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Design of control system instrumentation based on structural modeling with criteria of quality of control (QoC) and cost

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Abstract

This paper deals the design of the control system instrumentation. The structural modeling links the physical variables of electric vehicle system in a road slope and ensures good quality of control QoC; where the real speed $v_{t+\delta t}$ is close of $v_{desired}$, despite the influence of disturbance due to the slope of road and the uncertainty of measurements from the sensors. The main contribution of this paper combines the merits of:

i) Study the QoC and the criterion of cost for electric vehicle in a road slope thanks to the quantification of physical variables using the graphical tree representation.

ii) Find the optimal instrumentation that satisfies a good quality of the control QoC with the lowest financial cost.

Keywords: **Control design, System Instrumentation, Structural Analysis, and Quality of Control.**

1. Introduction

Current needs of developing autonomous electric vehicles favor the orientation to offering the solutions of design control instrumentation.

Over the past few years, there has been significant research effort in the design of control system instrumentation [1]-[4]. The objective of designing a good control system is to determine the best control instrumentation scheme, that is to say, a set of sensors and actuators that allows the system to perform its mission despite the disturbance of one or several of its instruments. Reference [1] has presented the design using the function of fault tolerant system using structural analysis. The method of optimization the instrumentation is presented in reference [4] with dependability criteria.

In [5] addresses the problem of co-design of wireless network control system (WNCS). The quality of control (QoC) of system is considered in terms of the quality of service (QoS) of the wireless network which presents an approach of Co-design based on distributed Bayesian networks. This approach allows decisions to ensure good QoC for the mobile vehicle. Here, for our case study of quality of QoC, it concerns the ability to guarantee the performance and robustness of electric vehicle in design phase; Before study the QoC, we will give the specification of parameters that influence the QoC (which are the three sources of disturbances: the variable slope of the road α_t and the uncertainties of the sensors). To study the influence of disturbance on the performance of the system control, we need to fix different intervals of states QoC using the quantization of physical quantities by structural modeling approach.

2. Concept of the control system design

2.1 V cycle

The V cycle is the model of development in different electronics technologies [6] and software [7], it generalizes the development of complex systems, and several authors have shown the interest of the V cycle [8].

Industrial systems are characterized by the result of a combination of sub-system of different technologies, V cycle is the first tool used as a development model, and it has different phases, from requirement and analysis to validation of product [5].

The figure 1 indicates important steps of the development process; it starts by defining the requirements that presents the first step of the V model.

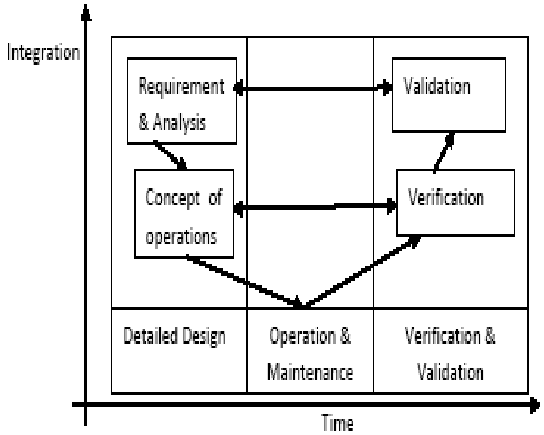

Fig.1 The V model of the process

We are interested in this figure 1 by the first development phase of a system which consists of analyzing the requirements and specifications, the second development phase of the system design, which start by definition of system architecture and hazard analysis (our case disturbance) based on a structural model that describe qualitatively the different relations between the physical variables for electric vehicle.

2.2 Performing control system and its instrumentation.

The instrumentation of a control system is composed by sensors and actuators that allow performing specified missions. These missions are not limited to the control of the process with respect to some specifications and objectives but include also supervision activities.

A controlled system can be modeled by a set of physical variables linked by a set of constraints, that is to say, a set of mathematical relations between these variables. The structural modeling is used to qualitatively represent the interaction between these variables without explicitly knowing the constraints [3]-[4].

The design of hardware control systems is characterized by a lack of available and precise information. Indeed, since this activity takes place early in the design process, a lot of choices are not fixed, such as the maintenance policies, the final choice about the suppliers, device sizing. The precise and accurate performance characteristics of the instruments are often unknown. In this article, the structural model offers an appropriate answer to model a system despite the lack of information.

2.3Architecture of hierarchical control

The architecture of hierarchical control is the vertical decomposition consists in decomposing the complexity of the control law in several hierarchical levels, thus forming a control structure called "multi-layer", the next diagram clearly explains the vertical decomposition of architectures [9].

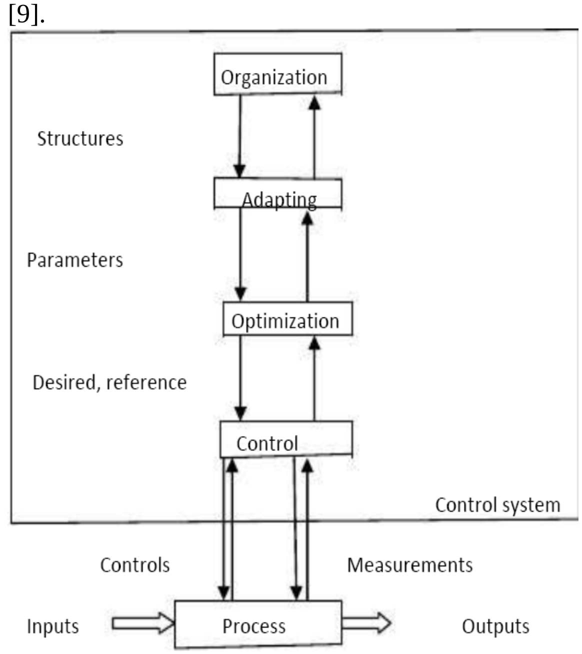

Fig.2 Hierarchical by vertical decomposition

We interest by the step of control dynamical process in figure 2, it allows controlling the various inputs of the process for a predefined objectives (desired performance, disturbance rejection) of the designer. For our case is to control the speed of the vehicle in road slope, in order to follow the real speed $v_{t+\delta t}$ of desired speed $v_{desired}$ despite the disturbance of electric vehicle system.

3. Structural Modeling:

Structural modelling requires a set of physical variables linked by a set of relations. It represents qualitatively the interaction between the variables and constraints. The structural analysis allows some properties such as observability, controllability and monitor ability properties, despite the little information in the model [1]- [4].

A structural analysis can be represented by a bipartite graph [4] which gives a representation of the links between the physical variables Z and constraints F of the process as follows [1]-[3]:

$$S:\{F\} X \{Z\} \to \{0,1,-1\}$$

• $S(f_i, z_i) = 1$ if and only if the variable z_i appears in the constraint fi and if its value can be deduced from the others variables appearing in f_i .

• $S(f_i, z_i) = -1$ if and only if the variable z_i appears in the constraint f_i but its value cannot be deduced from the others variables appearing in f_i .

• $S(f_i, z_i) = 0$ if the variable z_i does not appears in the constraint f_i .

The reason for the choice of structural analysis approach is that this analysis uses a poor knowledge of the system; it uses only the relation between constraints and variables [2].

The structural modelling is easily to construct in design phase. The types of variables in a structural modelling can be divided into [1]-[4], [10]-[14]:

• Known physical variables, from the sensors and actuators, another instruments.

• Physical variables are supposed unknown.

• Modes or states of the system for which the constraints are considered valid.

The types of constraints:

• Those related to physical constraints verified whatever the operating mode of the control system instrumentation.

• Those linking physical quantities and measurement capabilities (from sensor, actuators, ..).

• Those specific to particular modes or states of the system.

4. Formalizing and resolving the optimization problem

4.1 Design and Optimization Process

The design process of a control system consists of finding a first solution of potential hardware architecture; the designer assesses its characteristic (costs, QoC) in order to determine its weak points and the possible improvements. From that, new potential hardware architecture is deduced and the cycle goes on until a satisfactory solution is found according to the several technical and economic multi criteria [4].

The method consists of providing a description of the physical system from which all hardware architecture can be deduced indirectly and automatically, according to the structural analysis. Then, by integrating the constraints about the quality of control QoC and the cost criteria and finally, by solving the optimization problem, the designer obtains the optimal hardware architecture that satisfies the QoC constraints with the lowest cost.

4.2 Specification of QoC Constraints

The objective of design control system is to determine the instrumentation providing a minimal economic cost and level of QoC required. The level of QoC must be specified for each mission or task of control system design.

In this paper, the QoC is defined as the difference between the reference quantity $q_{desired}$ that we want to achieve, and real value of the physical quantity to be controlled q_{real} using structural analysis approach.

$$QoC = \left| q_{real} - q_{desired} \right| \tag{7}$$

The function QoC is consists to fix desired quality of control n. If a physical quantity q is required by a mission of system control instrumentation using the corresponding constraint is:

$$QoC(q) \le n \Rightarrow \begin{cases} QoC(q_1) \le n_1 \\ QoC(q_i) \le n_i \end{cases} \tag{8}$$

$$\Rightarrow \begin{cases} \left| q_{real_1} - q_{desired_1} \right| \le n_1 \\ \left| q_{real_i} - q_{desired_i} \right| \le n_i \end{cases}$$

4.3 Building and Solving of the Optimization Problem

The final optimization problem is obtained by adding the cost criterion to the quality of controls QoC constraints which are deduced from the specification and objectives. This criterion corresponds to a financial cost of the system and it is associated with the sum of the individual costs C_i of the instruments. The optimization problem is consequently given by:

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$$\begin{cases} Min\left(\sum_{1}^{k} C_{qi}\right) \\ \left|q_{real_1} - q_{desired_1}\right| \le n_1 \\ \left|q_{real_i} - q_{desired_i}\right| \le n_i \end{cases} \quad (9)$$

This problem interests to an Integer Linear Programming (ILP) problem which is a standard optimization problem [15]. This problem can be exactly solved by Branch and Bound or Branch and Cut algorithms, also stochastic algorithms such as genetic algorithms [15]. The final result of the optimization phase is to determine the optimal instrumentation systems which satisfy the QoC constraints, a lowest cost.

5. Study of quality control QoC:

We will give here the definition of QoC about the ability to guarantee the performance, and robustness of a control system, we will cite the parameters that influence the QoC :

- The slope α_t of the road (especially in the case of variable road slope.

-the measurement uncertainties of the instruments (the speed sensor $\varepsilon^t{}_v$, the inclinometer $\varepsilon^t{}_I$).

In this work, to evaluate the quality of control QoC , the set of parameters is necessary to allow the evaluation QoC criteria:

- The agreed measures for the instruments used (it is the area of possible variation of the measured quantity (minimum aptitude, maximum aptitude)).

- Thus, the cost of the instrument, it defines the cost of use of the component (installation, maintains,).

5.2 case study:

The considered process of electric vehicle moves on variable road slope, as shown in figure 3.

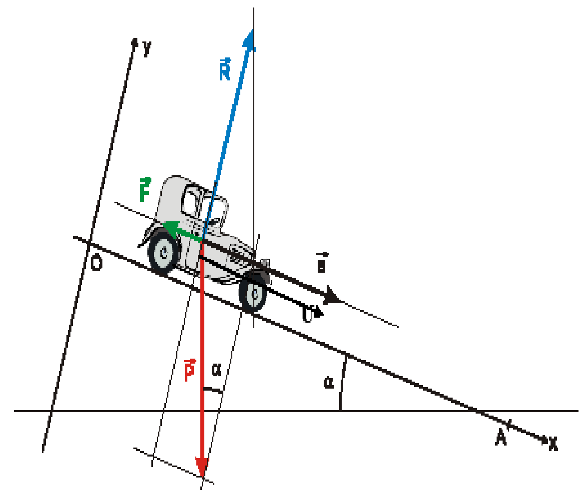

Fig.3 Electric vehicle moves on variable road slope[]

Consider the following variables used in this electric vehicle[2]: α_t, $\alpha_{t-\delta t}$ are the angle of slope, a_t is the total acceleration of the vehicle, a_y is the acceleration of the vehicle projected on the axis y, x_t is the position of the vehicle, $v_{t+\delta t}$, v_t are the speed of the vehicle, $t_{descent}$ is the time of descent the road slope, δt is the period of sampling, u_t is the control signal of the motor, and I_t is the measure given by the inclinometer, Ch the measure given by the chronometer, cv_t is the measure given by the sensor speed, GPS is the measure given by the GPS sensor.

The parameters are defined by [2]:

M is a fixed parameter used in the model and corresponding to the assumed mass of the vehicle, m_t is a real mass quantity of the vehicle, Δm_t is the variation of the mass due to the various transported loads at each trip, $\varepsilon^t{}_V$ is the uncertainty of the measurement error while v_t is the real speed, $\varepsilon^t{}_I$ is the uncertainty of the measurement error of inclinometer, $\Delta\alpha_t$ is the variation of the slope, R is external force of the electrical vehicle: reaction of the road.

The instruments that are available for this electric vehicle are [2]: Electrical motor, speed sensor, GPS sensor, inclinometer to measure the angle of slope, chronometer to measure time.

To study the influence of disturbances (the slope, the uncertainties of the instruments) on the quality of control QoC.

	α_t	$\alpha_{t-\delta t}$	R	a_t	$v_{t+\delta t}$	v_t	x_t	δt	$t_{descent}$	a_y	$\Delta\alpha_t$	u_t	cv_t	GPS	Ch	I_t	m_t	Δm_t	case of slope
f_1				1	1	1		1											variable
f_2	1			1								1							
f_3						1							1						
f_4							1							1					
f_5	1															1			
f_6	1		1							1									constant
f_7				1			1		1										constant
f_8	1	1									1								variable
f_9						1	-1												constant
f_{10}									1						1				constant
f_{11}								1							1				variable
f_{12}																	1	1	

Table 1: The global incidence matrix for electric vehicle system [3]

We will determine the different interval of different states of QoC according to this criterion:

$$QoC = \left| v_{t+\delta t} \quad - v_{desired} \right| \qquad (1)$$

The classification of variables used in the application:

- Two disturbances; slope α_t and the uncertainties of speed sensor ($\varepsilon^t{}_v$ =2.10^{-3}) and the inclinometer ($\varepsilon^t{}_I$ =2.10^{-3}).

- The table 2 gives intervals definition of variables, we chose arbitrarily the costs associated to each sensor and actuators are: Ci_u a cost for a motor, Ci_{Cv} a cost for speed sensor, Ci_I a cost for inclinometer.

Number of instrumentation		1	2	3	4	5	6	7	8	9	10	11	12	13
Data parameters	cv_t	14.999	9.999	7.999	13.999	12.999	16.999	17.999	5.999	15.499	16.999	16.199	15.899	16.009
	I_t	4.398	8.798	9.998	2.198	3.998	5.998	8.998	0.998	3.298	3.998	3.498	2.999	3.998
	u	210	240	250	150	170	200	240	270	200	240	230	240	240
The cost	Ci_{Cv}	3	4	2	3	4	5	6	3	5	4	5	3	4
	Ci_I	2	3	2	3	2	4	5	4	4	3	4	4	4
	Ci_u	10	11	10	10	11	14	13	20	10	11	12	15	15

Table 2: The 13 set of instrumentation: data parameters, cost[1]

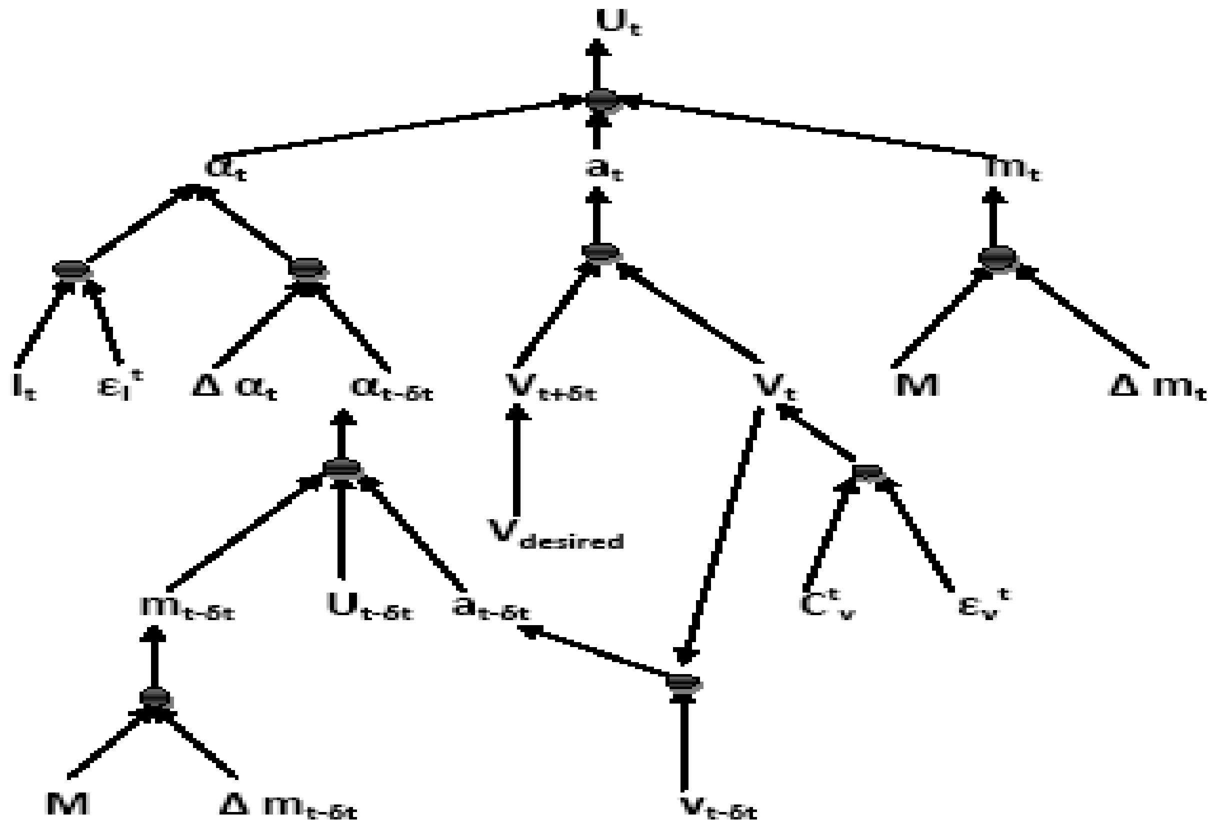

Fig.4 The different paths of the control u_t with several disturbance of electric vehicle system[3]

From the tree description of the system (in figure 5), we can quantify $v_{t+\delta t}$ the speed $v_{desired}$, (the reference) equal 16km/h, according to the graphical representation and by Translating the branch (figure 5) that links the variables of electric vehicle model:

$$v_{t+\delta t} = g\sin(\alpha_t) - \frac{Fr}{m} + \frac{u_t}{m} + v_t \qquad (7)$$

Knowing that c^t_v is the measured speed provided by speed sensor and I_t is the measured slope provided by inclinometer, with $I_t = \alpha_t + \varepsilon^t_I$ and $C^t_v = v_t + \varepsilon^t_v$, the friction of the road $\vec{F}$ is 100N, the air resistance is 50N, so the equation 7 becomes:

\

$$v_{t+\delta t} = g\sin(I_t - \varepsilon^t_I) - \frac{Fr}{m} + \frac{u_t}{m} + (c^t_v - \varepsilon^t_v) \qquad (8)$$

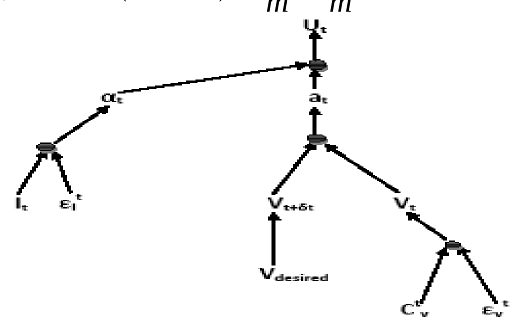

Fig.5 The branch of $v_{t+\delta t}$

Fig.6 shows that the structural analysis is an important tool for the approximation of a unknown physical quantity, in our case we controlled the speed $v_{t+\delta t}$ to maintain the desired speed $v_{desired}$ equal 16 km/h.

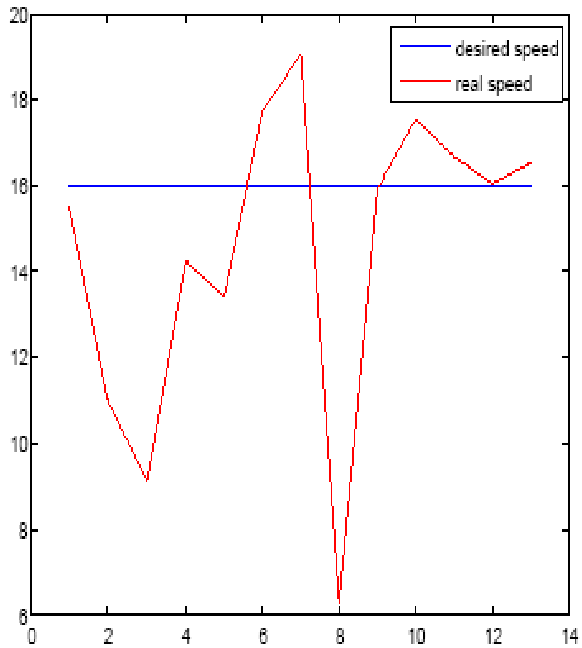

Fig.6 The approximation of speed $v_{t+\delta t}$ using structural analysis

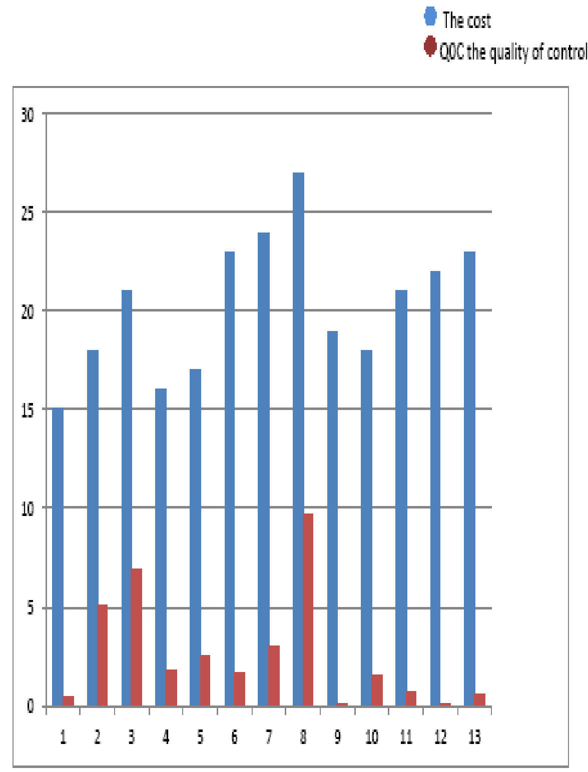

Fig.7 The histogram of quality of control QoC and cost using structural analysis

Applying the optimization problem presented in equation 9, and the value of the quality of control desired QoC equals 8. 10^{-2}. we obtain:

$$\begin{cases} Min\left(Ci_{final}\right) = Min\left(Ci_{C_v} + Ci_I + Ci_U\right) \\ \left|v_{t+\delta t_1} - v_{desired_1}\right| \le 8 \cdot 10^{-2} \\ \left|v_{t+\delta t_i} - v_{desired\, i}\right| \le 8 \cdot 10^{-2} \end{cases} \quad (14)$$

We have been able tracing the evolution of the cost (Ci_{final}) and the quality of control QoC, is shown in Fig. 7:

We discuss the state of quality of control according to the value of QoC as follows:

-QoC is good, if QoC ∈ [0 , 1 [

-QoC is degraded, if QoC ∈ [1, 3 [

-QoC is bad, if QoC ∈ [3 , 10[

From the result is shown in the figure 7, we obtained 13 pairs composed by two columns of colors red and blue, representing the cost of instruments and quality of control (QoC) respectively.

The pair 12 shows as An optimal case: good quality of control 0.067 near zero QoC ∈ [0 , 1[with cost equals 22.

6. Conclusion

In this paper, the structural modeling describes qualitatively different relations linking the physical quantities of electric vehicle moves a road slope and ensure a good quality of control QoC where the real speed $v_{t+\delta t}$ is close of $v_{Desired}$.

The influence of disturbance on the QoC system is usually due to the slope and the uncertainty of measurements from the sensors. The method considers a design problem through a little information on a database (the equations and relations). In this work, this method aims to find the optimal set of instruments according to good QoC, a lowest cost.

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