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Tunnel central control system enhanced with modern control approaches

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ABSTRACT

The tunnel central control system is designed for maintaining the necessary safety and resistance against failures as a system fully redundant at all levels. All hardware components of the control system and their connections are doubled. Control system is based on the programmable logic controllers (PLC's) and used the industrial buses on an optical and metallic physical layer. This system controls the traffic and all tunnel equipment systems (variable traffic signs, various lighting elements, ventilation system, etc.). Nowadays the control strategy is based on measured data inside the tunnel, metrological information and operator's commands. The control strategy or algorithm must be enhanced to obtain better or optimal results. Using of model predictive control (MPC) may lead to optimize the control way for chosen criteria. MPC can be implemented to PLC by several methods.

KEYWORDS: tunnel central control system, modern control

1. Introduction

The road tunnel and its central control system is a part of intelligent traffic system which requires a continuous 24-hour service all year. This requirement can be done by correct procedure during designing and implementation of whole parts of tunnel systems. The main systems are: Fire alarm and detection system, operation control and automation equipment, traffic control system, power supply, lighting system, ventilation system, water management, etc. Central control system (CRS) completely control all technology and traffic in the tunnel. CRS is realized by the redundant PLC on the automatic working control level. This solution increases availability and reliability of the system. Improving of safety level must be solved at the hardware level (selection of components with a defined SIL – safety integrity level) [9], [10]. The PLC (programmable logic controller) should by therefore simplistically describe as industrial computer, specially designed to control the industrial systems. Although PLCs are similar to „conventional" computers in term of hardware technology, they have specific features suited for industrial control: a) Rugged, noise immune equipment; b) Modular plug-in construction, allowing easy replacement or addition of units (e.g. input/output); c) Standard input/output connections and signal levels; d) Easily understood programming language; e) Ease of programming and reprogramming in-plant; f) Capable of communicating with other PLCs, computers and intelligent devices; g) Competitive in both cost and space occupied with relay and solid-state logic systems; These features make programmable controllers highly desirable in a wide variety of industrial plant and process control situations. Next chapters will deal with architecture of the control system, control algorithms design and implementation.

2. Increasing the system reliability

System redundancy can serve for recovery after the failure. The reserve parts of the system are those, the using of which would be obsolete, if other parts of the system work correctly.

Redundancy can be described in different groups: according to their using, according to the functionality and according to the fabrication.

a. According to their using:

Power redundancy – System should be powered at least two indifferent sources and should have a backup power source. The supply of power for the classified equipment in the case of a failure in the power supply from the public network is provided by a rotational backup source, i.e. a diesel generating set.

Sensor redundancy - if there is any measurement in the production process so important that its failure could shut down production, it is doubled. It is used to connect two sensors to the redundant module.

Network and media redundancy - Network and media redundancy works by creating multiple data paths within a network, between any and all locations. The nodes must be doubled too. If a cable, switch, or router suddenly fails, another pathway will be available to maintain the communication flow. Redundant systems deliver significant value in a host of industrial applications and are especially essential to tunnel systems [16].

Redundancy of communication buses - This is achieved by doubling the communication cards on both sides of the communication network.

CPU redundancy - the processors running the same program with the same data and in the event of failure of the main processor will assume control the standby processor. Of course, it must be provided with the redundancy of communication and input-output signals necessary to control.

b. According to the functionality:

Hot-standby redundancy - For tunnels systems is required the Hot-standby redundancy. With redundancy on all system levels (i.e. hardware, system software, application programming and maintenance, monitoring interfaces) hot-standby redundancy provides maximum reliability with outstanding convenience at the same time. Hot-standby redundancy enhances network redundancy by the following attributes:

- Fully automatic matching of process variables.
- Automatic failover upon detecting internal errors.
- Integrated self-tests for checking system status.
- Automatic system matching (system software, configuration, applications).
- Automatic application synchronization.
- Resistant to single-fault events.

c. According to the fabrication:

Safe redundancy - is the redundancy, where is redundant everything necessary for safe operation, for example: processors are redundant, but signal redundancy is not ensured.

Full redundancy - redundancy, where everything is redundant: power, wiring, sensors, signals, communications processors.

In Fig. 1 we can see the redundant control unit for tunnel system.

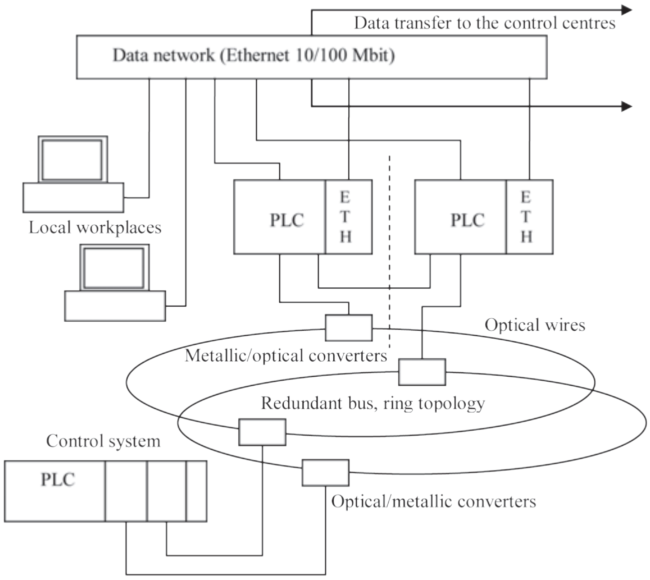

Fig. 1. Redundant wiring of the control unit [16]

3. Tunnel central control system (TCCS)

The central control system is a central unit of tunnel equipment. Coordinated operation of the various operating units of the tunnel, such as: energy system, ventilation system, lighting system, Fire detection and firefighting systems (FDS and FFS), electronic security systems (ESS), the information system, video surveillance, variable message signs (VMS) and others is achieved by using a special software equipment. In the past, the control of tunnel systems was used by supervisory control with partly automated fractionation processes. Currently, the automatic control is dominant and operators provide supervises upon running automated system. Architecture of the tunnel central control system is shown in Fig.2.

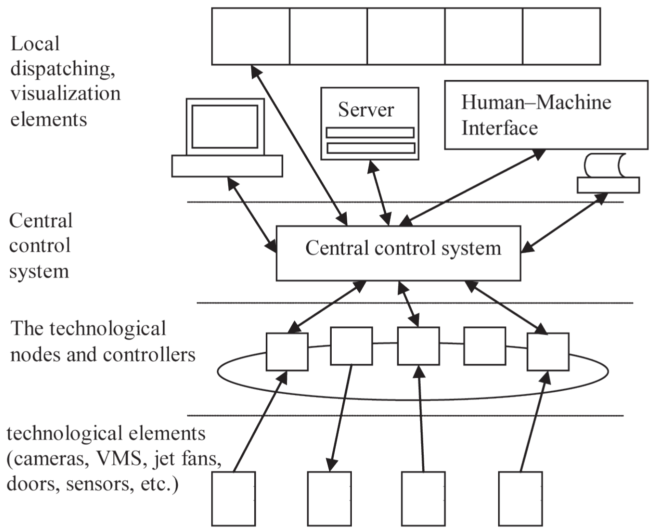

Fig. 2. Architecture of the tunnel central control system – block diagram [5]

3.1 Data for tunnel central control system

Traffic intensity is sensed by a camera system and the cars are then counted and sorted by categories in database system. More information about monitoring of the traffic and measurement can be found in [7], [8] and [18]. About the security by transferring the data is discussed in [4]. About communication networks is discussed in [11] and [12]. Gases emitted by combustion engine consist largely of oxides of nitrogen (NOx), carbon monoxide (CO), steam (H_2O) and particles (opacity) are sensed by special sensors. The actuators are: variable message signs (VMS), information boards, jet fans, doors, etc. We need the system identification to design the control algorithm [5].

The main tasks of system identification were the choice of model type and model order. It is advantageous obtain a linear time discrete model to consider the discrete character of controller. Although most real systems have non-linear input/output characteristics, many systems, when operated within nominal parameters (not „over-driven") have behavior that is close enough to linear that LTI system theory is an acceptable representation of the input/output behavior.

System identification is the study of modeling dynamic systems from experimental data. System (S): A defined part of the real world. Interactions with the environment are described by input signals, output signals and disturbances. Model (M): A description of a system. The model should capture the essential behavior of the system. Transportation systems modeling are described from other view in [21].

All linear models can be derived from general linear model by simplification. In the recursive identification the following linear dynamic models can be taken into consideration. These are ARX, ARMAX and OE models. All models based on the difference equation [2]:

$$y(t)+a_1y(t-1)+\cdots+a_{na}y(t-n_a) = b_1u(t-1)+\cdots+b_{nb}u(t-n_b). \quad (1)$$

This equation can describe the relation between input and output.

3.2 Recursive identification method

The recursive parameter estimation algorithms are based on the data analysis of the input and output signals from the process to be identified. This method can be used for parameter estimate of ARX model.

$$y(k)=\frac{B(q^{-1})}{A(q^{-1})}u(k)+\frac{1}{A(q^{-1})}n(k) \quad (2)$$

The essence of the Recursive Last Square (RLS) algorithm is calculation of new estimates parameters in step (k +1). For the derivation of RLS we assume that the estimated parameters are known at the time k and covariance matrix $P(k) = (W^TW)^{-1}$ is also known. W is the data matrix. We need to derive recursive relations for $\hat{\theta}(k+1)$ and $P(k+1)$. If we have measured values in step (k +1), then:

$$\bar{y}(k+1)=\begin{pmatrix}\bar{y}(k)\\ y(k+1)\end{pmatrix} \quad (3)$$

$$W(k+1)=\begin{pmatrix}W(k)\\ w^T(k+1)\end{pmatrix}$$
$$W^T(k+1)=\begin{pmatrix}W^T(k) & w(k+1)\end{pmatrix} \quad (4)$$

For the covariance matrix is valid the relation:

$$P(k+1)=\left[W(k+1)^TW(k+1)\right]^{-1}=\left[P^{-1}(k)+w(k+1)w^T(k+1)\right]^{-1} \quad (5)$$

The Matrix Inversion Lemma.
Theorem: Let $M = A+BC^{-1}D$. If A,C are regular then:

$$M^{-1}=A^{-1}-A^{-1}B(DA^{-1}B+C)^{-1}DA^{-1} \quad (6)$$

Next, using the Lemma we get:

$$P(k+1)=P(k)-P(k)W(k+1)\left[W^T(k+1)P(k)W(k+1)+1\right]^{-1}W(k+1)P(k) \quad (7)$$

We introduce:

$$\gamma(k+1)=\left[W^T(k+1)P(k)W(k+1)+1\right]^{-1} \quad (8)$$

It is valid that:

$$\hat{\theta}(k+1)=\hat{\theta}(k)+\Lambda(k+1) \quad (9)$$

where $\Lambda(t+1)$ is increment,

$$\Lambda(t+1)=L(t+1)\cdot\varepsilon(t+1) \quad (10)$$

where $L(t+1)$ is the gain and $\varepsilon(t+1)$ is prediction error,

$$\varepsilon(k+1)=y(k+1)-\hat{y}(k+1) \quad (11)$$

where $y(k+1)$ is a real value and $\hat{y}(k+1)$ is estimated value.

Recursive Least Squares Algoritm is given by sequence of relations:

$$\varepsilon(k+1)=y(k+1)-W^T(k+1)\cdot\hat{\theta}(k) \quad (12)$$

let us denote:

$$\begin{aligned}\gamma(k+1)&=\left[1+W^T(k+1)\cdot P(k)\cdot W(k+1)\right]^{-1}\\ \Rightarrow\ \gamma(k+1)&=1-\gamma(k+1)W^T(k+1)\cdot P(k)\cdot W(k+1)\\ L(k+1)&=\gamma(k+1)\cdot P(k)\cdot W(k+1)\\ P(k+1)&=P(k)-\gamma(k+1)\cdot P(k)\cdot W(k+1)\cdot W^T(k+1)\cdot P(k)\end{aligned} \quad (13)$$

The new estimate of the parameters $\hat{\theta}(k+1)$ is found:

$$\hat{\theta}(k+1)=\hat{\theta}(k)+L(k+1)\cdot\varepsilon(k+1) \quad (14)$$

Recursive algorithm must have initial conditions for $\hat{\theta}(0)=0$ a $\boldsymbol{P}(0)=c\boldsymbol{I}$, where c is an arbitrary large constant (e.g. 10^6). Using this algorithm we are able to create the model of the real system for the purpose of implementation the predictive control algorithm.

4. Model Predictive Control (MPC)

Predictive control is basically based on discrete or sampled models of processes. Therefore relevant relations and derivations are presented mainly in discrete area. The term "predictive control" denotes a class of control methods having a set of common properties: a mathematical model of the control system that is used for prediction of the future controlled output, known future trajectory of the required quantity, calculation of sequence of future control actions involving minimization of a proper cost function (usually quadratic) together with future trajectories of control increments and control deviation. Only the first proposed control action is performed and the whole minimization procedure is repeated in the next sampling period again. Usability of predictive control algorithms is quite wide and quality of control is usually higher than in the case of PID-controllers. They are applicable to unstable, multidimensional processes or processes with transport delay and compensate effects of measurable and non-measurable failures [1], [6]. Application of another approach of using the MPC in tunnel systems are discussed in [3], [13].

In this work we have applied the Dynamic Matrix Control (DMC) method which is one of the most spread approaches and creates the base of many commercially available MPC products. It is based on the model obtained from the real system [17]:

$$y(k) = \sum_{i=1}^{N} h_i u(k-i), \tag{15}$$

where h_i are Finite Impulse Response coefficients of the model of the controlled system. Predicted values may be expressed:

$$\begin{aligned}\hat{y}(n+k \mid n) &= \sum h_i \Delta u(n+k-i) + \hat{d}(n+k \mid n) = \\ &= \sum h_i \Delta u(n+k-i) + \sum h_i \Delta u(n+k-i) + \hat{d}(n+k \mid n),\end{aligned} \tag{16}$$

We assume that the additive failure is constant during the prediction horizon:

$$\hat{d}(n+k \mid n) = \hat{d}(n \mid n) = y_m(n) - \hat{y}(n \mid n) \tag{17}$$

Response can be decomposed to the component depending on future values of control and to the component determined by the system state in time *n*:

$$\hat{y}(n+k \mid n) = \sum h_i \Delta u(n+k-i) + f(n+k) \tag{18}$$

where *f(n+k)* is that component which does not depend on future values of action quantity:

$$f(n+k) = y_n(n) - \sum (h_{k+i} - h_i)\Delta u(n-i) \tag{19}$$

Predicted values within the prediction horizon p (usually *p>>N*) can be arranged to the relation (20):

$$\begin{aligned}&\hat{y}(n+1 \mid n) = h_1 \Delta u(n) + f(n+1)\\ &\hat{y}(n+2 \mid n) = h_2 \Delta u(n) + h_1 \Delta u(n+1) + f(n+2)\\ &\dots\\ &\hat{y}(n+p \mid n) = \sum_{i=p-m+1}^{p} h_i \Delta u(n+p-i) + f(n+p)\quad ,\end{aligned} \tag{20}$$

where the prediction horizon is k=1...p, with respect to m control actions. Regulation circuit is stable if the prediction horizon is long enough. The values may be arranged to the dynamic matrix G:

$$G = \begin{vmatrix} h_1 & 0 & \dots & 0 \\ h_2 & h_1 & \dots & 0 \\ \vdots & \vdots & & \vdots \\ h_p & h_{p-1} & \dots & h_{p-m+1} \end{vmatrix}, \tag{21}$$

and expression used for prediction can be written in the matrix form:

$$\hat{y} = Gu + f \tag{22}$$

Where $\hat{y}$ is a vector of contributions of action quantity and *f* is the free response vector. The objective of DMC controller is to drive the outputs as close to the setpoint as possible in a least-squares sense with the possibility of the inclusion of a penalty term on the input moves. Therefore, the manipulated variables are selected to minimize a quadratic objective that can consider the minimization of future errors:

$$J = \sum_{j=1}^{p}\left[\hat{y}(n+j \mid n) - w(n+j)\right]^2 + \lambda \sum_{j=1}^{m}\left[\Delta u(k+j-1)\right]^2 = \boldsymbol{e}^T + \lambda \boldsymbol{u}^T \tag{23}$$

Where *e* is a vector of future errors within the prediction horizon and *u* is a vector of increments of the action quantity during the control horizon, can be obtained analytically by computing the derivate of *J* and making it equal to 0, which provides the result:

$$u = (G^T G + \lambda I)^{-1} G^T (w - f) \tag{24}$$

Only the first element of vector *u* is really sent to the plant [1]. Next chapter deals with implementation of this algorithm to PLC.

4.1. Implementation

Automation Studio supports all the basic programming languages used in industrial automation according to IEC 61131: Ladder Diagram (LD), Function Block Diagram (FBD), Instruction List (IL), Structured Text (ST), Sequential Function Chart (SFC) and also supports high-level programming languages like Automation Basic, C++ and standard ANSI C. The biggest advantage of Automatic Code Generation affects those developers who already use MATLAB and Simulink for simulation and solutions design and to developers who used to tediously rework implemented structures in a language supported by Automation Studio in the past. In the procedures the Automatic Code Generation tool provided by B&R represents an innovation with endless possibilities that help to productively reform the development of control systems. The basic principle is simple: The module created in Simulink is automatically translated using Real-Time Workshop and Real-Time Workshop Embedded Coder into the optimal language for the B&R target system guaranteeing maximum performance of the generated source code. Seamless integration into an Automation Studio project makes the development process perfect [20]. Automatic code generation eliminates errors that may get introduced with manual coding and helps ensure that the final structured text produces numerical results on the PLC that closely match the results we saw in simulation. Since the tunnel central control system use programmable logic controllers (PLCs) it is suitable for real implementation.

4.2 Model in simulink

Using the model in Simulink the operation of the system was simulate. On the basis of result comparison we can confirm the theory of effectiveness of control [5].

5. Conclusion

The paper presents a methodology that has been used for design parametric models of the road tunnel system. Identification has many aspects and phases. In our work we use the parametric identification of real system using the measured data from the tunnel central control centre. Using of MPC may lead to optimize the control way for chosen criteria. This algorithm can be used in: traffic control system, ventilation system, lighting system or water management. By introducing predictive control it will be made possible to greatly reduce electric power consumption.

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