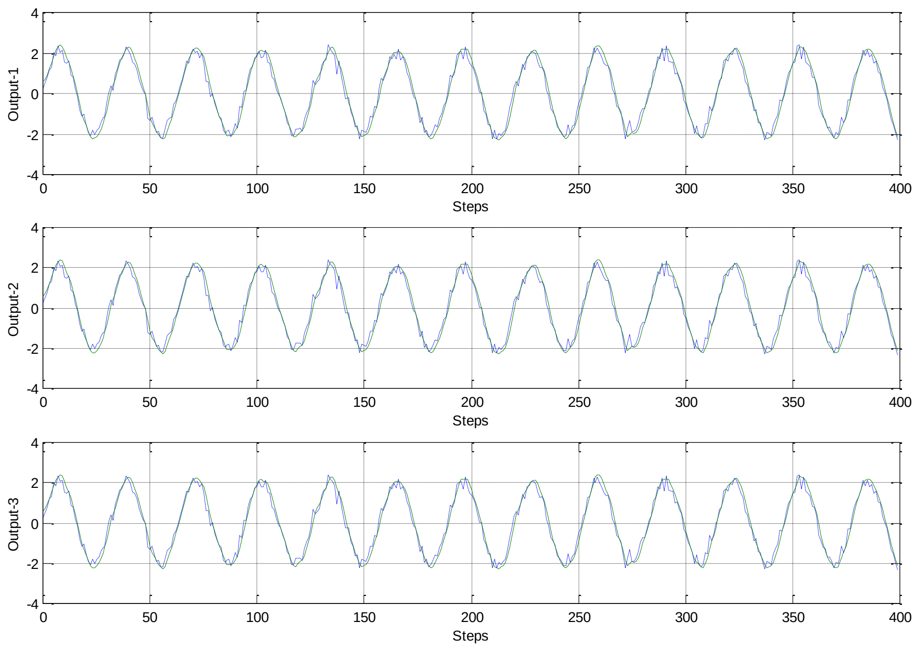


Fig. 1. - - - - is the measured signal of a sensor, ——— is the output of a DKF.

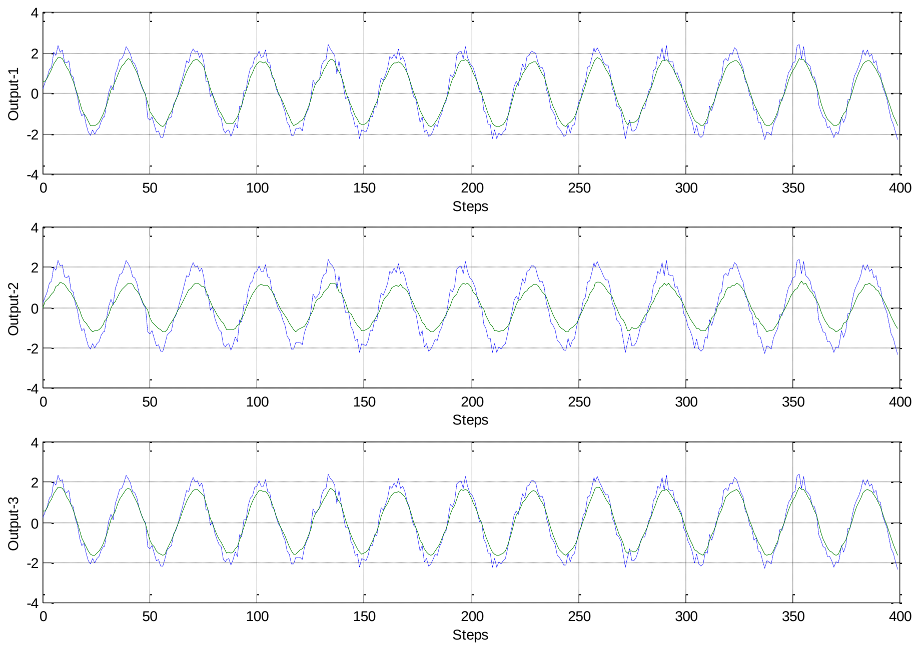


Fig. 2. - - - - is the measured signal of a sensor, ——— is the output of a DKF.

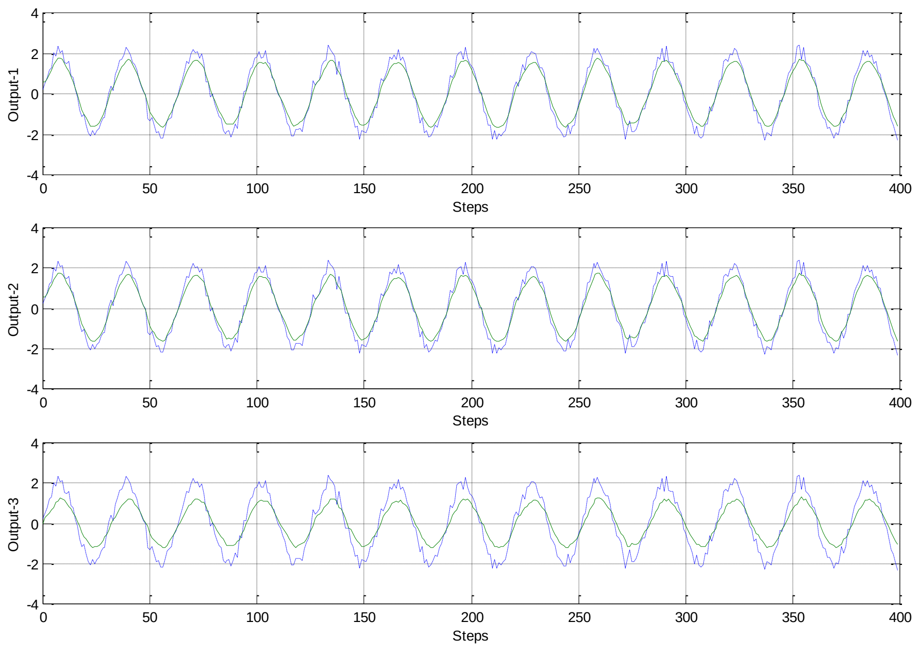


Fig. 3. - - - - is the measured signal of a sensor, ——— is the output of a DKF.

3.3. Adaptive Control System for Solution of Fault Tolerance Problem

Output – 3 of this thesis is related to the development of an adaptive control system for the solution of a fault tolerance problem

Adaptive control can provide the desirable behaviour of a process even though the process parameters are unknown or may vary with time. Conventional adaptive control requires that the speed of adaptation must be more rapid than that of the parameter changes. However, in practice, problems do arise when this is not the case. For example, when a fault occurs in a process, the parameters may change very dramatically. A new approach based on the simultaneous identification and adaptation of unknown parameters is suggested for the compensation of rapidly changing parameters. High dynamic precision adaptive control can be used for the solution of a fault tolerance problem in complex and multivariable processes and systems.

3.3.1. Determination of a mathematical model of a process

A mathematical model of a process on a stationary regime can be found from the sequence of Markov parameters using the classical Ho algorithm (Ho and Kalman 1966). The Markov parameters can be obtained from input – output relationships or more directly as an impulse response of the system. It is well known that according to the theorem of Kronecker the rank of the Hankel matrix constructed from the Markov parameters is equal to the order of the system from which the parameters are obtained. Therefore, by consistently increasing the dimension of the Hankel matrix Γ until

$$\text{rank } \Gamma_r = \text{rank } \Gamma_{r+1}$$

the order of the system can be obtained as equal to *r*. However, in practical implementation, this rank-order relationship may not give accurate results due to several factors: sensitivity of the numerical rank calculation and bias of the rank if information about the process is corrupted by noise. This problem can be avoided using singular value decomposition (SVD) of the Hankel matrix:

$$\Gamma = USV^T , \tag{1}$$

where

$$U^T U = V^T V = I ,$$

$$S = diag(\sigma_1, \sigma_2, ..., \sigma_l, \sigma_{l+1,} ...\sigma_n) .$$

Here U and V are orthogonal matrices. The diagonal elements of the matrix S (the singular values) in (1) are arranged in the following order $\sigma_1 > \sigma_2 > ... > \sigma_n > 0$. Applying the property of SVD to reflect the order of a system through the smallest singular value, the order of the system can be determined with the tolerance required. From practical point of view a reduced order model is more preferable. Taking into account that the best approximation in the Hankel norm sense is within a distance of σ_{l+1}, the model of order l can be found. However, a relevant matrix built from Markov parameters of this reduced order model should also be of the Hankel matrix. But it is not an easy matter to find such a Hankel matrix for the reduced order process. A simpler solution, although theoretically not the best, can be found from the least squares approximation of the original Hankel matrix (Zeiger and McEwen 1974; Kalman, Falb and Arbib 1974; and Moor 1981). The discrete time state-space realization of the process can be determined from the relationship between Markov parameters and representation of the Hankel matrix through relevant controllability and observability matrices of the process:

$$\Gamma = \begin{bmatrix} C_d \\ C_d A_d \\ C_d A_d^2 \\ . \\ . \end{bmatrix} \begin{bmatrix} A_d & A_d B_d & A_d^2 B_d & . & . \end{bmatrix} = \Omega \mathrm{E}, \qquad (2)$$

where

A_d is the system matrix of the discrete time state space realization of a system,

B_d is the control matrix of the discrete time state space realization of a system,

C_d is the output matrix of the discrete time state space realization of a system,

Ω is the observability matrix of the discrete time state space realization of a system,

E is the controllability matrix of the discrete time state space realization of a system.

The complete derivation of algorithms is given in Appendix 3.3.1.

3.3.2 The adaptive control system

Consider a continuous time single input - single output second order plant (a process) given in the following canonical state space realization form:

$$\begin{aligned} \dot{x} &= A_c x + B_c u \\ y &= C_c x \end{aligned}, \qquad (3)$$

where

$$A_c = \begin{bmatrix} 0 & 1 \\ a_{1p} & a_{2p} \end{bmatrix}, \quad B_c = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad C_c = \begin{bmatrix} c_{1p} & c_{2p} \end{bmatrix},$$

u is the control signal,

y is the output of the plant.

Assume that at the time t parameters a_{1p} and a_{2p} change dramatically due to a fault in the system, but parameters c_{1p} and c_{2p} remain constant. The mathematical model of plant (3) can be represented in the following form:

$$\begin{aligned} \ddot{x}_p &= (\bar{a}_{2p} + \Delta a_{2p}(t))\dot{x}_p + (\bar{a}_{1p} + \Delta a_{1p}(t))x_p + u \\ y_p &= \bar{c}_{2p}\dot{x}_p + \bar{c}_{1p}x_p \end{aligned},$$

where

$a_{1p} = \bar{a}_{1p} + \Delta a_{1p}(t)$,

$a_{2p} = \bar{a}_{2p} + \Delta a_{2p}(t)$,

$\bar{a}_{1p}, \bar{a}_{2p}, \bar{c}_{1p}, \bar{c}_{2p}$ are the nominal parameters (constant) of the plant,

$\Delta a_{1p}(t)$, $\Delta a_{2p}(t)$ are the biases of the plant parameters (variable) from their nominal values,

x_p is the plant state,

y_p is the plant output.

A desirable behavior of the plant can be determined by the following reference model:

$$\begin{aligned} \ddot{x}_m &= a_{2m}\dot{x}_m + a_{1m}x_m + g \\ y_m &= c_{2m}\dot{x}_m + c_{1m}x_m \end{aligned} , \qquad (4)$$

where

g is the input signal,

a_{1m} , a_{2m} , c_{1m} , c_{2m} are parameters of the model.

In order to compensate for the plant parameters' biases, a controller can be used. The closed loop system with the controller is represented in the following form:

$$\begin{aligned} \ddot{x}_p &= (\bar{a}_{2p} + \Delta a_{2p}(t))\dot{x}_p + (\bar{a}_{1p} + \Delta a_{1p}(t))x_p \\ &+ (\bar{k}_2 + \Delta k_2(t))\dot{x}_p + (\bar{k}_1 + \Delta k_1(t))x_p + g \quad , \end{aligned} \qquad (5)$$

where

$\bar{k}_1$, $\bar{k}_2$ are the constant parameters of the controller,

$\Delta k_1(t)$, $\Delta k_2(t)$ are the adjustable parameters of the controller.

The desirable quality of the process behavior can be obtained from the following relationships:

$$\bar{k}_1 + \bar{a}_{1p} = a_{1m}$$

$$\bar{k}_2 + \bar{a}_{2p} = a_{2m} .$$

According to equations (4) and (5), the error equation is obtained as follows:

$$\ddot{e} = a_{2m}\dot{e} + a_{1m}e + z_2\dot{x}_p + z_1 x_p , \qquad (6)$$

where

$$e = x_m - x_p ,$$

$$z_1 = \Delta a_{1p}(t) + \Delta k_1(t) ,$$

$$z_2 = \Delta a_{2p}(t) + \Delta k_2(t) .$$

It can be seen from equation (6) that in order to achieve the desirable error $e \to 0$, it is necessary to provide the following conditions:

$$z_1 \equiv 0 , \quad z_2 \equiv 0 . \qquad (7)$$

The conditions (7) can be achieved by adjusting parameters $\Delta k_1(t)$ and $\Delta k_2(t)$ according to the following laws (Astrom and Wittenmark 1995):

$$\Delta \dot{k}_1(t) = \sigma x_p \tag{8}$$

$$\Delta \dot{k}_2(t) = \sigma \dot{x}_p \,,$$

where $\sigma = Pe$.

The positive definite symmetric matrix P can be obtained from the solution of the relevant Lyapunov equation. The main problem associated with algorithms (8) is that all self-tuning contours are linked through the dynamics of the plant. The consequence is that high interaction of each contour with others will occur. This further results in poor dynamic compensation of plant parameters' biases Δa_{ip} (i=1,2,…m), where m is a number of self-tuning contours. The idea of decoupling self-tuning contours from plant dynamics, based on simultaneous identification and adaptation, is suggested for the solution of this problem with fault tolerance. This could considerably improve performance of the overall system, especially for high dimension and multivariable plants and processes.

It can be shown (Petrov, Rutkovsky and Zemlyakov 1980; Vershinin 1991) that the self-tuning contours will be decoupled from the plant dynamics if σ can be formed such that:

$$\sigma^* = \ddot{e} - a_{2m}\dot{e} - a_{1m}e \,.$$

It has been confirmed by the simulation that the performance of the system with these algorithms satisfied the desirable performance.

The following relationship can be obtained:

$$\sigma^* = (\Delta a_{2p}(t) + \Delta k_2(t))\dot{x}_p + (\Delta a_{1p}(t) + \Delta k_1(t))x_p \,. \qquad (9)$$

In order to solve equation (9) with two variable parameters, the following approach is suggested: Multiply both parts of equation (9) by state variables x_p and $\dot{x}_p$ and integrate the resultant equations on the time interval (t_1, t_2), where: $t_2 = t_1 + \Delta t$. Taking the initial conditions as $t_1 = 0$, $\Delta k_i = 0$, (i=1,2) the following equations are obtained:

$$\int_{t_1}^{t_1+\Delta t} \sigma^* x_p dt = \Delta a_{2p} \int_{t_1}^{t_1+\Delta t} \dot{x}_p x_p dt + \Delta a_{1p} \int_{t_1}^{t_1+\Delta t} x_p^2 dt$$

$$\int_{t_1}^{t_1+\Delta t} \sigma^* \dot{x}_p dt = \Delta a_{2p} \int_{t_1}^{t_1+\Delta t} \dot{x}_p^2 dt + \Delta a_{1p} \int_{t_1}^{t_1+\Delta t} x_p \dot{x}_p dt \,. \qquad (10)$$

Introduce the following notations:

$$\int_{t_1}^{t_1+\Delta t} \sigma^* x_p dt = c_1 \,, \qquad \int_{t_1}^{t_1+\Delta t} \sigma^* \dot{x}_p dt = c_2 \,,$$

$$\int_{t_1}^{t_1+\Delta t} x_p^2 dt = l_{11} \,, \qquad \int_{t_1}^{t_1+\Delta t} x_p \dot{x}_p dt = l_{21} \,,$$

$$\int_{t_1}^{t_1+\Delta t} \dot{x}_p x_p dt = l_{12}\,, \qquad \int_{t_1}^{t_1+\Delta t} \dot{x}_p^2 dt = l_{22}\,. \tag{11}$$

According to notations (11), equations (10) can now be written in the form:

$$\begin{aligned} c_1 &= \Delta a_{1p} l_{11} + \Delta a_{2p} l_{12} \\ c_2 &= \Delta a_{1p} l_{21} + \Delta a_{2p} l_{22} \end{aligned}\,. \tag{12}$$

From the solution of equations (12) the bias of the plant parameters Δa_{ip}, (i=1,2) can be determined. The controller can be adjusted according to the estimated parameter bias as:

$$\Delta k_i = -\Delta a_{ip}\,.$$

Therefore, conditions (7) are satisfied, which in turn means that the behavior of system (5) follows the desirable trajectories of model (4), even in the presence of dramatic plant parameters changes.

For the solution of equations (12) one needs to take into account of the hypothesis of quasi-stationarity of the process, where the interval time Δt is selected such that the biases of parameters Δa_{ip} must be constant at this interval. However, the interval Δt should be sufficiently large in order to accumulate a larger quantity of variables x_p and $\dot{x}_p$ for the solution of the equations.

The block-diagram of the described system with adaptive control algorithms is given in Appendix 3.3.2.

3.3.3. The numerical results

The Hankel matrix Γ, constructed from the Markov parameters (obtained from the experiment, see Appendix of Section 3), is as follows:

$$\Gamma = \begin{bmatrix} 6.5000000\text{e-}02 & 1.4550000\text{e-}01 & 1.6442500\text{e-}01 \\ 1.4550000\text{e-}01 & 1.6442500\text{e-}01 & 1.5056000\text{e-}01 \\ 1.6442500\text{e-}01 & 1.5056000\text{e-}01 & 1.2447038\text{e-}01 \end{bmatrix}. \qquad (13)$$

Applying the singular value decomposition procedure (1) on the Hankel matrix (13), it is found that

$$U = \begin{bmatrix} 5.1633320\text{e-}01 & 8.1190203\text{e-}01 & 2.7242453\text{e-}01 \\ 6.2194166\text{e-}01 & -1.3682059\text{e-}01 & -7.7101797\text{e-}01 \\ 5.8871776\text{e-}01 & -5.6753434\text{e-}01 & 5.7560070\text{e-}01 \end{bmatrix}$$

$$V = \begin{bmatrix} 5.1633320\text{e-}01 & -8.1190203\text{e-}01 & 2.7242453\text{e-}01 \\ 6.2194166\text{e-}01 & 1.3682059\text{e-}01 & -7.7101797\text{e-}01 \\ 5.8871776\text{e-}01 & 5.6753434\text{e-}01 & 5.7560070\text{e-}01 \end{bmatrix}$$

$$S = \begin{bmatrix} 4.2773559\text{e-}01 & 0.0000000\text{e}+00 & 0.0000000\text{e}+00 \\ 0.0000000\text{e}+00 & 7.4455532\text{e-}02 & 0.0000000\text{e}+00 \\ 0.0000000\text{e}+00 & 0.0000000\text{e}+00 & 6.1531296\text{e-}04 \end{bmatrix}. \qquad (14)$$

Using relations (1), (2) and (14) the discrete time state space realization of the reduced order system is obtained as follows:

$$A_d = \begin{bmatrix} 9.7950468\text{e-01} & -3.4211654\text{e-01} \\ 3.4211654\text{e-01} & 3.4867831\text{e-01} \end{bmatrix}$$

$$B_d = \begin{bmatrix} 3.3767560\text{e-01} \\ -2.2160613\text{e-01} \end{bmatrix}$$

$$C_d = \begin{bmatrix} 3.3767560\text{e-01} & 2.2160613\text{e-01} \end{bmatrix} \tag{15}$$

The behavior of the full order model and the reduced order model is given in Figure 1. It can be seen in Fig.1 and Appendix of Section 3 that the Markov parameters of the reduced order model are a close approximation to the Markov parameters of the original system.

Nominal parameters of the plant in the continuous time (3) are obtained from (15) as follows:

$$\bar{a}_{1p} = -3.1184, \quad \bar{a}_{2p} = -3.0517,$$

$$\bar{c}_{1p} = -0.0318, \quad \bar{c}_{2p} = 2.9132.$$

Parameters of model (4) are chosen as $a_{1m} = \bar{a}_{1p}$, $a_{2m} = \bar{a}_{2p}$, $c_{1m} = \bar{c}_{1p}$, $c_{2m} = \bar{c}_{2p}$.

The performance of the high dynamic precision adaptive control system is presented in Fig. 2 - 5.

Fig. 2. shows that the bias from the nominal parameter at time $t \geq 1$ sec. is $\Delta a_{1p} = 1$, ($\Delta a_{2p} = 0$). The adaptation is switched off.

Fig.3 shows the bias from the nominal parameter at $t \geq 1$ sec. with adaptation being switched on ($\Delta a_{1p} = 1$, $\Delta a_{2p} = 0$). It can be seen that the output of system y_p coincides with the model reference output y_m after $t \geq 4$ sec.

Fig. 4. shows that the bias from the nominal parameter at time $t \geq 1$ sec. is $\Delta a_{2p} = 1$, ($\Delta a_{1p} = 0$). The adaptation is switched off.

Fig. 5. shows the bias from the nominal parameter at $t \geq 1$ sec. with adaptation being switched on ($\Delta a_{2p} = 1$, $\Delta a_{1p} = 0$). It can be seen that the output of system y_p coincides with the model reference output y_m after $t \geq 9$ sec.

3.3.4 Summary

The high dynamic precision adaptive control system for the solution of a fault tolerance problem of a single-input-single-output process is suggested in this paper. The method, which is based on the simultaneous identification and adaptation of unknown process parameters, provides the decoupling of self-tuning contours from the plant dynamics. The control system compensates rapidly changing parameters when a fault occurs in a process. The mathematical model of the process is formed from Markov parameters which are obtained from the experiment as the process impulse response. The order of the model is determined using singular value decomposition of the relevant Hankel matrix. This allows a robust reduced order model representation to be obtained if the information about the process is corrupted by noise in an industrial environment. The adaptive control can therefore be used for the solution of a fault tolerance problem (Vershinin 2012a) in complex and multivariable processes and systems.

3.4. Adaptive Control System for a Solution of the Fault Tolerance Problem for MIMO Systems

Output - 4 deals with the development of an adaptive control system for the solution of the fault tolerance problem for systems with many inputs and many outputs (MIMO systems).

3.4.1. The approach

Consider a multivariable process with time-varying parameters. Assume that the process is described by the following equations:

$$\begin{aligned} \dot{x}_1 &= a_{11}(t)x_1 + a_{12}(t)x_2 + g_1 \\ \dot{x}_2 &= a_{21}(t)x_1 + a_{22}(t)x_2 + g_2 \end{aligned} \qquad (1)$$

where parameters $a_{ij}(t)$ ($i, j = 1, 2$) are considered as the sum of a constant term and a time varying term:

$$a_{ij}(t) = a_{ij}^0 + \Delta a_{ij}(t)$$

where: g_i ($i = 1, 2$) are the input signals to each channel of the Multi-Input-Multi-Output (MIMO) process.

The desirable behaviour of the process (plant) can be specified by a reference model in the form:

$$\begin{aligned} \dot{x}_{1m} &= a_{1m}x_{1m} + g_1 \\ \dot{x}_{2m} &= a_{2m}x_{2m} + g_2 \end{aligned} \tag{2}$$

In order to provide the desirable behaviour of the process (1) according to model (2) a feedback controller can be used. The overall system is described by the following equations:

$$\begin{aligned} \dot{x}_1 &= a_{11}(t)x_1 + a_{12}(t)x_2 + k_{11}(t)x_1 + k_{12}(t)x_2 + g_1 \\ \dot{x}_2 &= a_{21}(t)x_1 + a_{22}(t)x_2 + k_{21}(t)x_1 + k_{22}(t)x_2 + g_2 \end{aligned} \tag{3}$$

where

$k_{ij}(t) = k_{ij}^0 + \Delta k_{ij}(t)$,

k_{ij}^0 are constant parameters of the controller,

$\Delta k_{ij}(t)$ are time-varying parameters of the controller.

The following error equations can be obtained from the closed loop process (3) and the reference model (2):

$$\dot{e}_1 = a_{1m}e_1 + (\Delta a_{11}(t) + \Delta k_{11}(t))x_1 + (\Delta a_{12}(t) + \Delta k_{12}(t))x_2$$
$$\dot{e}_2 = a_{2m}e_2 + (\Delta a_{21}(t) + \Delta k_{21}(t))x_1 + (\Delta a_{22}(t) + \Delta k_{22}(t))x_2 \quad (4)$$

where

$e_i = x_i - x_{im}$.

It can be seen from the error equations (4) that in order to obtain a stable closed loop system it is necessary to provide the following conditions:

$$\Delta a_{ij}(t) + \Delta k_{ij}(t) = 0 . \quad (5)$$

With reference to the model reference adaptive control theory based on a Lyapunov function (Landau 1979; Astrom and Wittenmark 1995), the adaptive control laws for the system (3) are obtained in the following form:

$$\Delta\dot{k}_{11}(t) = \sigma_1 x_1$$
$$\Delta\dot{k}_{12}(t) = \sigma_1 x_2$$
$$\Delta\dot{k}_{21}(t) = \sigma_2 x_1 \quad (6)$$
$$\Delta\dot{k}_{22}(t) = \sigma_2 x_2$$

where: $\sigma_i = p_{ij}e_i$.

Positive definite symmetric matrices p_{ij} can be found from the solution of the matrix Lyapunov equation:

$$e^T(A_m^T P + PA_m)e = -e^T Qe$$

where

$$e^T = [e_1, e_2],$$

$$A_m = \begin{bmatrix} a_{1m} & 0 \\ 0 & a_{2m} \end{bmatrix},$$

$$P = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix},$$

$$Q = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}.$$

It can be seen from equations (4) and (6) that the adaptive contours are linked to the dynamics of the plant. Therefore, the approach is to decouple the adaptive contours in order to achieve a higher dynamic precision of the system behaviour. It can be shown (Petrov at al. 1980; Vershinin 1991) that the adaptive contours can be decoupled from the plant dynamics if σ_i ($\mathrm{i} = 1{,}2$) can be formed such that:

$$\sigma_i^* = (s + a_{im})e_i$$

where s denotes a Laplace variable.

It has been confirmed by the simulation that the performance of the system with these algorithms satisfied the desirable performance.

The block-diagram of the described system with adaptive control algorithms is given in Appendix 3.4.1.

Consider the first channel ($i = 1$) of the MIMO plant. For this case the following relationship can be obtained:

$$\sigma_1^* = (\Delta a_{11}(t) + \Delta k_{11}(t))x_1 + (\Delta a_{12}(t) + \Delta k_{12}(t))x_2 . \qquad (7)$$

In order to solve equation (7) with two variable parameters, the following approach is suggested. Multiply both parts of equation (7) by state variables x_i ($i = 1,2$) and integrate the new equations between the time interval (t_1, t_2), where: $t_2 = t_1 + \Delta t$. Taking the initial conditions as $t_1 = 0$, $\Delta k_{ij} = 0$, $(i, j = 1,2)$, the following equations are obtained:

$$\int_{t_1}^{t_1+\Delta t} \sigma_1^* x_1 dt = \Delta a_{11} \int_{t_1}^{t_1+\Delta t} x_1^2 dt + \Delta a_{12} \int_{t_1}^{t_1+\Delta t} x_1 x_2 dt$$

$$(8)$$

$$\int_{t_1}^{t_1+\Delta t} \sigma_1^* x_2 dt = \Delta a_{11} \int_{t_1}^{t_1+\Delta t} x_1 x_2 dt + \Delta a_{12} \int_{t_1}^{t_1+\Delta t} x_2^2 dt$$

Denote:

$$\int_{t_1}^{t_1+\Delta t} \sigma_1^* x_1 dt = c_1 \qquad \int_{t_1}^{t_1+\Delta t} x_1^2 dt = l_{11} \qquad \int_{t_1}^{t_1+\Delta t} x_1 x_2 dt = l_{12}$$

$$\int_{t_1}^{t_1+\Delta t} \sigma_1^* x_2 dt = c_2 \qquad \int_{t_1}^{t_1+\Delta t} x_1 x_2 dt = l_{21} \qquad \int_{t_1}^{t_1+\Delta t} x_2^2 dt = l_{22}$$

Equations (8) can be represented in the form:

$$\begin{aligned} c_1 &= \Delta a_{11} l_{11} + \Delta a_{12} l_{12} \\ c_2 &= \Delta a_{11} l_{21} + \Delta a_{12} l_{22} \end{aligned} \qquad (9)$$

From the solution of equations (9) the bias of the plant parameters $\Delta a_{ij}, (i, j = 1, 2)$ for each channel can be determined. The controller can be adjusted according to the estimated parameter bias as:

$$\Delta k_{ij} = -\Delta a_{ij} .$$

Therefore, conditions (5) are satisfied, which means that the behaviour of the system (3) follows the desirable trajectories of the model reference (2) even if the parameters of the plant are changing dramatically.

The block-diagram of the described system with adaptive control algorithms is given in Appendix 3.3.2.

3.4.2. Experimental results

Consider a MIMO process with 2 inputs and 2 outputs described by equations (1). The nominal parameters are: $a_{11}^0 = a_{12}^0 = -1$; $a_{21}^0 = a_{22}^0 = -2$. The reference model is described by equations (2) with parameters: $a_{1m} = -1$, $a_{2m} = -2$.

Fig. 1 shows that the biases from nominal parameters are deviated 100% from nominal parameters at time t =1 sec.: $\Delta a_{11} = \Delta a_{12} = 1$, $\Delta a_{21} = \Delta a_{22} = 2$. The adaptation is switched off. It can be seen that the system is unstable (x_1 and x_2) at time t =1sec.

Fig. 2 shows that the biases are the same as in Fig. 1, but the adaptation is switched on after time t =1sec. for parameters $a_{ij}(t)$, (i, j)=1,2. It can be seen that all parameters are adjusted at time t =10 sec. The state variables x_1 and x_2 of the process coincide with the state variables x_{1m} and x_{2m} of the reference model.

Fig. 3. The bias for the parameter Δa_{11} (=100% from a_{11}^0) is shown. It can be seen that adaptive control compensates the variation of the parameter a_{11}. States x_1 and x_2 coincide exactly with states x_{1m} and x_{2m}.

Fig. 4 illustrates an example when the parameter Δa_{12} is deviated 100% from a_{12}^0.

Fig. 5 illustrates an example when the parameter Δa_{21} is deviated 100% from a_{21}^0.

Fig. 6 illustrates an example when the parameter Δa_{22} is deviated 100% from a_{22}^{0}.

Figures 1 – 6 show that the adaptive control system gives a close tracking of the rapidly changing process parameters.

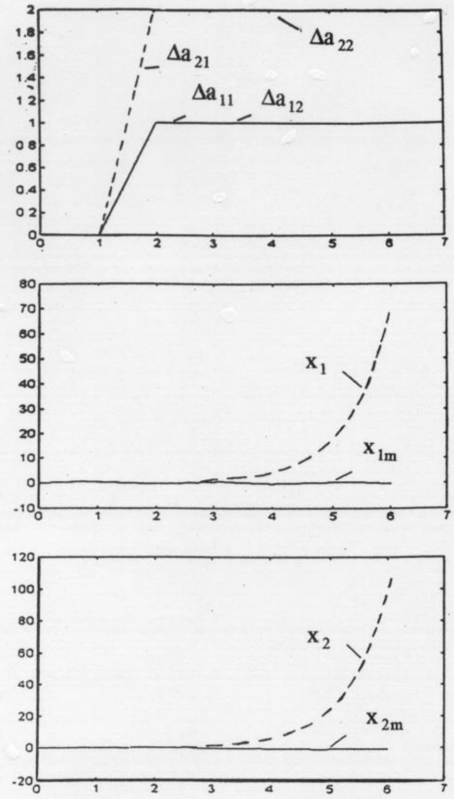


Fig. 1. Bias: $\Delta a_{11} = \Delta a_{12} = 1$, $\Delta a_{21} = \Delta a_{22} = 2$.
The adaptation is switched off

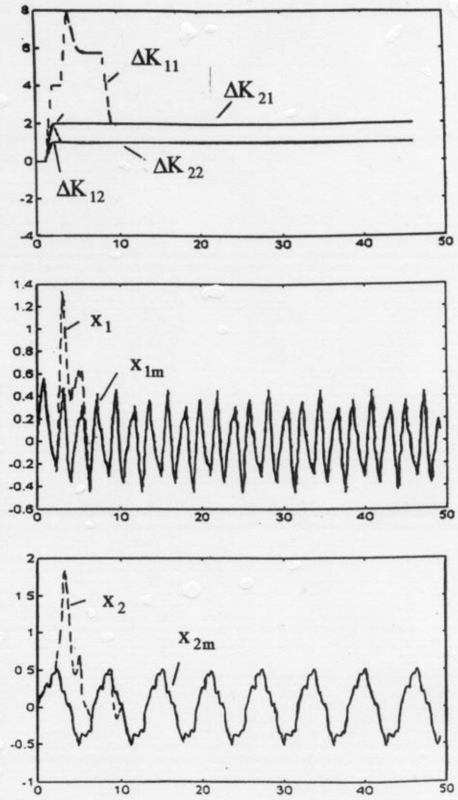


Fig. 2. Bias: $\Delta a_{11} = \Delta a_{12} = 1$, $\Delta a_{21} = \Delta a_{22} = 2$.
The adaptation is switched on.

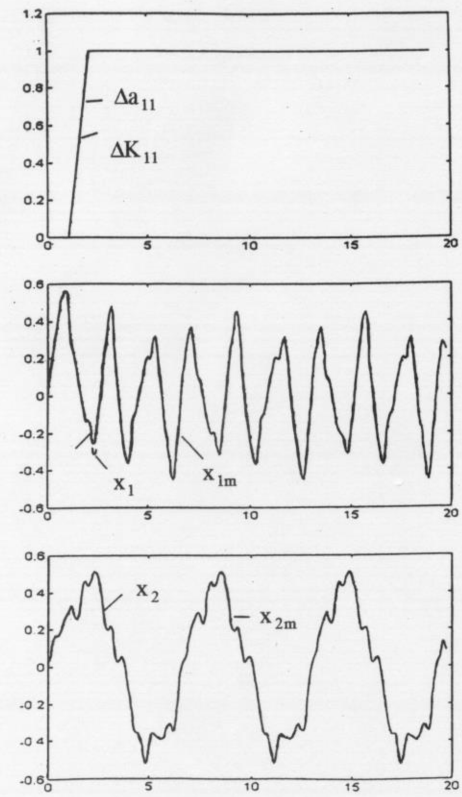


Fig. 3. Bias: $\Delta a_{11} = 1$, $\Delta a_{12} = \Delta a_{21} = \Delta a_{22} = 0$.
The adaptation is switched on.

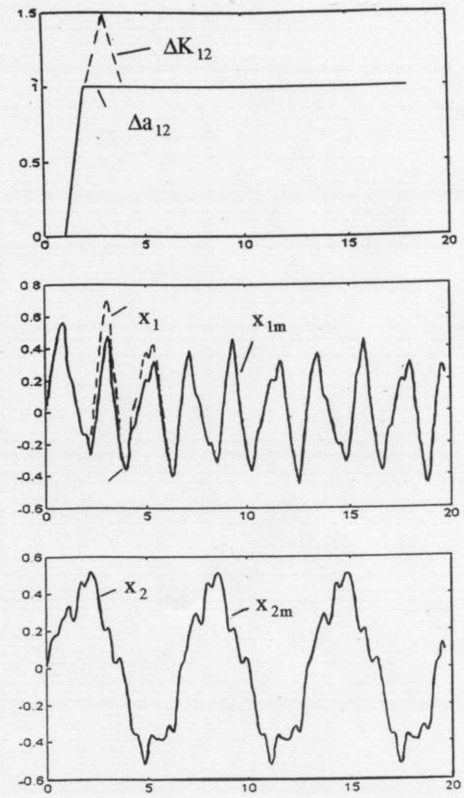


Fig. 4. Bias: $\Delta a_{12} = 1$, $\Delta a_{11} = \Delta a_{21} = \Delta a_{22} = 0$.
The adaptation is switched on.

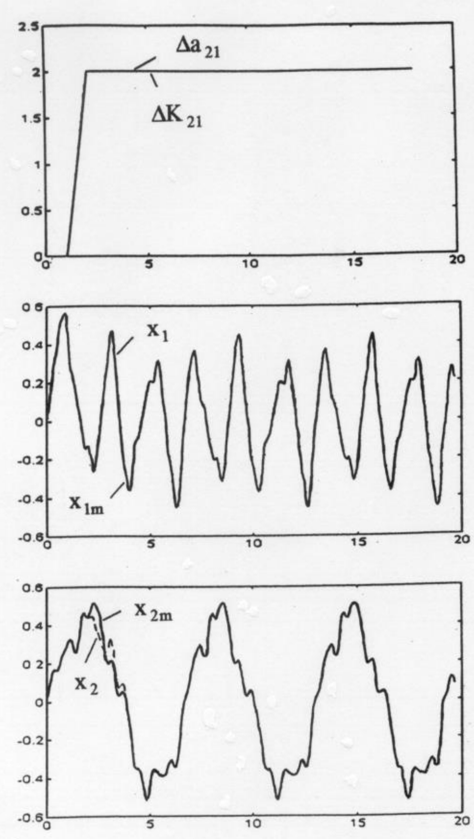


Fig. 5. Bias: $\Delta a_{21} = 2,\ \Delta a_{11} = \Delta a_{12} = \Delta a_{22} = 0$.
The adaptation is switched on.

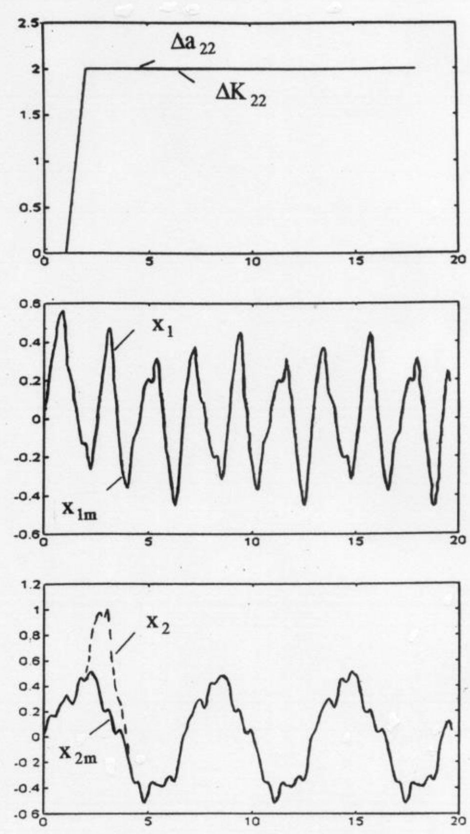


Fig. 6. Bias: $\Delta a_{22} = 2,\ \Delta a_{11} = \Delta a_{12} = \Delta a_{21} = 0$.
The adaptation is switched on.

3.4.3 Summary

The adaptive control system for multivariable processes is described in this paper. The method is based on the simultaneous identification and adaptation of unknown process parameters. When a fault occurs, the rapidly changing parameters in the MIMO process can be compensated by applying this method.

It should be taken into account that for the solution of equation (9), according to the hypothesis of quasi-stationary of the process, the time interval Δt is selected such that the bias of parameters Δa_{ij} must be constant at this interval. On the other hand, the interval Δt should be sufficiently large to accumulate values of variables x_i in order to avoid singularity of the solution of equation (9) and to provide the desirable accuracy of the adaptation.

3.5 Adaptive Control System for the Realization of the Decoupled Motion of an Aircraft with Required Dynamic Precision

Output – 5 is related to the development of an adaptive control system for the realisation of the decoupled motion of an aircraft with the required dynamic precision.

The requirements to manoeuvre a modern aircraft involve the development and realization of advanced control of a longitudinal and lateral aircraft motion. The manual control system for independent motion control of an aircraft on rolling and sideslip angles is given in (Guskov and Zagainov, 1980). The system depends upon a real-time measurement of air-dynamic coefficients of the aircraft, or requires the information from the tabulated parameters on all regimes of the aircraft motion. However, methods of precise measurement of air-dynamic coefficients in non-stationary conditions of the aircraft motion are not yet available at the present time. The exact parameters for all regimes of the aircraft motion cannot be obtained from a-priory measurements either. Therefore, a complete decoupled motion of an aircraft cannot be achieved.

In this paper the solution for a decoupled motion of an aircraft is obtained in the class of non-searching adaptive control systems with a reference model (Petrov et. al 1980). The new algorithms developed in this paper achieve a decoupled motion with desirable dynamic precision even in the conditions of high non-stationary of parameters. The robustness of the control system to the interaction of subsystems is accomplished as well.

3.5.1. Task formulation

The lateral motion of an aircraft (i.e. a plant) can be represented by the following equations:

$$\begin{aligned} \dot{\omega}_x &= M_x^{\omega_x}\omega_x + M_x^{\omega_y}\omega_y + M_x^{\beta}\beta + g_e \\ \dot{\omega}_y &= M_y^{\omega_y}\omega_y + M_y^{\omega_x}\omega_x + M_y^{\beta}\beta + g_h \\ \dot{\beta} &= \Lambda^{\beta}\beta + \omega_y \end{aligned} \tag{1}$$

where: g_e and g_h - are control signals from a pilot on relevant control surfaces,

$M_x^{\omega_x}$, $M_x^{\omega_y}$, $M_x^{\omega_\beta}$, $M_y^{\omega_x}$, $M_y^{\omega_y}$, $M_y^{\omega_\beta}$, Λ^{β} - are aerodynamic coefficients,

ω_x, ω_y - are angles of rotation of the aircraft around the **x** and **y** axis respectively (roll and pitch),

β - is the sideslip angle.

The task is as follows: a controller should be designed in such a way that the motion of the closed loop multivariable system "plant + controller" is decoupled on two separate motions – a roll and sideslip with the required performance according to the following reference models:

$$\dot{\omega}_{xm} + a_{0m}\omega_{xm} = g_e \tag{2}$$

$$\ddot{\beta}_m + b_{1m}\dot{\beta}_m + b_{0m}\beta_m = g_h \qquad (3)$$

where: ω_{xm}, β_m - are the roll and pitch angles of the reference model,

a_{0m}, b_{0m}, b_{1m} are constant parameters of the model.

Equations (2) and (3) represent the reference motion of the aircraft in roll and sideslip plans respectively.

Equation (1) can be re-written in the following form:

$$\begin{aligned} &\omega_x + a_0\omega_x = -a_{11}\beta - a_{12}\omega_y + g_e \\ &\ddot{\beta} + b_1\dot{\beta} + b_0\beta = -b_{11}\omega_x + g_h \end{aligned} \qquad (4)$$

where

$a_0 = -M_x^{\varpi_x}$, $\quad b_0 = M_y^{\omega_y} Z^{\beta} - M_y^{\beta}$,

$a_{11} = -M_x^{\beta}$, $\quad b_1 = -M_y^{\omega_y} - Z^{\beta}$,

$a_{12} = -M_x^{\varpi_y}$, $\quad b_{11} = -M_y^{\omega_x}$.

For the solution of the above task the following controls are defined:

$$\begin{aligned} &u_e = g_e - K_x\omega_x - R_{x\beta}\beta - R_{xy}\omega_y \\ &u_h = g_h - K_\beta\beta - K_y\dot{\beta} - R_{yx}\omega_x \end{aligned}$$

The closed loop equations are obtained as

$$\dot{\omega}_x + (a_0 + K_x)\omega_x = g_e - (a_{11} + R_{x\beta})\beta - (a_{12} + R_{xy})\omega_y$$
$$\ddot{\beta} + (b_1 + K_y)\dot{\beta} + (b_0 + K_\beta)\beta = g_h - (b_{11} + R_{yx})\omega_x \quad (5)$$

It can be seen from the above that the decoupled motion of the closed loop system will follow the reference models (2) and (3), if the following conditions are satisfied:

$$a_0 + K_x = a_{0m}, \quad a_{11} + R_{x\beta} = 0, \quad a_{12} + R_{xy} = 0, \quad (6)$$

$$b_1 + K_y = b_{1m}, \quad b_0 + K_\beta = b_{0m}, \quad b_{11} + R_{yx} = 0.$$

3.5.2. Synthesis of adaptation algorithms for a decoupled motion of an aircraft based on the direct method of Lyapunov

Due to time-varying nature of aerodynamic coefficients in non-stationary conditions of the aircraft motion, the parameters of the controller should be adjusted according to the biases of plant coefficients. This paper describes the solution for decoupled motion of an aircraft in the class of non-searching adaptive control systems with a reference model.

Consider the motion of the system “plant + controller” in the roll plan. On the nominal flight regime the following can be written:

$$\dot{\omega}_{xm} + (a_0^0 + K_x^0)\omega_{xm} = g_e - (a_{11}^0 + R_{x\beta}^0)\beta - (a_{12}^0 + R_{xy}^0)\omega_y \quad (7)$$

where

a_0^0, a_{11}^0 and a_{12}^0 are the nominal coefficients of plant (4) on the desirable flight regime in the roll channel,

K_x^0, $R_{x\beta}^0$ and R_{xy}^0 are the nominal coefficients of the controller in the roll channel.

According to equation (6) the following can be obtained:

$$K_x^0 = a_{0m} - a_0^0, \quad R_{x\beta}^0 = -a_{11}^0, \quad R_{xy}^0 = -a_{12}^0.$$

Due to the fact that parameters of an aircraft may not coincide with their nominal (computed) parameters on some flight regimes, the following can be written:

$$a_0 = a_0^0 + \Delta a_0, \quad a_{11} = a_{11}^0 + \Delta a_{11}, \quad a_{12} = a_{12}^0 + \Delta a_{12} \qquad (8)$$

where: Δa_0, Δa_{11} and Δa_{12} are the biases of plant coefficients from their nominal values in the roll channel.

Coefficients of the controller can be represented accordingly as

$$K_0 = K_0^0 + \Delta K_0, \quad R_{x\beta} = R_{x\beta}^0 + \Delta R_{x\beta}, \quad R_{xy} = R_{xy}^0 + \Delta R_{xy} \qquad (9)$$

where: ΔK_0, $\Delta R_{x\beta}$ and ΔR_{xy} are the adjustable parameters of the controller in the roll channel.

Comparing the first equation of system (5) with equation (7) and taking into account expressions (8) and (9), the equation of a state error is obtained:

$$\dot{e}_x + a_{0m}e = -(\Delta a_0 + \Delta K_x)\omega_x - (\Delta a_{11} + \Delta R_{x\beta})\beta - (\Delta a_{12} + \Delta R_{xy})\omega_y \qquad (10)$$

where: $e_x = \omega_x - \omega_{xm}$.

The following expressions are defined:

$$Y_1 = \Delta a_0 + \Delta K_x, \quad Y_2 = \Delta a_{11} + \Delta R_{x\beta}, \quad Y_3 = \Delta a_{12} + \Delta R_{xy} \qquad (11)$$

where: Y_1, Y_2 and Y_3 - are parametric biases.

Using definitions (11), equation (10) can be represented in the following form:

$$\dot{e}_x + a_{0m}e = -Y_1\omega_x - Y_2\beta - Y_3\omega_y \qquad (12)$$

The task of the adaptive control system is to provide the following equivalents:

$$e_x \equiv 0, \quad Y_1 \equiv 0, \quad Y_2 \equiv 0, \quad Y_3 \equiv 0$$

It can be admitted that on the desirable flight regime parameters biases Δa_0, Δa_{11} and Δa_{12} exist, but are constant, i.e.: $\Delta a_0 = const.$, $\Delta a_{11} = const.$ and $\Delta a_{12} = const.$ The algorithms of adaptation based on the direct method of Lyapunov (Astrom and Wittenmark 1995) are obtained as the following form:

$$\dot{Y}_1 = \gamma_1 e_x \omega_x \,, \quad \dot{Y}_2 = \gamma_2 e_x \beta \,, \quad \dot{Y}_3 = \gamma_3 e_x \omega_y \qquad (13)$$

In the case of the aircraft motion in the sideslip plan the following definitions are used:

$$b_0 = b_0^0 + \Delta b_0 \,, \quad b_1 = b_1^0 + \Delta b_1 \,, \quad b_{11} = b_{11}^0 + \Delta b_{11}$$

b_0^0, b_1^0 and b_{11}^0 are the nominal coefficients of plant (4) on the desirable flight regime in the sideslip channel,

Δb_0, Δb_1 and Δb_{11} are the biases of plant coefficients from their nominal values in the sideslip channel.

The coefficients of the controller in the channel of a sideslip angle are represented accordingly:

$$K_y = K_y^0 + \Delta K_y \,, \quad K_\beta = K_\beta^0 + \Delta K_\beta \,, \quad R_{yx} = R_{yx}^0 + \Delta R_{yx} \qquad (14)$$

where

K_y^0, K_β^0 and R_{yx}^0 - are the nominal coefficients of the controller in the sideslip channel,

ΔK_y, ΔK_β and ΔR_{yx} are the adjustable parameters of the controller in the sideslip channel.

Applying the methodology given above for the aircraft motion in the roll plan, the mathematical model of the adaptive control system for the sideslip angle is obtained in the following form:

$$\begin{aligned}
&\ddot{e}_\beta + b_{1m}\dot{e}_\beta + b_{0m}e_\beta = -Z_1\dot{\beta} - Z_2\beta - Z_3\omega_x \\
&\dot{Z}_1 = \gamma_4\sigma_\beta\dot{\beta} \\
&\dot{Z}_2 = \gamma_5\sigma_\beta\beta \\
&\dot{Z}_3 = \gamma_6\sigma_\beta\omega_x
\end{aligned} \tag{15}$$

where

Z_1, Z_2 and Z_3 - are parametric biases.

$\sigma_\beta = P_1 e_\beta + P_2\dot{e}_\beta$, $\quad P_1 = const.$, $P_2 = const.$

$Z_1 = \Delta b_1 + \Delta K_y$, $\quad Z_2 = \Delta b_0 + \Delta K_\beta$, $\quad Z_3 = \Delta b_{11} + \Delta R_{yx}$.

It is also admitted here that $\Delta b_0 = const.$ $\Delta b_1 = const.$ and $\Delta b_{11} = const.$ on the nominal flight regime. According to the direct method of Lyapunov, algorithms (15) provide a stable motion, i.e.: $e_\beta \equiv 0, \quad Z_1 \equiv 0, \quad Z_2 \equiv 0, \quad Z_3 \equiv 0$.

3.5.3. Synthesis of the adaptive control system based on the required dynamic precision of the states motion

Consider the adaptive control system operating for the sideslip channel. It can be shown that system (15) consists of three contours, which are connected through the linear unit with the following transfer function:

$$W(p) = \frac{1}{p^2 + b_{1m} p + b_{0m}}$$

The task of the each contour is to retain the following equivalents:

$$\Delta b_0 + \Delta K_\beta \equiv 0, \quad \Delta b_1 + \Delta K_y \equiv 0, \quad \Delta b_{11} + \Delta R_{yx} \equiv 0.$$

Each contour represents a tracking system, which is non-linear and non-stationary in nature. Because of the connection of all contours through the common unit, each contour reacts in dynamics not only on its own parametric bias Δb_0, Δb_1 or Δb_{11}, but it also reacts on parametric biases of other contours. Moreover, the dynamics of each contour depends on the input signals $g_h(t)$ through states $\beta_m(t)$, $\dot{\beta}_m(t)$ and $\ddot{\beta}_m(t)$ of the reference model. Such interconnections are not desirable due to the fact that in this case the dynamic characteristics of the adaptive system become uncertain. Therefore, invariant dynamics of tracking contours from the input signals as well as separation of dynamics of each contour from the interconnection with other contours should be provided. It can be shown (Petrov et. al. 1980; Vershinin 1991) that these problems could be solved if the followings are provided:

$$\Psi_y = -\gamma_4 Z_1, \quad \Psi_\beta = -\gamma_5 Z_2, \quad \Psi_{yx} = -\gamma_6 Z_3$$

where

$$\Psi_y = \sigma_\beta \gamma_4 \dot{\beta}, \quad \Psi_\beta = \sigma_\beta \gamma_5 \beta, \quad \Psi_{yx} = \sigma_\beta \gamma_6 \omega_x .$$

The dynamic of each tracking contour in this case is described as follows:

$$T_1 \frac{d\Delta K_y}{dt} + \Delta K_y = -\Delta b_1, \quad T_2 \frac{d\Delta K_\beta}{dt} + \Delta K_\beta = -\Delta b_0, \quad T_3 \frac{d\Delta R_{yx}}{dt} + \Delta R_{yx} = -\Delta b_{11}$$

where

$$T_1 = \frac{1}{\gamma_4}, \quad T_2 = \frac{1}{\gamma_5}, \quad T_3 = \frac{1}{\gamma_6} .$$

For the solution of this task the following variable is introduced:

$$\tilde{\sigma}_\beta = (p^2 + b_{1m} p + b_{0m}) e_\beta$$

where $p = \frac{d}{dt}$ is the derivative operand.

By substituting $\tilde{\sigma}_\beta$ instead of σ_β the following is obtained:

$$\tilde{\sigma}_\beta = -Z_1 \dot{\beta} - Z_2 \beta - Z_3 \omega_x \qquad (16)$$

It has been confirmed by the simulation that the performance of the system with these algorithms satisfied the desirable performance.

In order to find the parametric biases from equation (16) the following method is used: Define the time interval Δt where coefficients $b_0(t)$, $b_1(t)$ and $b_{11}(t)$ are constant. The adaptive contours are switched off in this time interval. The coefficients of adaptation are adjusted as:

$$\Delta K_y = -\Delta b_1, \quad \Delta K_\beta = -\Delta b_0 \quad \Delta R_{yx} = -\Delta b_{11} \tag{17}$$

Taking the initial conditions of the controller as $\Delta K_y = 0$, $\Delta K_\beta = 0$ and $\Delta R_{yx} = 0$ equation (16) can be modified as:

$$\tilde{\sigma}_\beta = -\Delta b_1 \dot{\beta} - \Delta b_2 \beta - \Delta b_{11} \omega_x \tag{18}$$

Multiplying equation (18) by $\dot{\beta}$, β and ω_x accordingly and integrating on the time-interval Δt the following is obtained:

$$\int_0^{\Delta t} \tilde{\sigma}_\beta \dot{\beta} dt = -\Delta b_1 \int_0^{\Delta t} \dot{\beta}^2 dt - \Delta b_0 \int_0^{\Delta t} \beta \dot{\beta} dt - \Delta b_{11} \int_0^{\Delta t} \omega_x \dot{\beta} dt$$

$$\int_0^{\Delta t} \tilde{\sigma}_\beta \beta dt = -\Delta b_1 \int_0^{\Delta t} \dot{\beta} \beta dt - \Delta b_0 \int_0^{\Delta t} \beta^2 dt - \Delta b_{11} \int_0^{\Delta t} \omega_x \beta dt \tag{19}$$

$$\int_0^{\Delta t} \tilde{\sigma}_\beta \omega_x dt = -\Delta b_1 \int_0^{\Delta t} \dot{\beta}\omega_x dt - \Delta b_0 \int_0^{\Delta t} \beta\omega_x dt - \Delta b_{11} \int_0^{\Delta t} \omega_x^2 dt$$

Introduce the following notations:

$$\ell_1 = \int_0^{\Delta t} \tilde{\sigma}_\beta \dot{\beta} dt\,, \quad c_{11} = -\int_0^{\Delta t} \dot{\beta}^2 dt\,, \quad c_{12} = -\int_0^{\Delta t} \beta\dot{\beta} dt\,, \quad c_{13} = -\int_0^{\Delta t} \omega_x \dot{\beta} dt$$

$$\ell_2 = \int_0^{\Delta t} \tilde{\sigma}_\beta \beta dt\,, \quad c_{21} = -\int_0^{\Delta t} \dot{\beta}\beta dt\,, \quad c_{22} = -\int_0^{\Delta t} \beta^2 dt\,, \quad c_{23} = -\int_0^{\Delta t} \omega_x \beta dt \qquad (20)$$

$$\ell_3 = \int_0^{\Delta t} \tilde{\sigma}_\beta \omega_x dt\,, \quad c_{31} = -\int_0^{\Delta t} \dot{\beta}\omega_x dt\,, \quad c_{32} = -\int_0^{\Delta t} \beta\omega_x dt\,, \quad c_{33} = -\int_0^{\Delta t} \omega_x^2 dt$$

Using notations (20), equations (19) can be re-written in the following form:

$$\begin{aligned} \ell_1 &= c_{11}\Delta b_1 + c_{12}\Delta b_0 + c_{13}\Delta b_{11} \\ \ell_2 &= c_{21}\Delta b_1 + c_{22}\Delta b_0 + c_{23}\Delta b_{11} \qquad (21) \\ \ell_3 &= c_{31}\Delta b_1 + c_{32}\Delta b_0 + c_{33}\Delta b_{11} \end{aligned}$$

The required coefficients Δb_1, Δb_0 and Δb_{11} can be obtained from the solution of the system of algebraic equations (21). The adaptation counters are then switched on in order to adjust the parameters of the controller according to equations (17) and (14). Thereafter the adaptation counters are switched off again and the operational cycle is repeated.

The adaptive control system for the roll channel operates in the similar fashion. According to equations (12) and (13) the following variable can be formed:

$$\tilde{\sigma}_x = (p + a_{0m})e_x$$

By using the procedure described above for the sideslip channel one can obtain that:

$$\tilde{\sigma}_x = -Y_1\omega_x - Y_2\beta - Y_3\omega_y \qquad (22)$$

For compensation of parametric biases (11) the following needs to be achieved:

$$\Delta K_x = -\Delta a_0, \quad \Delta R_{x\beta} = -\Delta a_{11}, \quad \Delta R_{xy} = -\Delta a_{12} \qquad (23)$$

Taking into account the initial conditions as $\Delta K_x = 0$, $\Delta R_{x\beta} = 0$ and $\Delta R_{xy} = 0$, equation (22) is re-written as:

$$\tilde{\sigma}_x = -\Delta a_0\omega_x - \Delta a_{11}\beta - \Delta a_{12}\omega_y$$

The parametric biases Δa_0, Δa_{11} and Δa_{12} can be obtained in an analogous manner to the approach described above for the sideslip channel. Coefficients K_x, $R_{x\beta}$ and R_{xy} of the adaptive control system for the roll channel are then calculated according to equations (23) and (9).

3.5.4. The numerical results

The mathematical model of the aircraft motion in the lateral plan is represented by equations (1). The reference models of aircraft dynamics on roll and sideslip angles are given by equations (2) and (3) respectively, where a_{0m} =1, b_{0m} =9 and b_{1m} =4.2 . It can be seen from Figure 1 that the aircraft dynamics on roll and sideslip angles (ω_x and β) coincide with the relevant dynamics of the reference models. The input signal on the roll channel is:

$g_e = g_{e1} + g_{e2}$,

where

$g_{e1} = \pm 1$,

$g_{e2} =$ 0.2sin11t+0.08sin3t.

The input signal on the sideslip channel is:

$g_h = g_{h1} + g_{h2}$,

where

$g_{h1} = 0$,

$g_{h2} =$ 0.2sin13t+0.1sin4t.

The coefficients of plant (1) are changed three times during 12 seconds from their nominal values. It can be seen from Figure 2 that the controller tracks well the plant coefficients. The time required by the adaptive system for processing the information is 0.25sec.

In the system described above the adaptation process consists of two parts, namely identification of plant parameters and adjusting the coefficients of the controller.

The time interval Δt should be defined in such a way that the coefficients of system (21) for the sideslip channel and the relevant coefficients for the roll channel become sufficiently large in order to solve the equations. On the other hand, however, the range of variations of the coefficients should be small enough in order to satisfy the desirable accuracy of the adaptation process.

The block-diagram of the system with adaptive control algorithms for separation of an aircraft motion on a roll and sideslip is given in Appendix 3.5.3.

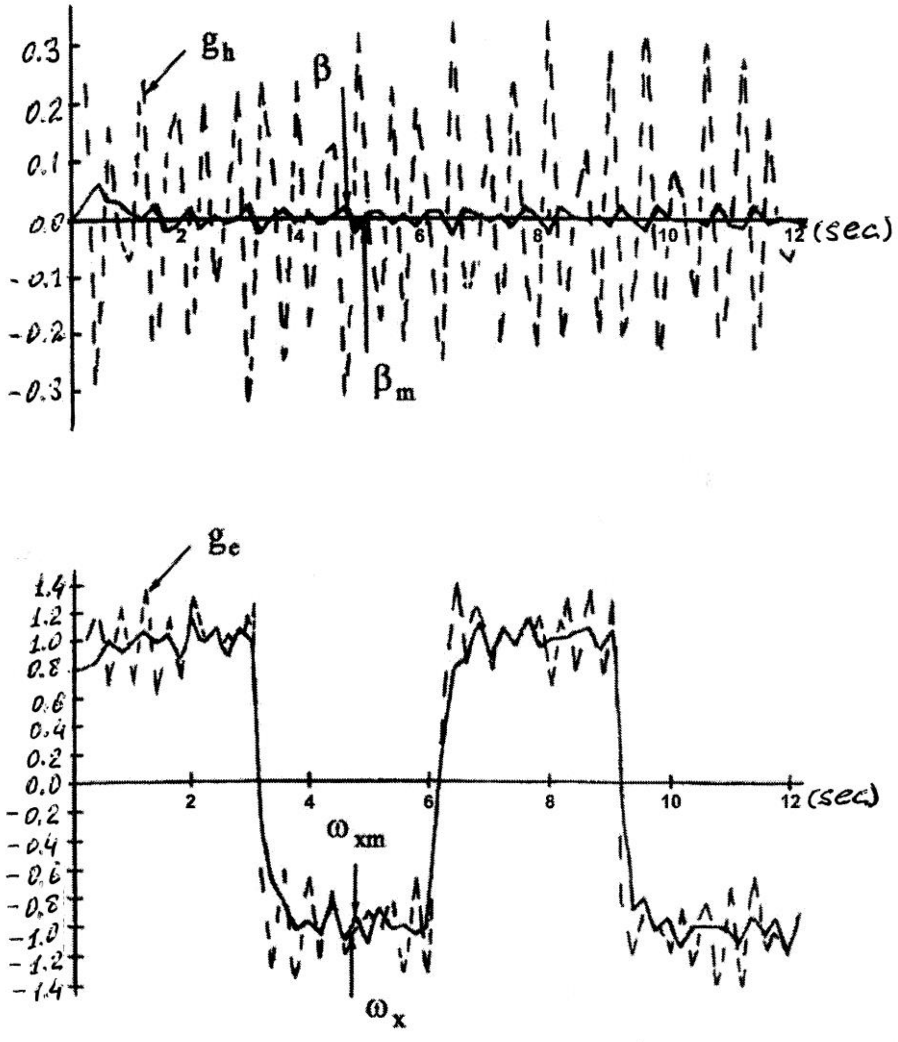


Figure 1. The aircraft dynamics on sideslip and roll angles and dynamics of the relevant reference models.

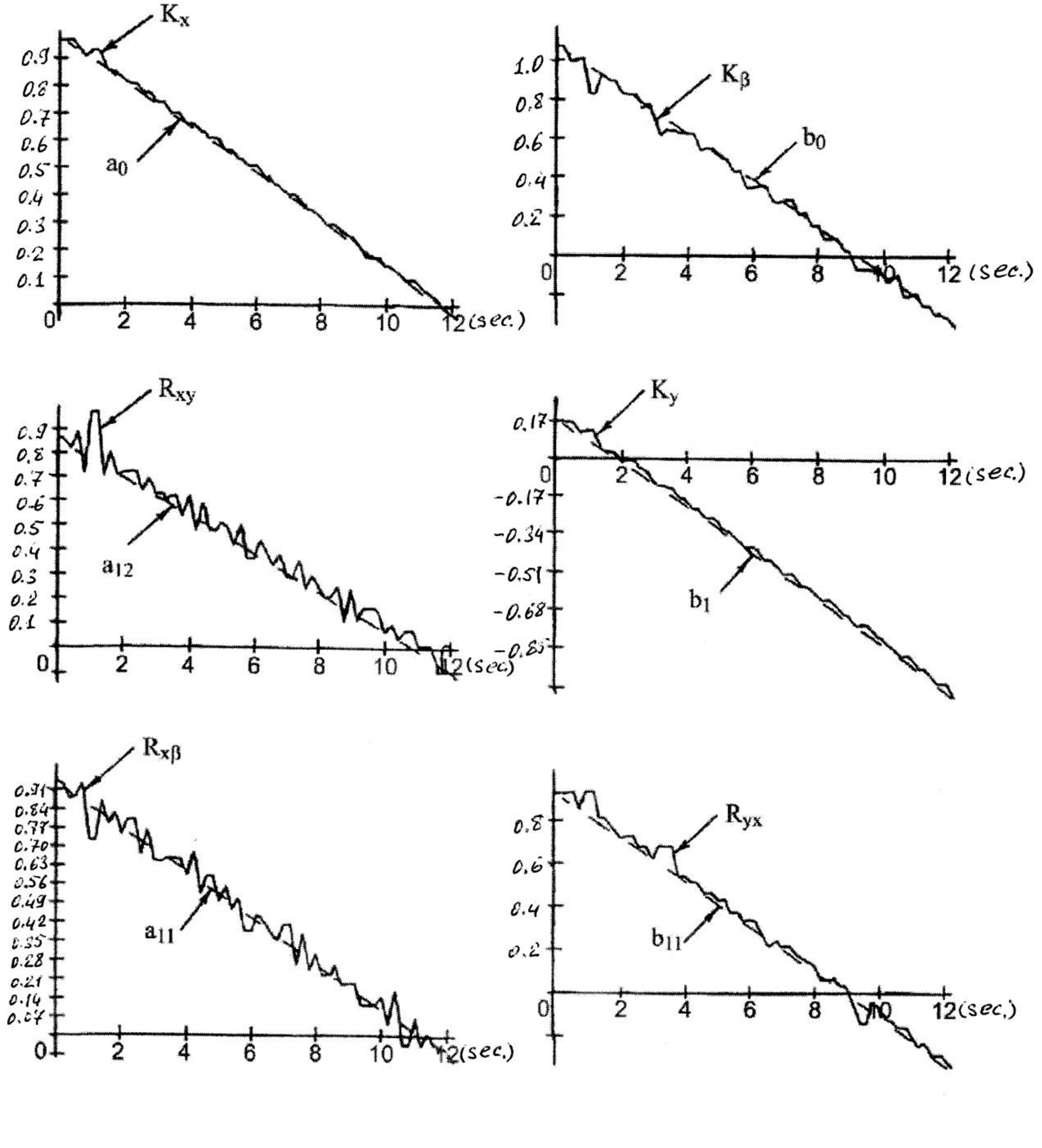


Figure 2. Plant coefficients and controller coefficients.

3.5.5 **Summary**

The adaptive control system described in this paper provides a decoupled lateral motion of an aircraft on roll and sideslip angles. The system allows the obtaining of the desirable dynamic precision of the states' motion in non-stationary conditions of the aerodynamic coefficients. The accuracy of states and parameters tracking is also improved due to the separation of adaptive contours from their interconnections to the plant's dynamics.

3.6. Adaptive Control System for Exhaust Emissions Reduction and Improvement of Fuel Economy in an Automotive Engine

Output - 6 of this thesis is related to the application of adaptive control algorithms for exhaust emissions reduction and the improvement of fuel economy in an automotive engine.

3.6.1 Project aim

The project aim is to develop an advanced control system for an automotive engine, which will allow the reduction of hydrocarbons, CO and NOx emissions due to the effective control of the air-to-fuel ratio (AFR) in individual cylinders. This, in turn, will result in the reduction of air pollutions, contributing to the solution of the environment problem in urban cities. The AFR control system proposed in the project can be used for both types of internal combustion engines: spark ignition and diesel engines. No additional hardware is required for the implementation of the system on production cars. Only new air-to-fuel ratio management software algorithms need to be implemented on an automotive Electronic Control Unit (ECU). Due to the self-tuning adaptation functions embedded in the algorithm, the manual adjustment and calibration process of a fuel management system will be substantially reduced. This will further reduce the production costs for manufacturers as well as the maintenance costs for car owners.

The new method of AFR control proposed in the project is based on the real-time identification of an engine model and refining of the model from low order to high order. It allows the reduction of fuel consumption as a result of the more precise matching of the identified engine model to the real engine.

3.6.2. Background

Increased competition in the automotive market has forced companies to find new solutions to improve fuel efficiency. Recent European regulations have imposed limits on exhaust emissions, which have further added pressure on companies to research into the design of efficient catalytic converters and advanced control strategies.

A three-way catalytic converter (TWC) employed on Spark Ignition (SI) engines, allows the reduction of exhaust carbon monoxide (CO), hydrocarbons (HC) and nitric oxides (NOx). However, the TWC becomes ineffective when the air-to-fuel ratio changes more than 1% from its stoichiometric level. An Exhaust Gas Oxygen sensor (EGO) is used on an engine in order to monitor the air-to-fuel ratio. Currently, most production automobiles are equipped with one EGO sensor, which provides information about the average mixture of exhaust gases from all the engine cylinders. This information is used by an Electronic Control Unit

(ECU) in order to adjust the fuel volume for fuel injection in the cylinders. However, although the *average* air-to-fuel ratio for all the cylinders is controlled around the stoichiometric level on most production automobiles, the functioning of the individual cylinders may differ from their stoichiometric level. Thus, the air-to-fuel ratio may be constantly lean or rich, which results in increased emissions. These results were shown, for example, in the work of Shulman and Hamburg (1993). In order to eliminate differences in the amounts of fuel injected in individual cylinders, fuel injectors can be matched for each engine during the manufacturing process. The data-table in the ECU is then adjusted according to the experimental results. Such a method is currently used for the production of high-end automobiles in the Jaguar car company, U.K. (Youson 2004). However, discrepancies between individual cylinders, valves characteristics and intake manifold parameters result in the misdistribution of the air-to-fuel ratio between the cylinders. Engine wear and the variation of the parameters of a fuel path and air path due to temperature fluctuations also contribute to the shift of the AFR from the stoichiometric level in individual cylinders, thus increasing the emission level of hydrocarbons, CO and NOx.

The required amount of fuel injected in cylinders can be calculated if the mathematical models of a fuel path and air path are known. The derivation of a continuous-time model of an intake manifold, throttle and cylinders are given in Lenz and Schroder (1998), together with a model of a fuel flow entering the combustion chamber. Non-linear effects of the throttle and cylinders are taken into account in these models. Although continuous-time models can describe the principle of operation of an engine and related air-fuel systems; discrete-time models represent more realistic behaviours of the above given systems. This is due to the event-based nature of engine functioning (Chang, Fekete and Powell 1993). A non-linear discrete engine model developed by Kand and Grizzle (1998) is based on periodic crankshaft angle sampling instead of the classical time-domain sampling. Scherer et al. (1998) developed a method which allows the estimating of the mass of air in cylinders using manifold pressure air mass and throttle angle sensors used on production automobiles (Scherer, Hart and Loffeld 1998). They suggest employing an adaptive Kalman filter to reduce pressure pulsations, which have a negative influence on the performance of the control system. The obtained information about the air mass in the cylinders can be used for the accurate control of the air-to-fuel ratio. A problem arises however, in the fact that the direct measurement of the fuel mass in the cylinders cannot be performed in practice. In order to solve this task, Turing and Geering (1994) proposed an adaptive observer, which takes into account wall-wetting dynamics in the full path. The oxygen sensor used in this system is of a switching type. Thus, the dynamics of such a type of sensor is highly non-linear, which decreases the accuracy of the fuel path parameters estimation. In order to obtain parameters of the wall-wetting model using the identification method, excitation signals are applied to the system. In particular, throttle steps are used to excite the fuel supply path**.** It should be noted that although the correlation between the fuel and air channels exists through the coupled engine’s dynamics, the deterioration of accuracy in the parameters identification using only throttle inputs is inevitable, when compared to the wall-wetting parameters determination with the direct excitation of a fuel channel by its own input signals. However, the direct excitation of the fuel path has not been implemented in this work.

Another approach to the gas mixture estimation in individual cylinders based on the information available from an automobile with only one λ-sensor (lambda sensor) is reported in Hasegawa, Akazaki, Komoriya, Maki and Hirota (1994). The method is based on the idea that the contribution of each cylinder in the λ-sensor measurement is different from the other cylinders on the relevant exhaust stroke. Thus, it may be possible to extract the information about the air-to-fuel ratio in individual cylinders if the correct correlation between the oxygen sensor signal and the AFR mixture in each cylinder is established. Such a correlation is obtained in the work of Watanaba, Tanaka, Kaneyasu, Asano and Baba (1997) from practical experiments. The relevant numerical coefficients are then substituted in the equation of the observer. Four PID controllers are used to the correct fuel injection independently in order to maintain the stoichiometric level of the gas mixture in the individual cylinders. The numerical coefficients for the observer were obtained from experiments for the particular type of the four cylinder SI engine. However, it is not practically possible to obtain the coefficients for each production engine and to set up these values in the air-to-fuel control system on each engine. This is due to differences between engines, components parameters variations, temperature fluctuation and engine wear.

A method for the air-to-fuel ratio estimation in individual cylinders for a diesel engine is presented in Moulin, Corde, Castagne and Rousseau (2004). The method is based on the inversion of the exhaust model and the switching of the estimation between cylinders depending on the crankshaft angle position. The time delay between the cylinder exhaust and the response of the oxygen sensor is estimated on-line in order to obtain the correct switching time for the cylinder allocation. The AFR in each cylinder is then calculated using the extended Kalman filter, which runs in parallel with the calculation of the augmented model of the exhaust manifold. However, there is no indication in this work concerning the determination of the gas mass flow from individual cylinders into the exhaust manifold. This information missing in Moulin, Corde, Castagne and Rousseau (2004) is actually essential for the estimation of the gas composition in the cylinders. Also, it is stated in this work that the simplified physical model of the exhaust has to be inverted in order to obtain the exhaust manifold inlet AFR. However, it is well known that any inverted model, given in the transfer function or state-space representation, needs to be checked on singularity (Golub and Van Loan, 1996), otherwise, the system may not function properly. The real automotive fuel path and air path subsystems are non-linear and time-varying due to temperature fluctuation and pressure pulsation. Thus, the functioning of the system described in Moulin, Corde, Castagne and Rousseau (2004) cannot be guaranteed on a real vehicle.

It is evident from the literature survey given above that there is not yet any commercially available engine management system which is capable of controlling the air-to-fuel ratio in individual cylinders. The implementation of the High Dynamic Precision Adaptive Control (HDPAC) system suggested in this proposal however will allow the reduction of CO, HC and NOx emissions without additional hardware and using only one oxygen sensor, which is installed on all production automobiles. Moreover, the overall production cost of vehicles can be reduced due to a relaxation of differences in amounts of fuel injected in individual cylinders.

3.6.3. Project objectives

The specific objectives of this work are:

1) To develop a methodology for the estimation of the air-to-fuel ratio in individual cylinders using only one EGO-sensor (Exhaust Gas Oxygen) located after the exhaust manifold. The sensor dynamics and the time-delay of exhaust gases between the cylinder exhaust and the sensor must also be taken into account.
2) To investigate the spectral information of a system performance in the whole range of working engine conditions (speed and load).

3) To consider methods of extracting a useful signal from a sensor signal (which includes sensor noise) in order to obtain a high signal-to-noise ratio, which is required to control the fuel injection system.
4) To determine the required sampling rate of the measurement system according to the sampling rate of available hardware in order to obtain the correct information concerning the AFR in individual cylinders.
5) To develop a prediction-correction algorithm for the synchronisation of such events as measurement sampling, engine cycles events and control correction signals.
6) To develop a stochastically based technique for on-line parameter estimation and adaptation for highly non-stationary systems. The novel elements of the development are:
    a) to execute low and high-order Extended Kalman filters simultaneously, the low order estimate providing the initial conditions for the high order estimate, thereby increasing the rate of convergence;
    b) to employ the adaptive control in order to compensate parameters' variations.
7) To carry out trials of the systems emerging from the above given objectives on an automotive engine.

3.6.4. Novelty

In order to control the air-to-fuel ratio in individual cylinders with high performance, a model of the engine must be known exactly. Mathematical models can be obtained using the flow-dynamics theory. However, such models represent a theoretical engine rather than a real, physical engine. Thus, the implementation of this model in the control system on a real automobile cannot guarantee the expected performance obtained from the computer simulation. It is shown in Ljung (1999) that model parameters can be obtained from an experiment using such identification techniques as Recursive Least Squares method (RLS), Instrumental Variables method (IV), Kalman Filter (KF), etc. The problem of parameters' variations in an engine (due to temperature fluctuation and engine wear) can be solved using adaptive control methods (Astrom and Wittenmark 1995). In practice however, a problem with the speed of the parameters' convergence can arise during the identification process, especially when the model is of a high order.

Many practical engineering applications such as automotive systems require to be modelled as high order systems. This research project proposes to develop a technique where systems are identified concurrently as both low and high order systems. The low order systems provide initial conditions for the higher order processes. This method is suitable for implementation as a robust on-line identification technique. Adaptive control strategies need to be applied to the plant parameters' compensation because an automotive engine is in fact a highly non-stationary plant. However, classical control approaches do not give high accuracy control in the case of multivariable plant application, due to the interaction of control signals between the channels of the MIMO system through machine structure and process materials. The new adaptive control strategy is proposed to overcome this problem.

3.6.5. Description of High Dynamic Precision Adaptive Control System Structure

The block-diagram of the High Dynamic Precision Adaptive Control System is represented in Figure 1. The input to the system is the signal for an electronic fuel injector, whereas the output is the measurement from the exhaust oxygen sensor. Due to uncertainties in the plant parameters, a serious problem may arise on certain regimes of plant control. The proposed research programme is aimed at solving this problem by employing a self-adaptive control law with optimal state estimation that comes into play where high accuracy is required.

It is proposed to generate a novel high accuracy, self-adaptive control law based on the following concept. It is known that with an appropriate state representation, the parameters of low order plant models used in a simultaneous parameter/state estimator based on the extended Kalman filter are correlated to parameters of higher order models. It is therefore proposed to investigate a system in which the steady-state parameters of the low order model are used as initial parameters in a higher order model. In this way, the range of convergence in the parameter space should be extended beyond that attainable with the higher order model alone and convergence should be faster. According to the block-diagram in Figure 1, the error vector, $\mathbf{e_1}$, of the lower estimator is monitored. When this has settled within the specified limits, the components of the plant parameter estimate vector, $\hat{\mathbf{p}}_1$, are used to update the higher dimensional parameter estimate vector $\hat{\mathbf{p}}$, of the higher order estimator with a knowledge of the aforementioned correlation. The error vector, **e**, of this estimator is continually monitored and used to control the software switch to maintain the high precision adaptive control law active ($u = U_a$).

For the purpose of obtaining the minimal realisation of a mathematical model of a plant, the Hanker Norm Approximation approach is proposed. The significant role of the Hankel matrix is that the rank of the matrix reflects the order of the corresponding system (Gantmacher 1961). According to the Adamyan, Arov and Krein theorem (Adamjan, Arov and Krein 1971), the best r-th rank approximating matrix of the original Hankel Matrix can be achieved within the distance of $\ell(r+1)$, where $\ell(r+1)$ is the $(r+1)$-th singular value of the original Hankel matrix. A practical algorithm for the solution of the minimal realisation problem using the Hankel matrix was proposed by Ho and Kalman (1966). However, Ho's algorithm does not take into account noise, which is almost always present in input-output signals in an industrial environment. In this case, important rank-order relationships may not reflect the real model of the plant. The solution of the approximation problem can be found using the Singular Value Decomposition (SVD) of the Hankel matrix (Moore 1978). This approach is based on the fact that the smallest singular value reflects the order of the Hankel matrix. The rank of the matrix and thus the order of the system can be found by arranging the singular values with required tolerance in the noise-corrupted case. In practice, the Markov parameters of the Hankel matrix may be produced as components of the system impulse response or input-output correlation.

The advantages of the approach described above are:

- the SVD provides a robust representation of the rank of the system in a noise corrupted case;
- the low order state-space model representation will result in faster processing on the automotive Electronic Control Unit (ECU). Using the shift-invariant structure of the Hankel matrix and standard SVD algorithms, the calculation process will be done much faster than by any other identification techniques used at the present time in industrial applications.

In the next step, the parameters obtained by the method described above are then used as initial conditions for the higher order process. An extended Kalman filter (EKF) was chosen as a more promising method for this application among other identification techniques. The advantages of the EKF are: parameters and state-space variables of a process can be obtained, and input-output noise can be reduced at the same time. A Kalman filter is a most optimal filter in the mean-least-squares sense. The filter is ideal for real time estimation using a microcontroller. This is because its mathematical formulation is made in terms of the state-space and the solution is computed recursively. The recursive nature of the filter means that memory requirements are kept to a minimum. Numerical simulation shows that the speed of convergence of the parameters of an EKF using initial conditions from a low order model is nearly 10 times faster than when using conventional identification with zero initial conditions. In order to compensate for the bias of plant parameters from nominal values, an adaptive control system is incorporated in the feedback loop.

3.6.6 Summary

The application of the adaptive control algorithm allows the channels of a MIMO system to be decoupled from their interconnection through the machine structure and process materials. It allows the pure control of the plant's individual parameters by its own regulator without the influence from other controls. The adaptive control system provides the compensation of the parameters' variations which occur due to temperature change and engine wear. The described system will allow the reduction of fuel consumption and the reduction of hydrocarbons, CO and NOx emissions due to the effective control of the air-to-fuel ratio in individual cylinders.

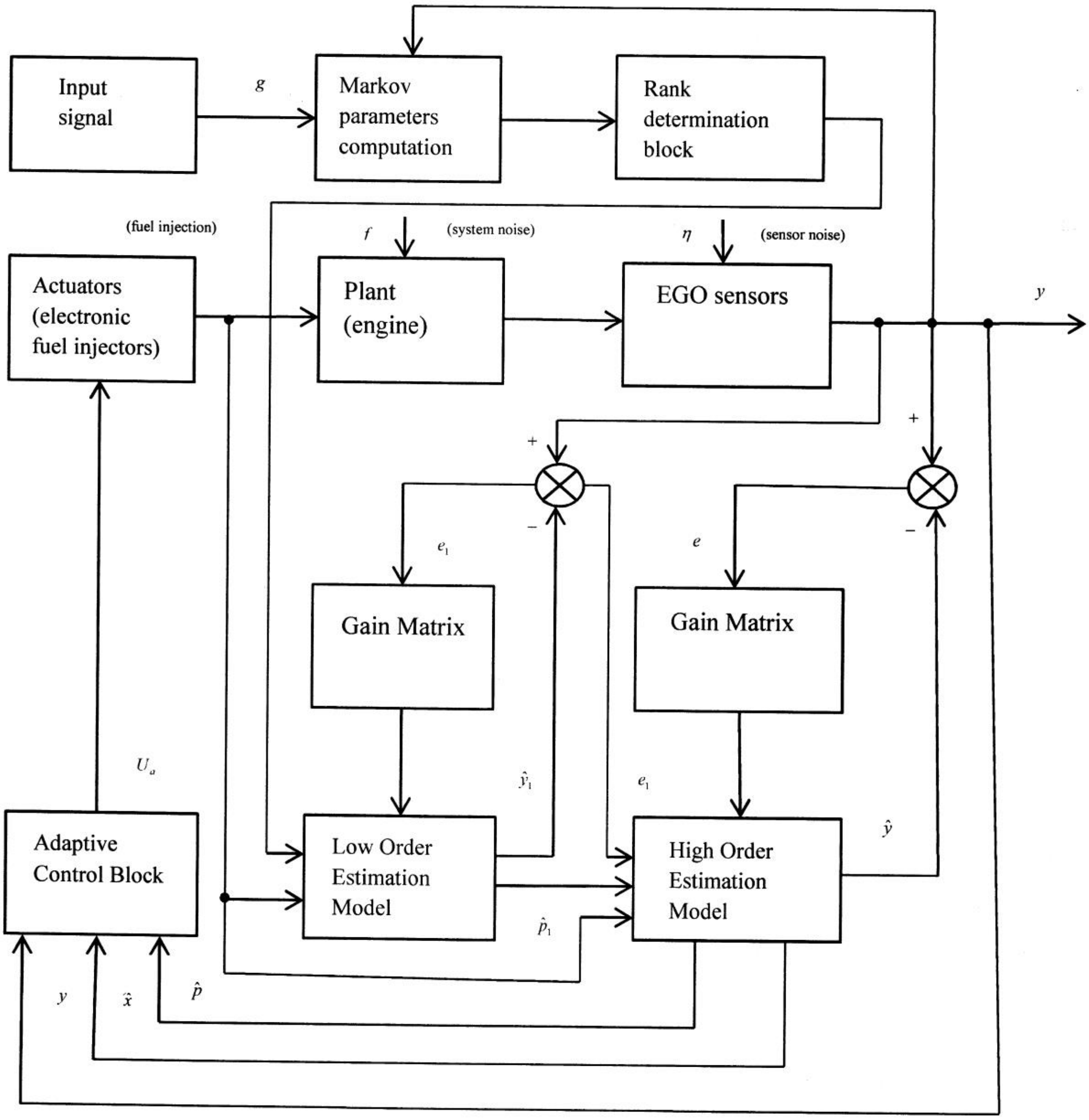


Figure 1 Adaptive control system for exhaust emission reduction and improvement of fuel economy in automotive engine.

Appendix of Section 3

Markov parameters obtained from the experiment:	*Markov parameters of the reduced order model:*
0.0000000e+00	0.0000000e+00
6.5000000e-02	6.4934730e-02
1.4550000e-01	1.4578163e-01
1.6442500e-01	1.6384913e-01
1.5056000e-01	1.5077128e-01
1.2447038e-01	1.2511681e-01
9.7003263e-02	9.7037520e-02
7.2809279e-02	7.1509116e-02
5.3273657e-02	5.0478548e-02
2.7143404e-02	3.4252666e-02
1.9054881e-02	2.2345734e-02
1.3274250e-02	1.3971877e-02
9.1920232e-03	8.3100499e-03
6.3351771e-03	4.6301281e-03
4.3498142e-03	2.3388797e-03
2.9776238e-03	9.8319708e-04
2.0333343e-03	2.3330942e-04
1.3857582e-03	-1.4099694e-04
9.4289895e-04	-2.9426412e-04
6.4072233e-04	-3.2618265e-04

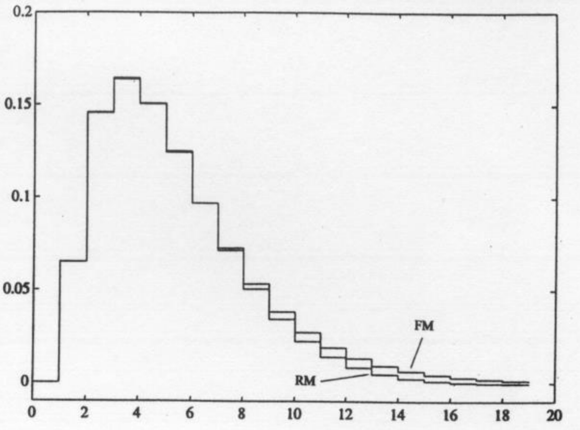


Fig.1. FM – the full order model (original system),
RM – the reduced order model.

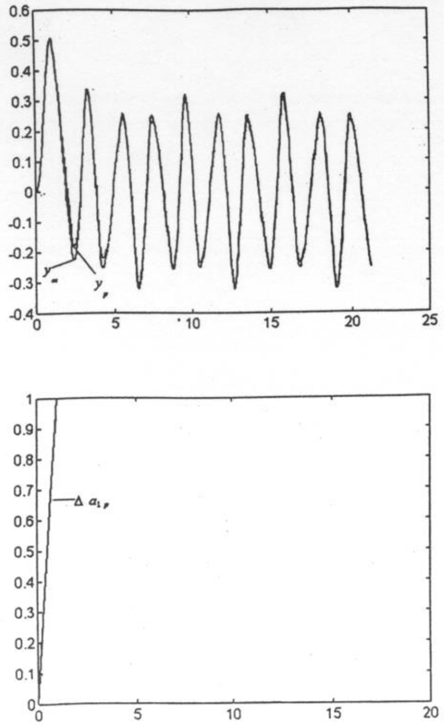


Fig. 2. Bias: $\Delta a_{1p} = 1$, $\Delta a_{2p} = 0$.
The adaptation is switched off.

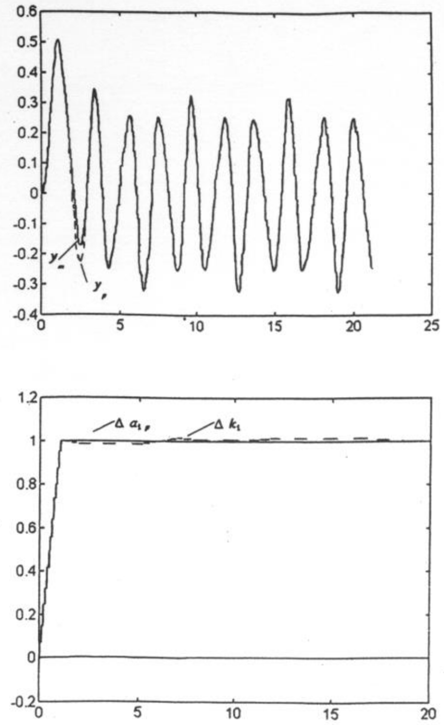


Fig. 3. Bias: $\Delta a_{1p} = 1$, $\Delta a_{2p} = 0$.
The adaptation is switched on.

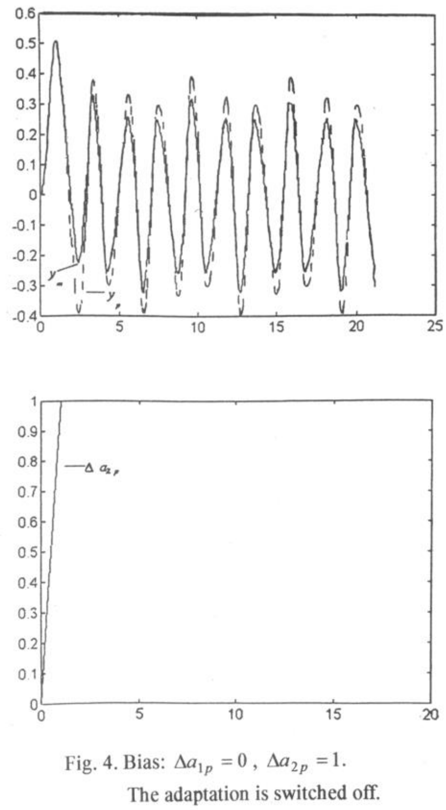


Fig. 4. Bias: $\Delta a_{1p} = 0$, $\Delta a_{2p} = 1$.
The adaptation is switched off.

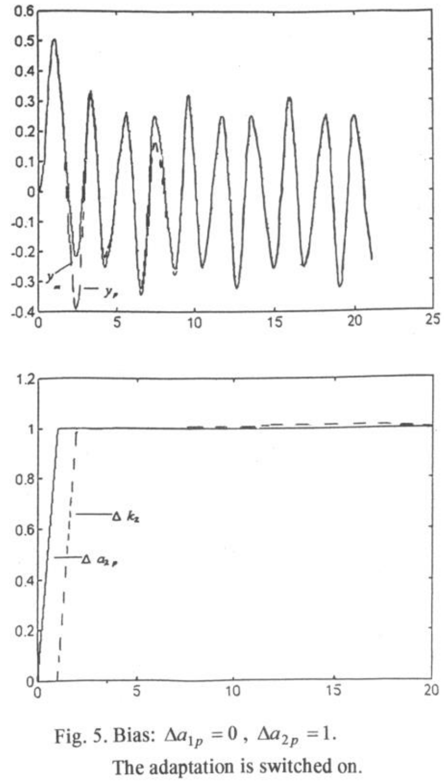


Fig. 5. Bias: $\Delta a_{1p} = 0$, $\Delta a_{2p} = 1$.
The adaptation is switched on.

4. Description of links between the outputs

- The outputs described in this thesis are linked in that they supplement each other. Industrial systems and processes include sensors which can be of a different nature. The method developed by the author for the sensor fusion allows the reliability of systems and processes to be improved in the case of the failure of some sensors.

- The decoupled control system allows the desirable performance of multivariable systems and processes to be obtained in the case when interconnections between channels exist via the dynamics of the system or process.

- The adaptive control system allows parameters' changes to be compensated, which can occur due to changes in environmental conditions.

- The method described in this thesis is based on simultaneous identification and adaptation. It allows the tracking of non-stationary parameters and provides the desirable behaviour of complex systems.

- The theoretical developments are supplemented by practical examples in this thesis.

5. The impact of the research: contribution to knowledge and practice

The impact of the author's work described in this thesis, is in several areas.

In civil aviation and in defence areas, the method described in Output – 5 of this thesis, allows the addition of a new capability to an aircraft to change its motion on the required axis of the motion without the interaction with axes of the flight motion (the decoupled motion of aircraft). This idea has been noticed and cited by other researchers who design control systems for the F-16 fighter aircraft (Fung, Wong, Hugh, Liu and Li 2008). The results, developed by the author for the sensor fusion, have been used by the USA Department of Defence (DoD) for projects related to the Space-Based Remote Sensing (Air Force Branch, Program SBIR 2017, Technology Area(s): Space Platforms, Topic Number AF171-069, 2017).

The applications of the algorithms developed by the author in the sensor fusion for the improvement of safety in cars on roads are given in the work of Ahmadi-Pour, Ludwig and Olaverri-Monreal (2017). According to the citation of the author's work in Guo, He, Lv, Yan and Lendasse (2018) and Abdulrahim, Weibley, Lee, Lind, Armanious and Suh (2018), the sensor fusion is a very promising direction for the development of Unmanned Air Vehicles (UAV). It is well known that GPS (Global Positioning System) does not provide reliable navigation information in some situations. For example, the GPS signal does not penetrate concrete buildings, or when a vehicle is located under a concrete bridge, or when a GPS signal is reflected from buildings or structures in a city. In order to obtain reliable position information, the inertial navigation system based on the sensor fusion can be used (Norton 2017).

The sensor fusion can be very useful for the tracking task for robot-manipulators (Kochetkov, Rassadin and Utkin 2017). According to Mergin and Premi (2017), the author's results can also be used in medical applications. The obstacle-avoidance for mobile robots is another field in which the results of the author's work can provide improved performance (Wu, Hong and Pan 2015). The friction estimation for the fault detection in an electromechanical system is described in Angeloni, Ermidoro, Previdi and Savaresi (2015). The data fusion technique is also used for the localisation of vehicles (Choi, Hur and Seo 2014). It is also interesting to note that the European Space Agency (ESA) is interested in applying new ideas for planetary exploration by a rover equipped with vision systems and sensors. The sensor fusion method developed by the author of this thesis can be applied on such systems (Zereik, Biggio, Merlo and Casalino 2011).

In many practical applications such as chemical engineering for example, the mathematical model of the process is not available. The method to obtain the mathematical model of a process from an experiment is described in the author's work (Vershinin 2014). Moreover, according to a journal publication by Bravo, Moscoso-Vásquez and Alvarez (2014), the model of a chemical process can be obtained from the experimental data based on the identification techniques given in Vershinin (2014).

6. Contribution of other people to the output and research

- The results described in the outputs have been developed by the author of this thesis. The research has been personally, internally and externally funded from a number of sources.

7. Conclusions and further research

- The author has presented the results of his work to two industrial companies: Samsung Heavy Industries Co. and Hyundai Motor Co. in South Korea during a visit to these companies. These visits were supported by the Engineering and Physical Sciences Research Council (EPSRC) titled: “Travel grant in control of multi-axis machinery/flexible manufacturing”. (Veshinin 2001c, 2001d). These results have been further extended. The author has demonstrated new results to Nissan Automotive (UK), the Jaguar Land Rover Company (JLR, UK), the ZF Company and other industrial organisations (Vershinin 2004a, 2005a, 2005c, 2006a, 2007a, 2007b, 2008b, 2013a, 2013b, 2013d, 2013k, 2014b, 2014e, 2015e, 2016). These results can be used in order to improve the reliability and performance of the motion of a conveyor with car components in multi-axis machinery/flexible manufacturing industrial processes, which are used in manufacturing companies.

- The author has presented his results to the Japanese Telecommunications Company NTT DoCoMo Hokkaido Inc. during a visit to this company (Vershinin 2001a). The developed algorithms for interconnected MIMO systems can be transferred to the automotive sector, in particular for Connected Cars, Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. The author demonstrated practical test results of the V2V and V2I communication on real cars and roads (Vershinin 2012d – 2012f, 2013f, 2014c – 2014d, 2014g, 2015a – 2015d, 2017b, 2018c). Also, the author presented the developed results in workshops which were specifically organised to build consortiums of organisations for applications for UK and European grants in the area of Intelligent Transportation (Vershinin 2012b, 2012c, 2014b, 2015c, 2017a). The research results presented in Outputs 1, 2, 3, 4 and 6 can be applied to the topics of the advertised grants for the reduction of fuel consumption and emissions in vehicles, Green Cities, adaptive cruise control and cooperation fleet management.

- The results related to Output – 3 are presented in Vershinin (2012a).

- The author was invited to write the recommendation for the UK Government, Academia and Industry (Intelligent Mobility Skills Strategy. Growing New Markets in Smarter Transport, 2016). The practical results, which were obtained for the monitoring of parameters from automotive sensors related to Output - 2, were presented in the annual report of the Intelligent Transport Systems Group (ITS UK) in Vershinin (2015b).

- The author together with colleagues from the Mathematics Applied Research Group initiated the preparation of a project proposal for a grant to the European Union Program FP-7 Marie Curie Action. The project proposal was successful and the consortium received the grant for the duration of 4 years, Project ID: No. 612707; Dynamics of and in Complex Systems (DIONICOS) EU FP-7 Project, 2014. There are 19 partner organisations from 12 countries in this Consortium led by Coventry University. The author conducted the presentation related to Output-2 in the partner organisation: the Institute of Control Sciences of the Russian Academy of Sciences, ICS RAS (Vershinin 2017b).

- The results of Output – 2 can also be applied to other areas. For example, the information fusion based on the algorithm developed in Output – 2 can be used for CCD cameras in order to obtain better quality images (Vershinin 2013e).

- In order to improve the reliability of electromechanical systems, the sensor fusion technique developed in Output – 2 can be applied (Stahl et al. 2014).

- It is a widely used practice in the automotive industry to use the Controller Area Network (CAN – bus) in order to transmit information from multiple sensors on a car. Thus, further work will be required in order to implement the sensor fusion algorithms developed in Output-2 on cars. The simulation of signal transmission using the Controller Area Network is given in Nnadiekwe, Vershinin and Schulz (2015).

- The results developed in Outputs 1, 2, 3 and 4 can be used for further developments in areas related to Intelligent Transport Systems. In particular, for enhancing the performance of adaptive cruise control, the independent control of actuators on the active suspension system on a car, to improve the safety of driving by employing multiple sensors to access the traffic situation around a car. The information fusion from different types of sensors can also improve the safety of autonomous vehicles (Nkoro and Vershinin 2014). Other areas of possible applications are given in Branishtov et al. (2014, 2015); Gaiduk et al. (2002a, 2002b, 2003a – 2003c); Kataev et al. (2017); Loukianov et al. (2002); Vershinin et al. (1999); Vershinin et al. (2001a, 2001b, 2001e 2001h); Vershinin (2001c, 2001d, 2001f, 2001g, 2001i); Vershinin (2002b, 2002c); Vershinin et al. (2002); Vershinin (2004a); Vershinin (2005b, 2005d); Vershinin (2006b); Vershinin et al. (2006); Vershinin (2007a – 2007d); Vershinin et al. (2008); Vershinin (2008a, 2008d – 2008g, 2009a – 2009c, 2010a – 2010b, 2011a – 2011g, 2012a - 2012e, 2013c, 2013f – 2013i, 2014c, 2014d, 2014f, 2014h - 2014l, 2017a, 2017b, 2018a, 2018d, 2018h).

- The High Dynamic Precision Adaptive Control System (HDPAC) for the separation of an aircraft motion on a roll and sideslip, presented in Output - 5, can provide new functionalities to aircraft. In particular, it will allow a commercial aircraft to avoid a collision with another aircraft during a flight in a more efficient way compared with traditional flight methods, without any additional modifications of the aircraft. Moreover, the above method can allow an aircraft to escape from a direct hit by a moving object in the air. At the same time, an aircraft which possess a system based on the method described in this thesis has much better advantages in the air. It can also hit a flying target faster and more accurately compared with aircraft which are in service at the present time. These ideas can constitute many new research and development projects, which can be used in order to start new PhD projects and can be offered to civil aircraft and/or defence industries.

The objectives of this thesis have been achieved. The developed methods and algorithms can also be applied to a variety of industrial applications including:

- Multi-machine power and speed control of an electric power station employing several engines working on a common electric generator (which can be considered as a load);
- Control of power and speed in a railway locomotive or a ship from several diesel (electric) engines connected to one common load;
- Speed control of an industrial conveyer with a variable load employing multiple electric motors.

The decentralised control allows building the overall system with the following advantages:

- Reliability of the overall system (fault tolerance);
- Scalability: open to reconfiguration (new subsystems can be easily connected to the existed system if additional driven force is required);
- Independent control of each subsystem by its own processor unit allows the use of less power and cheaper local processers compared with a central equivalent processor.

Future work can be concentrated on the development of adaptive control algorithms for non-linear systems. For example, a real aircraft possesses non-linear dynamics. The employment of an adaptive control system can improve the flight performance of an aircraft and reduce the fuel consumption.

Another area of future work can be related to the investigation of the robustness of systems and processes. It is a well-known fact that in practice, systems with adaptive control algorithms may not perform well when the systems' parameters change considerably from their nominal (calculated) values. Such systems may become unstable. Complex and multivariable systems and processes can be especially prone to this problem. Therefore, the detailed analysis of the behaviour of such systems and processes on their robustness in different working conditions should be performed. Control algorithms should be designed in order to provide robustness to systems and processes.

Many control systems, which are widely used today in domestic and industrial applications, are designed in order to compensate parameters which are not changed very quickly. For example, there are systems to control the temperature in the cabin of a car for climate control or to control a water heating boiler in a building. However, different types of control algorithms are required for such plants as aircraft. Aircraft function in more heavy conditions, i.e. the parameters of an aircraft change very fast due to changes in altitude and speed. Organisations working on the solutions of such tasks however do not necessarily publish their results in the public domain. Thus, although, researchers have achieved very advanced results in their areas, these results are often not available to the public. However, the application of such algorithms for civil aircraft could reduce fuel consumption and make a considerable contribution to improving the environment.

The algorithms described in this thesis for the separation of aircraft motion on a roll and sideslip can improve safety in flight.

The sensor fusion algorithm developed by the author allows improvement in the reliability of the information when the data are fused from multiple sensors, which can be of a different nature. Sensor fusion is considered as a very important instrument in some specific areas such as military applications. For example, the competition for the grant based on publications related to sensor fusion and the author's publication in particular, has been advertised by the USA Department of Defence DoD 2017.1, Air Force Branch, Program SBIR 2017, Technology Area(s): Space Platform, Topic Number AF171-069.

It should be pointed out that recently, sensor fusion techniques have become very popular in areas related to Intelligent Transport Systems. In particular, autonomous vehicles are equipped by different types of sensors, i.e. automotive RADARs, laser scanners (LIDARs), ultrasonic sensors and video cameras. The data fusion algorithms are used in order to obtain complete and reliable information from these sensors for the navigation of autonomous vehicles. Practical implementations of such systems on autonomous vehicles can be seen on DARPA Urban Challenge completions (Defence Advanced Research Projects Agency).

The sensor fusion techniques developed by the author of this thesis can also be used for the further development of smart sensors. Such smart sensors can in turn be used for homes, buildings and infrastructure in projects related to Smart Cities (Vershinin and Fedyanin 2018). Sensor fusion can improve the reliability of the information from sensors in many engineering areas (Balasubramanian et al. 2015; Cuscov et al. 2011; Dipayan et al. 2014; Nagaraja et al. 2014, 2017; Pande at al. 2013, 2014; Mohan et al. 2015; Rinki et al. 2014, 2015a – 2015c; Timin at al. 2019; Vershinin and West 2001; Vershinin 2002a, 2002b, 2013e, 2017c, 2018e – 2018g).

The above examples demonstrate the increased interest of researchers and practitioners in areas which are described in this thesis.

It has been mentioned before that the work of this thesis has been devoted to the improvement of very specific systems and processes. For example, systems and processes where parameters change very fast or dramatically or where reliability is the main concern. These include aerospace systems, chemical or nuclear industrial batch reactors and related systems and processes. Although these areas are extremely important for society, they are of interest to a restricted range of specialists who are directly working on solutions for these tasks. The author of this thesis is planning to work further on technology transferring, i.e. from aerospace to automotive applications. This, in turn, will widen the auditory of specialists, researchers and practitioners who will use the obtained results for other applications.

References

Adamjan, V.M., Arov, D.Z. and Krein, M.G. (1971) 'Analytic properties of Schmidt pairs for a Hankel operator and the generalised Schur-Takaqi problem'. *Math.USSR Sbornik* 15, 31-73

Astrom, K.J. and Wittenmark, B. (1995) *Adaptive Control*. Mineola, N.Y.: Dover Publications

Balasubramanian, K.B.,Karthikeyan, R., Kadambi, G. and Vershinin, Y. (2015) 'A Formulation of One-Dimensional Search Technique for 2D DOA Estimation Using Orthogonally Polarized Components of Linear Array'. *IEEE Antennas and Wireless Propagation Letters* 14 (1-1), 1117 – 1120. DOI: 10.1109/LAWP.2015.2395072

Branishtov, S. A., Vershinin, Y. A., Tumchenok, D. A. and Shirvanyan, A. M. (2015) 'Automated traffic control system in railways'. *Proceedings of the IEEE 2015 International Conference on Mechanical Engineering, Automation and Control Systems (MEACS)*. held 1-4 December 2015 at Tomsk, Russia. Piscataway, NJ.: IEEE

Branishtov, S.A., Vershinin, Y.A., Tumchenok, D.A. and Shirvanyan, A.M. (2014) 'Graph methods for estimation of railway capacity'. *The IEEE 17th International Conference on Intelligent Transportation Systems (ITSC-2014)*. held 8-11 October 2014 at Qingdao, China. Piscataway, N.J.: IEEE, 525 - 530. DOI: 10.1109/ITSC.2014.6957743

Carlson, N. A. (1990) ‘Federated square root filter for decentralized parallel processes.’ *IEEE Transactions on Aerospace and Electronic Systems* AES-26 (3), 517-525

Chang, C.-F., Fekete, N.P. and Powell, J.D. (1993) *Engine Air-Fuel Ratio Control using an Event-based Observer*. SAE Paper No. 930766.

Chong, C. Y., Mori, S. and Chang, K. C. (1990) ‘Distributed multitaget multisensor tracking’. in *Multi-Target Multi-Sensor Tracking*. ed. by Bar-Shalom, Y. Norwood, MA: Artec House

Cuscov. I., Krishnamoorthy, S. and Vershinin, Y.A. (2011) ‘Energy Storage and Powertrain Systems for Electric Vehicle’. *Proceedings of The 14th IEEE Intelligent Transport Systems Conference ITSC-2011*. held 5-7 October 2011 at University of Washington D.C, USA. Piscataway, N.J: IEEE, 698-703

Egardt, B. (2014) *Stability of Adaptive Controllers*. New York: Springer

European Union FP-7 Marie Curie Action, Project ID: No 612707 (2014) *Dynamics of and in Complex System (DIONICOS) EU FP-7 Project (2014).* Call identifier FP7_PEOPLE-2013-International Research Staff Exchange Scheme (Coventry University is the Leading Organisation for the consortium with 19 partner organisations from 12 countries; Yuri Vershinin is the contributor to this project).

Fedyanin, D. and Vershinin, Y. (2018) 'On Distributed Reflexive Complex Mechanisms of Decision-making in a Transportation System of a Smart City'. *International Journal of Engineering and Technology (IJIT)* 7 (2.28), 164 – 167

Gaiduk, A.R., Vershinin, Y.A. and Jawaid, A. (2003a) 'Algorithm for Computer Aided Optimal Control System Design'. *SME Society of Manufacturing Engineers* 1-5

Gaiduk, A.R., Vershinin, Y.A. and Jawaid, A. (2003b) 'Synthesis of Large Scale Liner Distributed Systems'. *Proceedings of the IEEE International Symposium on Intelligent Control (ISIC-2003)*. held October 5-8 2003 at Westin Galleria Huston, Texas, U.S.A.

Gaiduk, A.R., Vershinin, Y.A. and Jawaid, A. (2003c) 'A method of Synthesis of a Multivariable System with Decoupled and Interconnected Channels'. *Proceedings of the IEEE International Symposium on Intelligent Control (ISIC-2003)*. held October 5-8 2003 at Westin Galleria Huston, Texas, U.S.A.

Gaiduk, A.R., Vershinin, Y.A. and West, M.J. (2002a) 'Neural Networks and Optimization Problems'. *Proceedings of the 2002 IEEE International Conference on Control Applications*. held September 2002 at Glasgow, Scotland, U.K, 37-44

Gaiduk, A.R., Vershinin, Y.A. and Jawaid, A. (2002b) 'Algorithm for Computer Aided Optimal Control System Design'. *Proceedings of the 2002 IEEE International*

Conference on Control Applications. held September 2002 at Glasgow, Scotland, U.K, 187-192

Gantmacher, F.R. (1961) *The Theory of Matrices*. trans. by Hirsch, K.A. vols 1&2, New York: Chelsea

Golub, G.H. and Van Loan, C.F. (1996) *Matrix Computation.* 3rd edn. Baltimore and London: The Johns Hopkins University Press

Guskov, Y.P. and Zagainov, G.I. (1980) *Aircraft Flight Control*. Moscow: Mashinostroenie

Hasegawa, Y, Akazaki, S, Komoriya, I., Maki H. and Hirota, T. (1994) *Individual Cylinder Air-Fuel Ratio Feedback Control using and Observer*. SAE Paper No. 940376.

Hashemipour, H.R., Roy, S. and Laub, A.J. (1988) 'Decentralized structures for parallel Kalman filtering'. *IEEE Transactions on Automatic Control* AC-33, 88-94

Ho, B.L. and Kalman, R.E. (1966) 'Effective construction of linear state-variable models from input/output functions'. *Proceedings of the Third Allerton Conference*. held 1966 at Illinois, 449-459

Holding, D.J., Garvey, S.D., Giacomini, I. and Vershinin, Y. (1999) 'An Adaptive / Variable Structure Control Algorithm Applied to an Inverted Pendulum-like

Problem'. *Proceedings of the International Conference on Control Sciences, Institute of Control Sciences of Russian Academy of Sciences*. held 29 June – 2 July 1999 at Moscow, 92 – 94

Kalman, R.E., Falb, P.L. and Arbib, M.A. (1974) *Topics in Mathematical System Theory*. New York: McGraw Hill

Kang, Jun-Mo and Grizzle, J.W. (1998) 'Engine A/F and Torque Control by using Secondary Throttles'. *IFAC Advances in Automotive Control*, 201-208

Kataev, D., Kutyakov, E., Evgeniy, Y. and Vershinin, Y.A. (2017) 'The sub-Gramian method as a tool for the automotive suspension tuning'. *Proceedings of the IEEE 11^th^ International Conference on Management of Large Scale Systems Development MLSD 2018, ICS*. held 1 – 3 October 2018 at Moscow, Russian Federation.

Kerr, T. H. (1996) 'Extending decentralized Kalman filtering results for novel real-time multisensor image fusion and/or restoration'. *SPIE* 2755, 548-564

Kochetkov, S.A., Utkin, V.A. and Vershinin, Y.A. (2017) 'Tracking Problem for Induction Electric Drive under Influence of Unknown Perturbation'. *The 20th IFAC World Congress, (IFAC WC 2017)*. held July 2017 at Toulouse, France. IFAC PapersOnLine 50-1 (2017) 9790-9795, Oxford: Elsevier Ltd

Kokotovic, P.V. (1991) *Foundation of Adaptive Control*. Heidelberg: Springer-Verlag

Landau I.D. (1979) *Adaptive Control*. New York: Marcel Dekker, Inc.

Levy, B.C., Castanon, D.A., Verghese, G.C. and Willsky, A.S. (1983) 'A scattering framework for decentralized estimation problem'. *Automatica* 19 (4), 373-384

Ljung, L. (1999) *System Identification Theory for the User*. 2nd edn. New York: Prentice Hall

Loukianov, A., Canedo, J.M., Astorga, G.J.R. and Vershinin, Y.A. (2002) 'Observer-Based Sliding Mode Block Control of DC Motors with Controlled Excitation.' *Proceedings of the IEEE Transmission and Distribution Conference*. held 2002 at Sao Paulo, Brazil.

Mayne, D.Q. (1966) 'A solution of the smoothing problem for linear dynamic systems'. *Automatica* 4 (2), 73-92

Mazumdar, D., Kadambi, G.R., Vershinin, Y.A. and Rashid, I. (2014) 'On Hartley Image Rejection Receivers and Adaptive Sinusoidal'. *Proceedings of the IEEE 17th International Conference on Intelligent Transportation Systems (ITSC-2014).* held 8-11October 2014 at Qingdao, China, 508 - 513, DOI: 10.1109/ITSC.2014.6957740

Moore, B.C. (1978) 'Singular value analysis of linear systems Part 1 and Part 2'. *Dept. Elec. Eng., University of Toronto, Toronto, Ont*. Systems Control Report 7801 and 7802.

Moor, B.C. (1981) ‘Principal component analysis in linear systems: Controllability, observability and model reduction’. *IEEE Transactions on Automatic Control* 26, 17–32

Moulin, P, Corde, G., Castagne, M. and Rousseau, G. (2004) *Cylinder Individual AFR Estimation based on a Physical Model and using Kalman Filters*. SAE Paper No.2004-01-0422.

Nagaraja, N., Kadambi, G., Palade, V. and Vershinin, Y. (2017) ‘3D spectrum hole detector using support vector machine to enable D2D overlay on the heterogeneous CR network’. *The IEEE International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS 2017)*. held 2017 at Japan.

Nagaraja, N. Kadambi, G. Vershinin, Y. (2014) ‘Co-operative Spectrum sensing using CR node binary decision regression on estimated wireless path-loss curves’. *Procedings of the IEEE International Conference on Electronics and Communication Systems IEEE ICECS-2014*. held 13-14 February 2014 at India, 1-4, DOI: 10.1109/ECS.2014.6892567

Nise, N.S. (2015) *Control Systems Engineering*. Hoboken, NJ.: Wiley

Nkoro, A.B. and Vershinin, Y.A. (2014) ‘Current and Future Trends in Applications of Intelligent Transport Systems on Cars and Intelligent Infrastructure’. *Proceedings of the IEEE 17th International Conference on Intelligent Transportation Systems*

(ITSC-2014). held 8-11October 2014 at Qingdao, China, 514 - 519, DOI:10.1109/ITSC.2014.6957741

Nnadiekwe, B.E., Vershinin, Y.A., and Schulz, S. (2015) ‘Simulation of Signal Transmission in Motion Simulator using Controller Area Network (CAN-bus)’. *Proceedings of the IEEE 18th International Conference on Intelligent Transportation Systems, ITSC-2015*. held 15-18 September 2015 at Spain.

Pande, S., Pande, V., Kadambi, G. and Vershinin, Y. (2014) ‘A Layer 2 Wired-Wireless Interworking Model to Achieve Throughput Improvement’. *The 6th International Conference on New Technologies, Mobility and Security (NTMS 2014)*. held 30 March – 2 April 2014 at Dubai, United Arab Emirates, 1-4. DOI: 10.1109/NTMS.2014.6813997

Pande, S., Tambakad, V., Kadambi, G. and Vershinin, Y. (2013) ‘An Analytic Model for Route Optimization in Load Shared Wireless Mesh Network’. *European Modelling Symposium (EMS-2013).* held 22 November 2013 at Manchester, UK, 543-548. DOI: 10.1109/EMS.2013.90.

Petrov, B.N., Rutkovsky, V.Y. and Zemlyakov, S.D. (1980) *Adaptive coordinate-parametric control of non-stationary plants*. Moscow: Nauka

Rao, B.S. and Durrant-Whyte, H.F. (1991) ‘Fully decentralized algorithm for multisensor Kalman filtering’. *IEE Proceedings* 138 (5)

Mohan, R., Malathi, S., Kadambi, G.R. and Vershinin, Y. (2015) ‘Design and Analysis of an Integrated Opto-Electronic Oscillator Based Biosensor’. *ICOP 2015*’. held 20-22 February 2015 at the University of Calcutta, India.

Sastry, S. and Bodson, M. (2011) *Adaptive Control: Stability, Convergence, and Robustness*. New York: Dover Publications

Scherer M., Hart M. and Loffeld, O. (1998) ‘Kalman Filtering, an Effective Method for Different Applications in A/F Ratio Control’. *IFAC Advances in Automotive Control*. New York: Pergamon, 201-208

Schweppe, F.C. (1973) *Uncertain Dynamic Systems*., Englewood Cliffs, NJ.: Prentice-Hall.

Sharma, R., Kadambi, G., Vershinin, Y.A. and Mukundan K.N. (2015a) ‘Deafness Avoidance in MANETs through Exchange of Link ID Broadcasts’. *The IEEE Proceedings on Fifth International Conference on Communication Systems and Network Technologies (CSNT)*. held April 2015 at Gwalior, India, 159-163. DOI: 10.1109/CSNT.2015.106.

Sharma, R., Kadambi, G., Vershinin, Y.A. and Mukundan, K.N. (2015b) ‘Dual Polarised Directional Communication Based Medium Access Control Protocol for Performance Enhancement of MANETs’. *The IEEE Proceedings of the Fifth International Conference on Communication Systems and Network Technologies (CSNT)*. held April, 2015 at Gwalior, India, 185-189. DOI: 10.1109/CSNT.2015.104

Sharma, R., Kadambi, G., Vershinin, Y.A. and Mukundan K.N. (2015c) ‘Multipath Routing Protocol to Support Dual Polarised Directional Communication for Performance Enhancement of MANETs’. *The IEEE Proceedings of the Fifth International Conference on Communication Systems and Network Technologies (CSNT)*. held April, 2015 at Gwalior, India,258-262.

Sharma, R., Kadambi, G., Vershinin. Y. A. and Mukundan K.N. (2014) ‘A Survay of MAC Layer Protocols to Avoid Deafness in Wireless Networks Using Directional Antenna’. in *Handbook of Research on Progressive Trends in Wireless Communications and Networking.* ed.by M.A. Matin Hershey, PA: IGI Global Publications, 479 - 517

Shulman, M.A. and Hamburg, D.R. (1993) *Non-ideal properties of Z_rO_2 and T_iO_2 exhaust gas oxygen sensors*. SAE Paper No. 800018.

Sinha, P.K. (1984) *Multivariable Control: An Introduction*. New York: Marcel Dekker

Speyer, J.L. (1979) ‘Computation and transmission requirements for a decentralized liner-quadratic Gaussian control problem’. *IEEE Transactions on Automatic Control*AC-24, 266-269

Stahl, K., Abdulsamad, G., Vershinin, Y.A. and Leimbach K.-D. (2014) ‘State of the Art and Simulation of Motion Cueing Algorithms for a Six Degree of Freedom

Driving Simulator'. *The IEEE 17th International Conference on Intelligent Transportation Systems (ITSC-2014).* held 8-11 October 2014 at Qingdao, China, 537 - 541. DOI: 10.1109/ITSC.2014.6957745.

Timin, V.H., Kustov, A.Y., Kurdukov, A.P. and Vershinin, Y.A. (2019) 'Optimal anisotropic filtering for linear digital non-stationary systems with non-centered external disturbances'. *Automation and Remote Control.* New York: Springer

Turing, R.C. and Geering, H.P. (1994) *Model-Based Adaptive Fuel Control in an SI Engine*. SAE Paper No. 940374.

Vershinin, Y.A. (2018a) 'Simulation of Electric Vehicle Charging'. *Electric Vehicle Charging Infrastructure Conference, Innovate UK and the Office for Low Emission Vehicles, Congress Centre*. held 10th July 2018 at London.

Vershinin, Y.A. (2018b) 'High Dynamic Precision Control System'. *International Journal of Electrical and Electronic Engineering Research (IJEEER)* 8 (2) 13-18

Vershinin, Y.A. (2018c) 'V2X communication'. *Connected and Autonomous Vehicles Research and Development Conference; Innovate UK, Knowledge Transfer Network, Centre for Connected and Autonomous Vehicles*. held 26th of June 2018 at Cavendish Conference Centre, London.

Vershinin, Y.A. (2018d) 'Decentralized Control of a Multivariable System'. *International Journal of Industrial Electronics and Electrical Engineering, (IJIEEE)* 6 (7), 66-68

Vershinin, Y.A. (2018e) 'A Sensor Fusion Method'. *The Proceedings of the International Conference on Control, Automation, Robotics and Vision Engineering, IASTEM*. held 19-20 May 2018 at Oxford, UK.

Vershinin, Y.A. (2018f) 'On-Line Reconfiguration of a Control System based on Information Fusion'. *The Proceedings of the International Conference on Control, Automation, Robotics and Vision Engineering*, *IASTEM*. held 19-20 May 2018 at Oxford, UK.

Vershinin, Y.A. (2018g) 'A Sensor Fusion Method.' *International Journal of Electrical, Electronics and Data Communication (IJEEDC).* Institute of Research and Journals (IRAJ) 6 (7), 7 – 9

Vershinin, Y.A. (2018h) 'Decentralized Control of a Multivariable System.' *The Proceedings of the International Conference on Control, Automation, Robotics and Vision Engineering, IASTEM*. held 19-20 May 2018 at Oxford, UK.

Vershinin, Y. and Fedyanin, D. (2018) 'On Distributed Reflexive Complex Mechanisms of Decision-Making in a Transportation System of a Smart City'. *International Conference on Communication, Management and Information Technology (ICCMIT 2018)*. held 2-4 April 2018, Madrid, Spain.

Vershinin, Y.A. (2017a) ‘Road Traffic Flow Modeling and Signal Optimisation for Fuel Economy and Emissions Reduction based on Experimental Data’. *Workshop on Autonomous Systems, ICS RAS*. held 18 December 2017 at Moscow.

Vershinin, Y. (2017b) ‘Modelling and simulation of road transport networks in Coventry City’. *European Union Project Conference: Holistic Personal public Eco-mobility (HoPE)*. held 9 May 2017 at Brussels, Belgium.

Vershinin, Y. (2017c) *Decentralized Kalman Filter*. [presentation] August 2017 at the Institute of Control Sciences of the Russian Academy of Sciences (ICS RAS), Moscow.

Vershinin, Y. (2016) *Design and testing of a Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication system based on the spread-spectrum modulation technique*. [presentation] November 2016 at the ZF-TRW-Conekt Company, Solihull, UK.

Vershinin, Y.A. (2015a) ‘Automotive Telemetry System for V2V and V2I Communication’. *Connected Vehicles Interest Group Conference, ITS United Kingdom, Transport Systems Catapult*. held 16 July 2015 at Milton Keynes, UK.

Vershinin, Y.A. (2015b) ‘Automotive telemetry system designed at Coventry University.’ *Intelligent Transport Systems Annual Review ITS UK*, 34 - 35.

Vershinin, Y.A. (2015c) ‘Design of Automotive Telemetry Systems for Autonomous Vehicle and Vehicle to Infrastructure Communication’. *The European Technology Platform on Smart Systems Integration (EPoSS) / KTN Workshop on IoT Large Scale Pilots, HORIZON 2020 Work Programme*. held 26th June 2015 at London, UK.

Vershinin, Y. (2015d) ‘Modelling and simulation of the traffic flow in complex transport networks in the case of emergency situations’. ‘*The EPSRC Workshop “CHANGE 2015: Modelling Changes in Socio-Economic Systems*. held 14 July 2015 at London.

Vershinin, Y. (2015e) *Automotive telemetry system*. [presentation] January 2015 at Rolls Royce Automotive, Chichester, UK.

Vershinin, Y.A. (2014a) ‘Adaptive Control System for Solution of Fault Tolerance Problem’. in *Lecture Notes in Electrical Engineering 247, IAENG Transactions on Engineering Technologies*. ed. by Haeng Kon Kim, Sio-long Ao, Mahyar A. Amouzegar and Burghard B. Rieger. New York: Springer, 197-208

Vershinin, Y. (2014b) *Automotive Controller Area Network and vehicle security*. [presentation] December 2014 at SBD Automotive, Milton Keynes, UK,.

Vershinin, Y. (2014c) ‘Modelling and simulation of road transport networks’. *Networking Transportation Networkers (NTN) Conference*. held 9-10 September 2014 at Coventry University, UK.

Vershinin, Y.A. (2014d) ‘Autonomous Vehicle’. *Driverless Cars Challenge Conference*, *Technology Strategy Board (TSB)*. held 30 July 2014 at London.

Vershinin, Y. (2014e) *A Hardwire-in-the-Loop system for a test rig with an automotive ECU*. [presentation] February, 2014 at the Jaguar and Land Rover Company (JLR), Castle Bromwich, West Midlands, UK.

Vershinin, Y.A. (2014f) ‘The automotive telemetry system’. *THE ISSUE-2014 (Traffic Health Environment Intelligent Solutions for Sustaining Urban Economies) Conference: Sustainable Transport Technologies - Collaboration for Innovation, EU FP-7*. held 11 February 2014 at Loughborough, UK,.

Vershinin, Y.A. (2014g) ‘A wireless telemetry system and its application for monitoring of parameters of transport’. *THE ISSUE-2014 (Traffic Health Environment Intelligent Solutions for Sustaining Urban Economies) Conference: Sustainable Transport Technologies - Collaboration for Innovation*. held 12 February 2014 at Loughborough UK.

Vershinin, Y.A. (2014h) ‘Keynote Speech on Optimization of Road Traffic Networks.’ *The World Congress on Engineering and Computer Science 2014 (WCECS-2014)*. held 22-24 October 2014 at The University of California, Berkeley, San Francisco, USA.

Vershinin, Y. (2014i) *Application of Artificial Intelligent (AI) Fuzzy-Logic algorithms for the automotive suspension system design*, [invited talk in the office of Professor

Lotfi A. Zadeh] held 24 October 2014 at the University of California at Berkeley, San Francisco, USA.

Vershinin, Y.A. (2014j) ‘Automotive telemetry system’. *The NATO Workshop on Advanced Autonomous Vehicles*. held 18 July 2014 at Coventry University.

Vershinin, Y. (2014k) ‘Automotive Active Suspension System’. *Research Excellence Framework 2020*. held 14 May 2014 at Coventry University.

Vershinin, Y. (2014l) ‘Road traffic flow modelling and signal optimization for fuel economy and emissions reduction in Coventry City based on experimental data’. *The MECO 39 Conference*. held 8-10 April 2014 at Coventry University.

Vershinin, Y. (2013a) *An automotive networking system based on the CAN-Open communication protocol: the design, testing and implementation on police cars*. ‘The consultancy project for General Motors Co. UK’ (Yuri Vershinin is the Principle Investigator).

Vershinin, Y.A. (2013b) ‘Application of Controller Area Network for Car's Parameters Monitoring’. *14th international CAN Conference (iCC-2013)*. held 12-13 November, 2013 at Paris, France.

Vershinin, Y. (2013c) ‘Modelling and simulation electric cars and optimal allocation of electric charging stations’. *Workshop of Networking Transportation Networkers*.

held 26 September 2013 at Coventry University, Applied Mathematics Research Centre, Techno-Centre.

Vershinin, Y.A. (2013d) ‘Automotive telemetry systems based on Controller Area Network.’ *The First international Mobile-Machine Conference (MMC-2013)*. held 12-13 June 2013 at Nurnberg, Germany.

Vershinin, Y.A. (2013e) ‘Digital Non-Contact Surface Reconstruction Scanner’. in S.I. Ao, Oscar Castillo, Craig Douglas, David Dagan Feng and Jeong-A Lee (eds.) *Proceedings of the International Multi-Conference of Engineers and Computer Scientists* ‘Lecture Notes in Engineering and Computer Science’. held 13-15 March 2013 at Hong Kong 2202 (1), 478-483

Vershinin, Y.A. (2013f) ‘Keynote Speech on Automotive parameters monitoring based on a telematics system’. *International Multi-Conference of Engineers and Computer Scientists 2013, IMECS 2013, the International Conference of Electrical Engineering (ICEE 2013)*. held 13-15 March 2013 at Hong Kong.

Vershinin, Y.A. (2013g) ‘Solving transport problems on screen’. *Highways Magazine* April 2013, 23-24

Vershinin, Y.A. (2013h) ‘Passive and Active Suspension Systems for Automotive Applications’. *The 5th International Conference on Modelling, Identification and*

Control (ICMIC-2013). held 31 August - 1 September 2013 at Cairo University, Egypt.

Vershinin Y.A. (2013i) ‘Application of Automotive Telemetry Systems’. *Event for Collaboration with Business Organizations “INTRIGUE – 2013*”. held 20 March 2013 at Coventry University.

Vershinin, Y. (2013j) ‘Adaptive Control System for Solution of Fault Tolerance Problem for MIMO Systems’. in S. I. Ao, Oscar Castillo, Craig Douglas, David Dagan Feng and Jeong-A Lee (eds.) *Proceedings of the International Multi-Conference of Engineers and Computer Scientists 2013 (IMECS 2013)* ‘Lecture Notes in Engineering and Computer Science’. held 13-15 March 2013 at Hong Kong 2202 (1), 117–120

Vershinin, Y. (2013k) *Controller Area Network and CAN-Open system design, test and implementation on police cars*. [presentation] March 2013 at the Millbrook Techno-Centre, UK.

Vershinin, Y. A. (2012a) ‘Application of Self-tuning Control System for Solution of Fault Tolerance Problem’ in S.I. Ao, Craig Douglas, W. S. Grundfest and Jon Burgstone (eds.) *Proceedings of the World Congress on Engineering and Computer Science 2012 (WCECS-2012), International Conference on Modeling, Simulation and Control 2012* ‘Lecture Notes in Engineering and Computer Science’. held 24-26 October 2012 at San Francisco, USA 2201 (1), 1206-1210 , , , Vershinin, Y.A. (2012b) ‘Optimization of Road Transport Networks.’ *European Union Frame Work Program - 7 Conference*. held 18-19 July, 2012 at Brussels, Belgium.

Vershinin, Y.A. (2012c) ‘Performance Enhancement of Suspension System of Railway Carriage’. *RailBE Conference for the EU FP-7 Programme*. held 26-27 June 2012 at Warsaw, Poland.

Vershinin, Y.A. (2012d), ‘Intelligent Transport Systems and their Applications for the Optimization of Traffic Flow, Fuel Economy and Emissions Reductions’. [invited speech] *International Conference of Mechanical Engineers (ICME), World Congress of Engineers, WCE-2012*. held 4-6 July 2012 at Imperial College, London.

Vershinin, Y.A. (2012e) ‘Sensor fusion for the improvement of reliability of an automotive navigation system’. *Self-Driving Vehicles Conference, the ICT KTN, GRACE and RIN*. held 1 March 2012 at the University of Nottingham, Sir Colin Campbell Building, Jubilee Campus.

.

Vershinin, Y.A. (2011a) ‘Traffic Safety’. *Intelligent Mobility – Making it a Commercial Reality Conference*. held 11 November 2011 at the National Space Centre, Leicester, UK.

Vershinin, Y.A. (2011b) ‘Automotive Telematics.’ *Driving Innovation Conference, UK*. held 15 September 2011.

Vershinin, Y.A. (2011c) ‘Emergency Evacuation from Car Parking Areas’. *The 9th User Group Conference on Advanced Interactive Modelling and Simulation of Urban Networks*. held 12-13 September 2011 at Chateau d'Ermenonville, France.

.

Vershinin, Y.A. (2011d) ‘Remote automotive parameters monitoring’. *The TRL Academy Symposium (Transport Research Laboratory)*. held 14th of July 2011 at London, UK.

Vershinin, Y.A. (2011e) ‘Optimization of Road Traffic Network’. *Workshop in the Institute of Control Sciences of the Russian Academy of Sciences*. held June 2011 at the Russian Academy of Sciences.

Vershinin, Y.A. (2011f) ‘Automotive active suspension system’. *Parliamentary Launch “Research That Matters”, UK Government*. held 17 May 2011 at the House of Commons, London, UK.

Vershinin, Y. (2011g) ‘Automotive Wireless Telemetry’. *Automotive Show, National Exhibition Centre (NEC)*. held February 2011 at N.E.C Birmingham, UK.

Vershinin, Y.A. (2010a) ‘Intelligent Transport Systems’. *The 8th Users Group Conference, Transport Simulation Systems (TSS) Company*. held October 2010 at Barcelona, Spain.

Vershinin Y. (2010b) ‘Driver performance monitoring in different driving and environmental conditions’. *Driving Simulation Conference, Oktal Company*. held September 2010 at Paris, France.

Vershinin, Y. (2009a) ‘Monitoring of vehicle performance using automotive sensors’. *Autolink-2009 Show*. held 28 April 2009 at Banks’s Stadium Walsall.

Vershinin, Y. (2009b) ‘Automotive parameters monitoring system’. *Automotive Simulation Conference, Transport Simulation Systems (TSS) Company*. held 2009 at Barcelona, Spain.

Vershinin, Y. (2009c) ‘Automotive telemetry system for parameters monitoring.’ *Automotive Show, Birmingham,*. held February 2009 at the NEC, Birmingham.

Vershinin Y.A., Rizzoni G. and Utkin V. (2008) ‘Special Issue on Advanced Control Systems in Automotive Applications’. *International Journal of Modelling, Identification and Control (IJMIC)* 3 (3)

Vershinin, Y. (2008a) ‘Driver parameters monitoring using wireless technology.’ *Health Application for Wireless Technology Conference, CPD4 Health Innovation*. held 15-19 December 2008 at the University of Bradford.

Vershinin, Y.A. (2008b) *Adaptive Control System for Exhaust Emissions Reduction and Improvement of Fuel Economy in Automotive Engine*. [presentation] 2008 at the NISSAN Automotive Company, UK.

Vershinin, Y.A. (2008c) ‘Adaptive control system for separation of aircraft motion on roll and sideslip’. *Proceedings of the 2nd International Symposium on Systems and Control in Aerospace and Astronautics (ISSCAA-2008).* held 2008 at China.

Vershinin, Y. (2008d) ‘Automotive driving simulation’. *Workshop in the MSRSAS*. held 2008 at Bangalore, India.

Vershinin, Y. A. (2008e) ‘Development of an automotive navigation system’. *Transport: Developments and Applications in Russia Conference*. held 2008 at Dimitrov City, Moscow Region.

Vershinin, Y. (2008f) ‘Vehicle’s parameters monitoring.’ *Research Workshop in the Institute of Control Sciences*. held 2008 at the Russian Academy of Sciences, Moscow.

Vershinin, Y. (2008g) ‘Driving simulation.’ *Automotive Simulation Conference, Oktal Company*. held 2008, at Paris, France.

Vershinin, Y. (2007a) ‘Complex multi-axis machinery.’ *Industrial meeting in the MSRSAS*. held 2007 at Bangalore, India.

Vershinin, Y. (2007b) *Digital data-acquisition system*. [presentation] 2007 at Continental AG (Automotive), Frankfurt, Germany.

Vershinin, Y. (2007c) ‘Telematics systems’. *DTI Mission - Global Watch for Mechatronics Conference organised by the DTI UK (Department for Trade and industry), ICS RAS*. held 2007 at Moscow, Russia.

Vershinin, Y. (2007d) *Automotive Telemetry System*. ‘Automotive Show–2007’. held 2007 at the National Exhibition Centre (NEC), Birmingham, UK.

Vershinin, Y.A., Elsholz, L. and Kloth, C. (2006) ‘Design a Hardware-in-the-Loop Rollover Detection System based on a Solid-State Gyroscope’. *Apply and Innovate Conference*. held September 2006 at Karlsruhe, Germany.

Vershinin, Y. (2006a) *An electronic system for car’s fuel parameters monitoring and control*. [presentation] 2006 at Siemens VDO, Birmingham, UK, 2006.

Vershinin, Y. (2006b) ‘Telematics System’. *Telematics Valley Seminar*. held 2006 at Gothenburg, Sweden.

Vershinin, Y. (2005a) *Instrumentation and measurement systems in automotive applications*. [presentation] 2005 at the Robert Bosh GmbH Company, Bangalore, India.

Vershinin, Y. (2005b) *Active suspension systems analysis and design*. [presentation] 2005 at the MSRSAS, Bangalore, India.

Vershinin, Y. (2005c) *Automotive Controller Area Network (CAN-bus).* [presentation] 2005 at the Riva Electric Cars Company, Bangalore, India.

Vershinin, Y.A. (2005d) 'Automotive navigation system'. *EU FP-6 meeting "Global Systems for Telematics" (GST)*. held 2005 at Brussels, Belgium.

Vershinin, Y. (2004a) *Measurement of vehicle dynamics parameters based on an accelerometer and solid-state gyroscope*. [presentation] December 2004 at the Aston-Martin Automotive Company, UK.

Vershinin, Y.A. (2004b) 'A Method of Separation of an Aircraft Motion on a Roll and Sideslip.' *Aircraft Engineering and Aerospace Technology*. 76,(2), 179-184.

Vershinin, Y.A. (2002a) 'Data Fusion Algorithm for Multisensor Systems' *Proceedings of the Fifth International Conference on Information Fusion (Fusion - 2002)*,. held 2002 in Annapolis, Maryland, U.S.A, . 1, 341–345.

Vershinin, Y.A. (2002b) '3D Digital Surface Reconstruction Scanner for Medical Application'. *Proceedings of the Fourth IASTED International Conference: Signal and Image Processing*. held August 12-14 at Hawaii, U.S.A, 491 – 496,

Vershinin, Y.A. (2002c) 'Determination of a mathematical model of a flight simulator for the pitch and roll channels using the Kalman Filter techniques'. *The First Conference of Users of Flight Simulators in UK Universities*. held 2002 at Liverpool, U.K.

Vershinin, Y.A., Gaiduk, A.R., West, M.J. and Medvedev, M.Y. (2002) ‘Synthesis of Decentralized Nonlinear Control Systems with Uncertainties’. *The First International NAISO Congress on Autonomous Intelligent Systems (ICAIS’2002)*. held January 2002 at Australia.

Vershinin, Y.A. and West, M.J. (2001) ‘A New Data Fusion Algorithm Based on the Continuous-Time Decentralized Kalman Filter’. *IEE workshop: Target Tracking: Algorithms and Applications*. held October 2001 at The Netherlands, 16/1-16/6

Vershinin, Y.A., Garvey, S.D. and Holding, D.J. (2001a) ‘High Dynamic Precision Adaptive Control System for Solution of Fault Tolerance Problem’. *Proceedings of The 4th IFAC Symposium on Intelligent Autonomous Vehicles (IAV2001)*. held September 2001 at Sapporo, Japan, 277-283

Vershinin, Y. (2001a) *Decoupled control of MIMO systems*. [presentation] September 2001 at the NTT DoCoMo Hokkaido Inc., Sapporo City, Japan.

Vershinin, Y.A. (2001b) ‘Adaptive Control System for Realization of Decoupled Motion of Aircraft with Required Dynamic Precision’. *Proceedings of the 4th IFAC Symposium on Intelligent Autonomous Vehicles (IAV2001).* held September 2001 at Sapporo, Japan, 368-376.

Vershinin, Y.A., Garvey, S.D. and Holding, D.J. (2001b) ‘High Dynamic Precision Adaptive Control System for Solution of Fault Tolerance Problem of SISO Process’.

Proceedings of the 4th IFAC Workshop "On-Line Fault Detection and Supervision in the Chemical Process Industries" (CHEMFAS-4). held June 2001 at Jejudo Island, South Korea, 123-128

Vershinin, Y. (2001c) *Kalman filter techniques for industrial applications*. [presentation] June 2001 at the Samsung Heavy Industries Company according to the EPSRC Grant "Complex Multi-axis Machinery/Flexible Manufacturing Systems", GR/R53289/01, Pusan City, South Korea.

Vershinin Yuri (2001d) *Complex Multi-axis Machinery*. [presentation] June 2001 at the Hyundai Motor Company according to the EPSRC Grant "Complex Multi-axis Machinery/Flexible Manufacturing Systems", GR/R53289/01, Bussan City, South Korea.

Vershinin, Y.A., Garvey, S.D. and Holding, D.J. (2001c) 'Adaptive Decentralized Control of Complex Multi-Axis Machinery'. *Proceedings of the 32nd International Symposium on Robotics (ISR-2001)*. held April 2001 at Seoul, South Korea 2, 887-893

Vershinin, Y.A. (2001e) 'Performance Enhancement of Distributed Systems through Decentralized Control and Sensor Fusion'. *A DERA/IEE Workshop on Intelligent Sensor Processing*. held 14 February 2001 at U.K.

Vershinin, Y.A., Garvey, S.D. and Holding, D.J. (1999) 'Decentralized Optimal Control of Complex Multi-axis Machinery'. *Proceedings of the International*

Conference on Control Sciences, Institute of Control Sciences of Russian Academy of Sciences. held 29 June – 2 July 1999 at Moscow, 118 – 120

Vershinin, Y.A. (1991) 'Guarantee of tuning independence in multivariable systems'. *Proceedings of the 5-th Leningrad Conference on theory of adaptive control systems: "Adaptive and expert systems in control"*. held 1991 at Leningrad.

Wang T., Lu G., et al. (2018) "Multi-sensor based condition monitoring of rotary mashines: An approach of multidimensional time-series analysis", *Measurement*, 134, 326-335

Watanabe, K. (1992) *Adaptive Estimation and Control: Partitioning Approach*. London: Prentice Hall International

Watanaba, A., Tanaka S., Kaneyasu, M., Asano, M. and Baba, S. (1997) *A Single-chip RISC Microcontroller Boarding on MY1998*. SAE Paper No. 970863.

Wall, Jr. J.E., Willsky, A.S. and Sandell, Jr. N.R (1981) 'On the fixed-interval smoothing problem'. *Stochastics* 5, 1-41

Willner, D., Chang, C.B. and Dunn, K.P. (1976) 'Kalman filter algorithms for a multisensor system'. *Proceedings of the 15th Conference on Decision and Control*. held 1996 at Clearwater, FL, 570-574

Yianni, S., Braithwaite, G., Wong, A., Osowski, C., Arthur, J., Brighton, J., Chapman, I., Ghali K., Waterson, B. and Vershinin, Y. (2016) *Intelligent Mobility Skills Strategy*. *Growing New Markets in Smarter Transport: The report of the Transport Systems Catapult (TSC) for the UK Government*, *Academia and Industry*. [online] available from <https://www.researchgate.net/publication/311965959_Intelligent_Mobility_Skills_Strategy_Growing_New_Markets_in_Smarter_Transport_The_Report_of_the_Transport_Systems_Catapult_TSC_October_2016_UK> [17 January 2019]

Youson, M. (2004) *Diesel Genes* Jaguar Cars Co.

Zeiger, H.P. and McEwen A.J. (1974) 'Approximate linear realizations of given dimension via Ho's algorithm'. *IEEE Transactions on Automatic Control* 19, 153.

APPENDIX 1:

CITATIONS

(i) Vershinin, Y.A. ‘A data fusion algorithm for multisensor systems’. *The Fifth International Conference on Information Fusion*. held 2002 at Annapolis, Maryland, U.S.A. Piscataway, NJ: IEEE, 1, 341–345.

Cited in...

Wang T., Lu G., et al. (2018) “Multi-sensor based condition monitoring of rotary mashines: An approach of multidimensional time-series analysis”, *Measurement*, 134, 326-335

Mc Dermott, M. (2014) ‘Cognitive Sensor Platform’. *International Journal of Electrical and Computer Engineering (IJECE)*. 4 (4), 520~531

USA Department of Defence DoD 2017.1 (2017) *Improved Data Fusion Techniques for Space-Based Remote Sensing*, USA Department of Defence DoD 2017.1, Air Force Branch, Program SBIR 2017, Technology Area(s): Space Platforms, Topic Number AF171-069.

Ahmadi-Pour M., Ludwig T., Olaverri-Monreal C. (2017) ‘Statistical Modelling of Multi-Sensor Data Fusion’. *IEEE 2017 International Conference on Vehicular Electronics and Safety (ICVES 2017)* held 2017 at Vienna, Austria. DOI: 10.1109/ICVES.2017.7991925

Myat Su Nwe, Hla Myo Tun (2017) ‘Implementation of Multisensor Data Fusion Algorithm’. *International Journal of Sensors and Sensor Networks* 5 (4), 48-53

Guo J., He B., Lv P., Yan T. and Lendasse A. (2018) ‘Data Fusion Using OPELM for Low-Cost Sensors in AUV’. in: Cao J., Cambria E., Lendasse A., Miche Y., Vong C. (eds.) *Proceedings of ELM-2016*, ‘Proceedings in Adaptation, Learning and Optimization.’ New York: Springer, 9

Abdulrahim, M., Weibley, N., Lee, D., Lind, R.C., Armanious, G.J, and Suh, P.M. (2018) ‘Aeroservoelastic Control of UAV Wings Using a Distributed Sensing, Computing, and Actuation Architecture’. *Atmospheric Flight Mechanics Conference, AIAA SciTech Forum.* held 2018 at Kissimmee, FL.

Norton, A.H. (2016) ‘Design of an Inertial Positioning Device (IPD)’. *The UNSW Canberra at ADFA Journal of Undergraduate Engineering Research* 9 (1)

Kochetkov, S., Rassadin, Y. and Utkin, V. (2017) ‘Disturbance rejection in the tracking problem for robot-manipulators’. *2017 IEEE International Workshop on Metrology for AeroSpace (MetroAeroSpace)*. held 21-23 June 2017 at Padua, Italy,

Ancy Mergin, A. and Godwin Premi, M.S. (2017) ‘Pixel level fusion of medical signals using DCT, DWT and hybrid (DWT-DCT) transform based on maximum selection rule-a comparison’. *International Conference on Computing Methodologies and Communication (ICCMC).* held 18-19 July 2017 at Erode, India. DOI: 10.1109/ICCMC.2017.8282596

Swetha, A. and Raol, J. R. (2017) 'Continuous Time H-Infinity Filter with Asymptotic Convergence'. *International Research Journal of Engineering, IT & Scientific Research (IRJEIS)* 3 (4), 69-78

Department of Defence USA (2017) 'Improved Data Fusion Techniques for Space-Based Remote Sensing'. *Department of Defence USA, Branch: Air Force, TECHNOLOGY AREA(S): Space Platforms, Program: Small Business Innovation Research (SBIR), Topic Number: AF 171-069*, AF-105 [online] available from https://www.acq.osd.mil/osbp/sbir/solicitations/sbir20171/index.shtml

Liu Xingbin, et al., (2016) "Research progress in multi-phase data fusion technology in multi-phase flow", *Petroleum Instruments*, 6 – 9.

Wu, C-H., Hong, W-Z. and Pan, S-T. (2015) 'Performance Evaluation of Extended Kalman Filtering for Obstacle Avoidance of Mobile Robots'. *Proceedings of the International MultiConference of Engineers and Computer Scientists 2015 IMECS 2015*. held March 18 – 20 at Hong Kong, 1.

Angeloni, F., Ermidoro, M., Previdi, F. and Savaresi, S.M. (2015) *A friction estimation approach to fault detection in electromechanical systems* IFAC-Papers On Line 48-21Amsterdam: Elsevier, 720–725.

Choi, S-T., Hur, W-S. and Seo, S-W. (2014) 'Cooperative localization based on topology matching'. *2014 IEEE 6th International Symposium on Wireless Vehicular*

Communications (WiVeC). held 14-15 Sept 2014 at Vancouver, BC, Canada. Piscataway, NJ: IEEE

Stahl, K., and Leimbach, K.-D. (2014) 'Vehicle dynamics simulation by using hardware in the loop techniques'. *2014 IEEE 17th International Conference on Intelligent Transportation Systems (ITSC)*. held 8-11 October 2014 at Qingdao, China. Piscataway, NJ: IEEE. DOI: 10.1109/ITSC.2014.6957742

Stahl, K. and Leimbach, K.-D. 'Hardware in the Loop Simulator for Vehicle Dynamics Investigation'. *Heilbronn Workshop on Research in Mechatronics*. held December 2013 at Heilbronn, Germany, 23-27

Banerjee, T.P. and Das, S. (2012) 'Multi-sensor data fusion using support vector machine for motor fault detection'. *Information Sciences* Amsterdam: Elsevier, 217, 96-107. DOI: 10.1016/j.ins.2012.06.016

Zhang, M.B. and Sun, X.J. (2012) 'Identification Method for Multichannel Multisensor ARMA Signal with Colored Measurement Noises'. *Applied Mechanics and Materials* 220-223, 1922-1928

Li, Y., Wu, R, and Zhang, T. (2012) 'Multi-scale fusion and estimation for multi-resolution sensors'. *IEEE 11th International Conference on Signal Processing (ICSP).* held 21-25 Oct. 2012 at Beijing, China. Piscataway, NJ: IEEE

Zereik, E., Biggio, A., Merlo, A. and Casalino G. (2011) ‘Vision-Based Perception and Sensor Data Integration for a Planetary Exploration Rover’. *Proceedings of the 11th Symposium on Advanced Space Technologies in Robotics and Automation, ASTRA 2011, ESA/ESTEC, European Space Agency – Automation and Robotics (A&R) Section*. held April 12-14, 2011 at Noordwijk, The Netherlands.

Wang, Y-M. and Peng, D-L. ‘A simulation platform of multi-sensor multi-target track system based on STAGE’. *8th World Congress on Intelligent Control and Automation (WCICA).* held 7-9 July 2010 at Jinan, China. DOI: 10.1109/WCICA.2010.5554332

Jaradat, M.A.K and Langari, R. (2009) ‘A hybrid intelligent system for fault detection and sensor fusion’. *Applied Soft Computing* Amsterdam: Elsevier, 9 (1), 415-422. DOI: 10.1016/j.asoc.2008.05.001

Gu, Q-T. and Fang, J. (2009) ‘Global Optimality for Generalized Federated Filter’. *Journal Acta Automatica Sinica* 35 (10), 1310-1316. DOI:org/10.1016/S1874-1029(08)60112-3

Kirti, S. and Scaglione, A. (2008) ‘Scalable distributed Kalman filtering through consensus’. *IEEE International Conference on Acoustics, Speech and Signal Processing, ICASSP 2008.* held 2008 at Las Vegas, NV. Piscataway, NJ: IEEE

Jaradat, M.A.K.R. (2005) *A hybrid system for fault detection and sensor fusion based on fuzzy clustering and artificial immune systems.* Unpublished PhD thesis. Texas: A&M University

Ersoy, Y, and Efe, M. (2007) 'Fused and Adaptive Modified Wave Estimators for Navigation Systems'. *Commun. Fac. Sci. Univ. Ank. Series A2-A3: Physics, Engineering Physics and Astronomy* 51 (1), 17-30

Zhe Ren Song (2007) "Multi-scale fusion estimation algorithm and its application in navigation system ",*Telecommunications Technology*, 6, 109 – 115.

Guo, Q. and Song-Nian, Y. (2006) 'Distributed multisensor data fusion based on Kalman filtering and the parallel implementation'. *Journal of Shanghai University (English Edition)*. New York: Springer, 10 (2), 118–122

Xu X-L and Tang, J-F. (2006) 'A New Sequential Weighed Fusion Method with Colored Noise and Time Delay'. *International Conference on Machine Learning and Cybernetics.* held 13-16 August 2006 at Dalian, China. Piscataway, NJ: IEEE

Ersoy, Y. and Efe, M. (2006) 'Fused and Adaptive Modified Wave Estimators for Navigation Systems'. *9th International Conference on Information Fusion.* held 10-13 July 2006 at Florence, Italy. DOI: 10.1109/ICIF.2006.301711

Jaradat, M.A.K. and Langari, R, (2005) 'A Hybrid Real-Time System for Fault Detection and Sensor Fusion Based on Conventional Fuzzy Clustering Approach'.

The 14th IEEE International Conference on Fuzzy Systems. held 25-25 May 2005 at Reno, NV, USA. DOI: 10.1109/FUZZY.2005.1452391

(ii) Vershinin, Y.A. (2014) 'Adaptive Control System for Solution of Fault Tolerance Problem'. in *Lecture Notes in Electrical Engineering 247, IAENG Transactions on Engineering Technologies.* ed. by Haeng Kon Kim, Sio-long Ao, Mahyar A. Amouzegar and Burghard B. Rieger, New York: Springer Publications, Chapter 15 197-208

Cited in...

Bravo, G.M.M., Moscoso-Vásquez, M. and Alvarez, H.D. (2014) 'Scaleup of Batch Reactors Using Phenomenological-Based Models'. *Industrial & Engineering Chemistry Research* 53 (22), 9439–9453. DOI: 10.1021/ie500587r

Balasubmanian, R. K. (2015) "Development of Novel Approaches For High Resolution Direction Of Arrival Estimation Techniques", PhD thesis, Coventry University, UK.

(iii) Vershinin, Y.A (2004) ‘A Method of Separation of an Aircraft Motion on a Roll and Sideslip’. *Aircraft Engineering and Aerospace Technology* 76 (2), 179-184

Cited in...

Fung, E.H.K., Wong, Y.K., Liu, H.H.T and Li, Y.C. (2008) ‘Multiple specification controller design for F-16 fighters’. *Aircraft Engineering and Aerospace Technology* 80 (5), 510-515 [online] available from https://doi.org/10.1108/00022660810899874

APPENDIX 2 – Portfolio Outputs

1. Vershinin, Y.A. (2018) 'High Dynamic Precision Control System'. *International Journal of Electrical and Electronic Engineering Research* 8 (2), 13-18.

2. Vershinin, Y.A. (2002) 'A data fusion algorithm for multisensor systems'. *The Fifth International Conference on Information Fusion*. held 2002 at Annapolis, Maryland, U.S.A. Piscataway, NJ: IEEE,1 341–345.

3. Vershinin, Y.A. (2014) 'Adaptive Control System for Solution of Fault Tolerance Problem'. in *Lecture Notes in Electrical Engineering 247, IAENG Transactions on Engineering Technologies*. ed. by Haeng Kon Kim, Sio-long Ao, Mahyar A. Amouzegar and Burghard B. Rieger. New York: Springer Publications, 197-208.

4. Vershinin, Y. (2013) 'Adaptive Control System for Solution of Fault Tolerance Problem for MIMO Systems'. in Castillo, S. I. A, O., Douglas, C., Feng D.D. and Lee, J-A. (eds.) *Proceedings of the International Multi-Conference of Engineers and Computer Scientists 2013 (IMECS 2013)*, held March 13-15, 2013 at Hong Kong. 'Lecture Notes in Engineering and Computer Science' 2202 (1), 117–120.

5. Vershinin, Y.A. (2004) ‘A Method of Separation of an Aircraft Motion on a Roll and Sideslip’. *Aircraft Engineering and Aerospace Technology* 76 (2), 179-184

6. Vershinin Y.A. (2008) ‘Adaptive Control System for Exhaust Emissions Reduction and Improvement of Fuel Economy in Automotive Engine’. [presentation] 2008 at the Nissan Automotive Company.

APPENDIX 3

APPENDIX 3.1.4.

The complete derivation of adaptive algorithms for Chapter 3.1.4 "Synthesis of the adaptive control algorithms"

The quadratic function *V* can be chosen as follows:

$$V = \gamma E^T PE + tr(YY^T), \qquad (20)$$

where

$\gamma = const$

$P - is\ simmetric\ matrix.$

$Q - is\ negative\ definite\ matrix$

The time derivative for the function *V* is obtained as follows:

$$\dot{V} = \gamma \dot{E}^T PE + \gamma E^T P\dot{E} + tr(\dot{Y}Y^T + Y\dot{Y}^T) = \gamma (A^m E + YX)^T PE + \gamma E^T P(A^m E + YX) + tr(\dot{Y}Y^T + Y\dot{Y}^T) =$$
$$\gamma [(A^m E)^T + (YX)^T]PE + \gamma E^T P(A^m E + YX) + tr(\dot{Y}Y^T + Y\dot{Y}^T) =$$
$$\gamma [E^T (A^m)^T + X^T Y^T]PE + \gamma E^T PA^m E + \gamma E^T PYX + tr(\dot{Y}Y^T + Y\dot{Y}^T) =$$
$$\gamma E^T (A^m)^T PE + \gamma X^T Y^T PE + \gamma E^T PA^m E + \gamma E^T PYX + tr(\dot{Y}Y^T + Y\dot{Y}^T) =$$
$$\gamma E^T ((A^m)^T P + PA^m)E + \gamma X^T Y^T PE + \gamma E^T PYX + tr(\dot{Y}Y^T + Y\dot{Y}^T)$$

Taking into account that

$$Q = (A^m)^T P + PA^m)$$

the following is obtained:

$$\dot{V} = \gamma E^T QE + \gamma X^T Y^T PE + \gamma E^T PYX + 2tr(\dot{Y}Y^T)$$

According to the theory of matrices:

$$\gamma X^T Y^T PE = \gamma E^T PYX = tr(PEX^T Y^T)$$

Then, the following is obtained:

$$\dot{V} = \gamma E^T QE + 2tr(\gamma PEX^T Y^T) + 2tr(\dot{Y}Y^T) =$$
$$\gamma E^T QE + 2tr(\gamma PEX^T Y^T + \dot{Y}Y^T) =$$
$$\gamma E^T QE + 2tr[(\gamma PEX^T + \dot{Y})Y^T].$$

According to equation (18) with the admission that $R(t) \equiv 0$, the following is obtained:

$$\dot{Y} = \Psi$$

Therefore, the first derivative of the Lyapunov function can be represented as follows:

$$\dot{V} = \gamma E^T QE + 2tr[(\gamma PEX^T + \Psi)Y^T]. \qquad (21)$$

Represent the adaptive control algorithm in the following form:

$$\Psi = -\gamma PEX^T \qquad (22)$$

Then, the derivative of the Lyapunov function is represented as:

$$\dot{V} = \gamma E^T QE \tag{23}$$

Taking into account that A^T is Hurvitch matrix, the following is obtained:

$$\dot{V} \le 0 \tag{24}$$

It follows from the above that motion of the system (16) with the algorithms (25) is stable and conditions (5) and (6) are satisfied.

APPENDIX 3.3.1.

The complete derivation of a mathematical model of a process for Chapter 3.3.1 "Determination of a mathematical model of a process"

A mathematical model of a process on a stationary regime can be found from the sequence of Markov parameters using the classical Ho algorithm (Ho and Kalman 1966). The Markov parameters can be obtained from input – output relationships or more directly as an impulse response of the system. It is well known that according to the theorem of Kronecker the rank of the Hankel matrix constructed from the Markov parameters is equal to the order of the system from which the parameters are obtained. Therefore, by consistently increasing the dimension of the Hankel matrix Γ until

$$\text{rank}\,\Gamma_r = \text{rank}\,\Gamma_{r+1}$$

the order of the system can be obtained as equal to *r*. However, in practical implementation, this rank-order relationship may not give accurate results due to several factors: sensitivity of the numerical rank calculation and bias of the rank if information about the process is corrupted by noise. This problem can be avoided using singular value decomposition (SVD) of the Hankel matrix:

$$\Gamma = USV^T, \qquad (1)$$

where

$$U^T U = V^T V = I,$$

$$S = diag(\sigma_1, \sigma_2, ..., \sigma_l, \sigma_{l+1,} ...\sigma_n) .$$

Here U and V are orthogonal matrices. The diagonal elements of the matrix S (the singular values) in (1) are arranged in the following order $\sigma_1 > \sigma_2 > ... > \sigma_n > 0$. Applying the property of SVD to reflect the order of a system through the smallest singular value, the order of the system can be determined with the tolerance required. From practical point of view a reduced order model is more preferable. Taking into account that the best approximation in the Hankel norm sense is within a distance of σ_{l+1}, the model of order l can be found. However, a relevant matrix built from Markov parameters of this reduced order model should also be of the Hankel matrix. But it is not an easy matter to find such a Hankel matrix for the reduced order process. A simpler solution, although theoretically not the best, can be found from the least squares approximation of the original Hankel matrix (Zeiger and McEwen 1974; Kalman, Falb and Arbib 1974; and Moor 1981). The discrete time state-space realization of the process can be determined from the relationship between Markov parameters and representation of the Hankel matrix through relevant controllability and observability matrices of the process:

$$\Gamma = \begin{bmatrix} C_d \\ C_d A_d \\ C_d A_d^2 \\ . \\ . \end{bmatrix} \begin{bmatrix} A_d & A_d B_d & A_d^2 B_d & . & . \end{bmatrix} = \Omega \mathrm{E} , \qquad (2)$$

where

A_d is the system matrix of the discrete time state space realization of a system,

B_d is the control matrix of the discrete time state space realization of a system,

C_d is the output matrix of the discrete time state space realization of a system,

Ω is the observability matrix of the discrete time state space realization of a system,

E is the controllability matrix of the discrete time state space realization of a system.

The Hankel matrix can be represented as:

$$\Gamma = \begin{bmatrix} h_1 \; h_2 \; h_3 \; \ldots \\ h_2 \; h_3 \; h_4 \; \ldots \\ h_3 \; h_4 \; h_5 \; \ldots \\ \ldots \; \ldots \; \ldots \; \ldots \end{bmatrix}$$

where: h_1, h_2, h_3 ,…, h_k, - are Markov parameters (Gandmakner 1959),
(k= 1, 2, 3, 4, 5,…, ∞).

Also, the Hankel matrix can be represents in the following form:

$$\Gamma = \begin{bmatrix} C_d B_d & C_d A_d B_d & C_d A_d^2 B_d & \ldots \\ C_d A_d B_d & C_d A_d^2 B_d & C_d A_d^3 B_d & \ldots \\ C_d A_d^2 B_d & C_d A_d^3 B_d & C_d A_d^4 B_d & \ldots \\ . & . & . & \ldots \end{bmatrix}$$

Denote by $\bar{\Omega}$ as the modified matrix Ω which is obtained by the shift-up operation.
Then the following can be obtained:

$$\Omega A = \begin{bmatrix} C_d \\ C_d A_d \\ C_d A_d^2 \\ . \\ . \end{bmatrix} = \bar{\Omega}$$

Denote by $\tilde{E}$ as the modified matrix E which is obtained by the shift-left operation. Then the following can be obtained:

$$AE = \begin{bmatrix} A_d B_d & A_d^2 B_d & \dots \end{bmatrix} = \tilde{E}$$

Denote by $\bar{\Gamma}$ as the modified matrix Γ which is obtained by the shift-up operation. Then the following can be obtained:

$$\Omega AE = \begin{bmatrix} C_d \\ C_d A_d \\ C_d A_d^2 \\ . \\ . \end{bmatrix} A \begin{bmatrix} B_d & A_d B_d & A_d^2 \; B_d \dots \end{bmatrix} = \bar{\Gamma}$$

According to minimax property of SVD and taking a condition: $\sigma_l > \sigma_{l+1}$, the following is obtained:

$$\Gamma = \Omega E$$

where

$$\Omega = US^{1/2},$$

$$E = S^{1/2} V$$

The least-squares solution for

$$\Omega A_d^1 = \bar{\Omega}$$

$$A_d^2 E = \tilde{E}$$

can be obtained in the following form:

$$A_d^1 = \Omega^+ \bar{\Omega}$$

$$A_d^2 = \tilde{E} E^+$$

$$A_d^1 = A_d^2 = A_d$$

here "+" represents the pseudo-inverse:

$$\Omega^{+} = S^{-1/2}U^{T}$$

$$E^{+} = V^{T}S^{-1/2}$$

Therefore,

$$A_d = \Omega^{+}\bar{\Omega} = S^{-1/2}U^{T}US^{1/2}$$

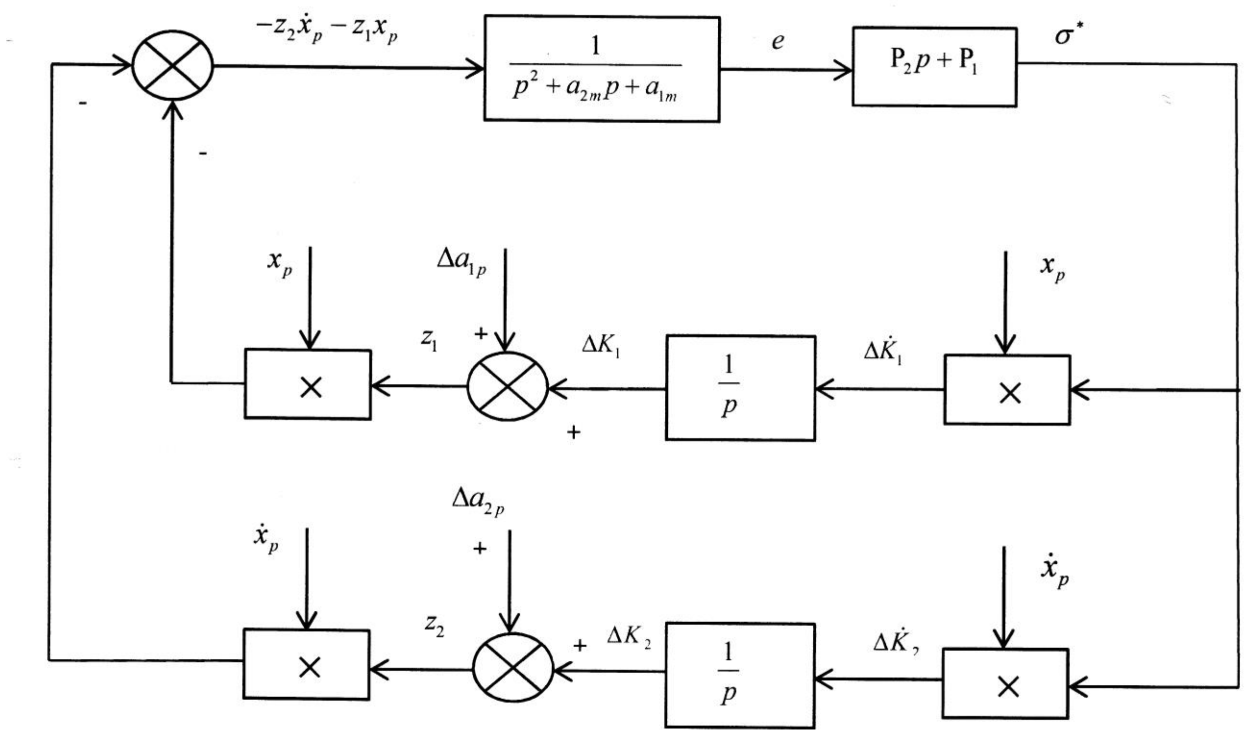
$$A_d = \tilde{E}E^{+} = S^{1/2}VV^{T}S^{-1/2}$$

The following is assigned:

B_d = first column of E,

C_d = first column of Ω.

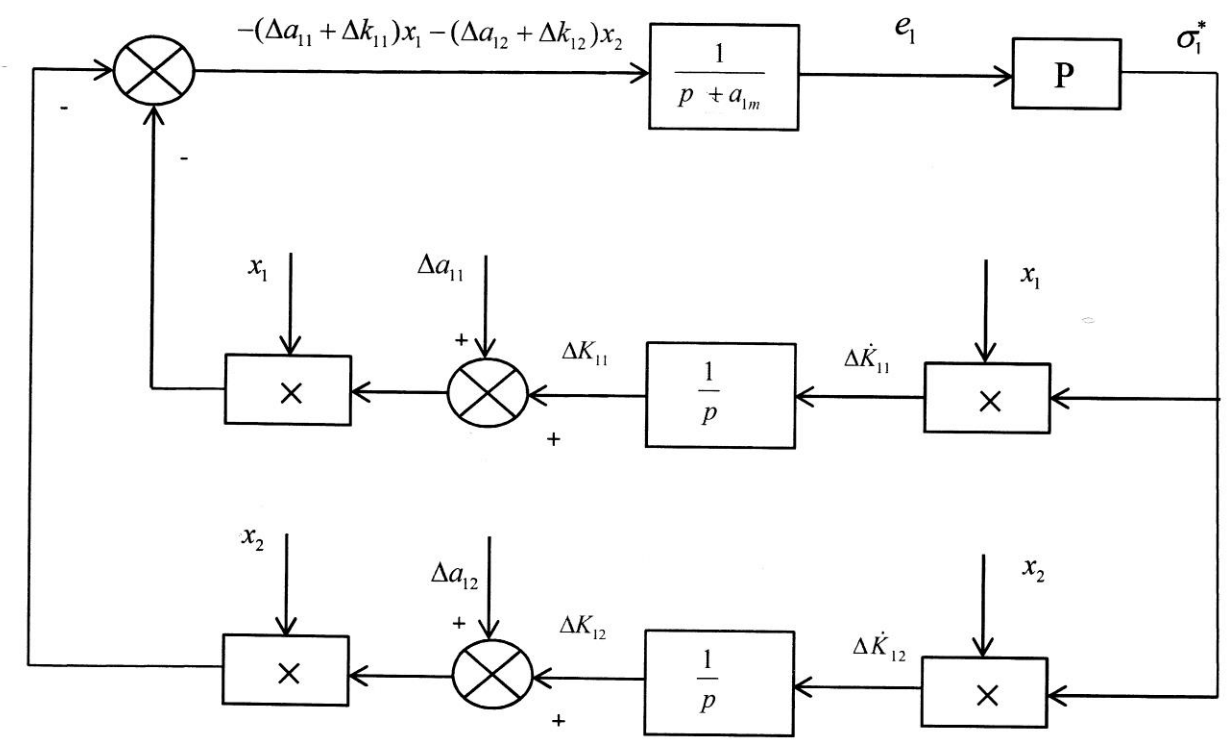
APPENDIX 3.3.2.



Here: p - denotes the operation of differentiation.

Figure A-3.3.2. The block-diagram of the system described by equations (6) and (8) in Chapter 3.3.2.

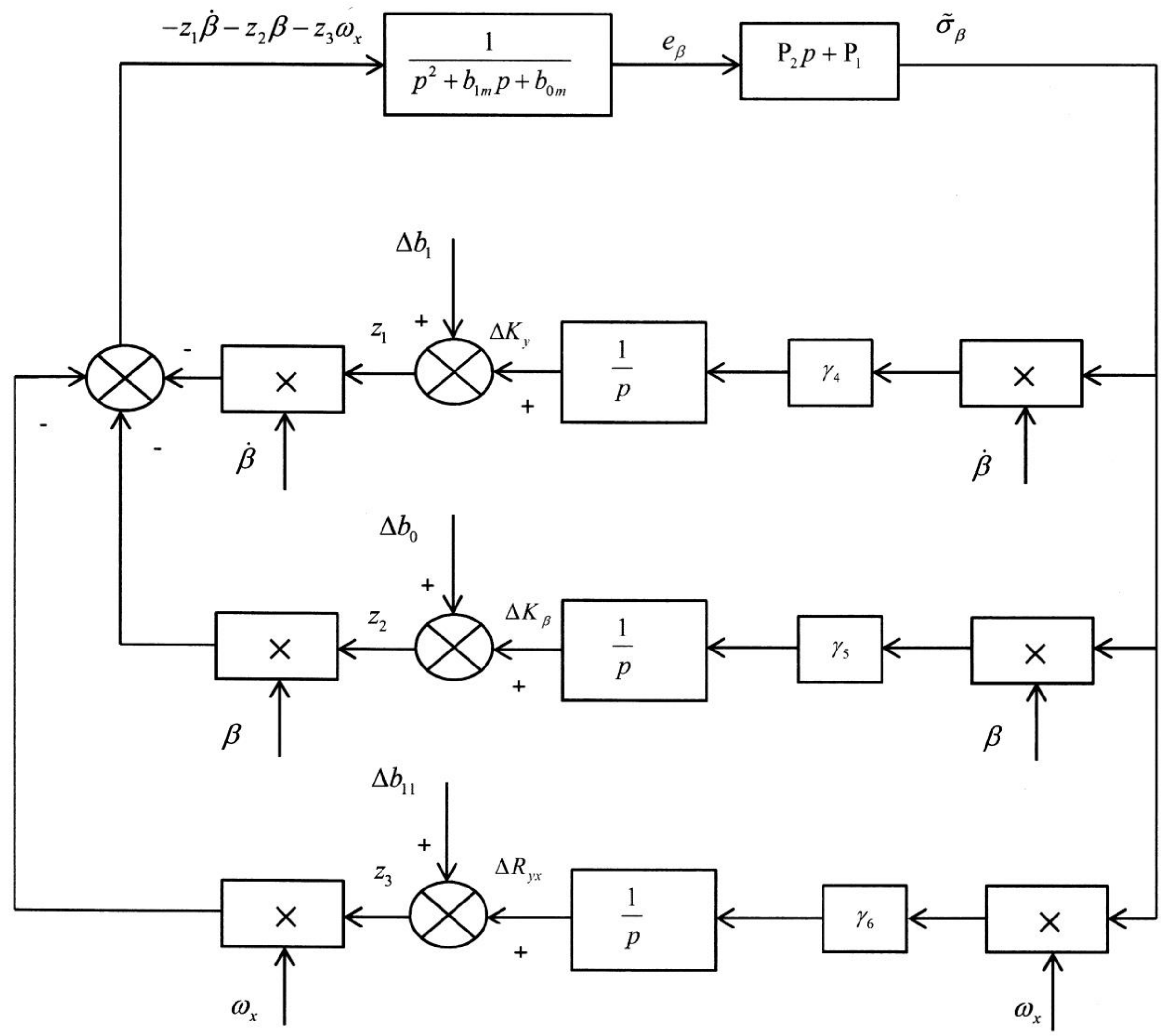
APPENDIX 3.4.1.



Here: p - denotes the operation of differentiation.

Figure A-3.4.1. The block-diagram of the first channel (i=1) of the system described by equations (4) and (6) in Chapter 3.4.1.

APPENDIX 3.5.



Here: p - denotes the operation of differentiation.

Figure A-3.5. The block-diagram of the system described by equations (15) and (16) in Chapter 3.5.