Map-Based Active Compensation of Lateral Vibrations in Elevators

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Abstract. Lateral vibration in elevators has an important effect in the comfort levels perceived by the passengers. This phenomenon is highly affected by the geometry of the guide rails and the load distribution of the car. In this connection, irregularities in the former behave as perturbations that excite the oscillation of the vehicle. The effect is more and more important as the speed of the elevators increase, which is the current trend in the industry. In order to improve the performance of medium and high speed elevators, the present paper describes a method for compensating the lateral oscillations appearing in an elevator due to the irregularities of the guide rails. The proposed approach makes use of a mapping algorithm developed by the authors for identifying, learning and efficiently storing the geometrical configuration of the rails as a combination of straight line segments. The system is conceived for active roller guides, whose position can be continuously controlled in order to dampen the oscillations of the vehicle and to compensate the perturbations caused by the geometry of the guide rails.

In order to develop the system and validate its performance, a 2D virtual environment in Matlab Simulink © is used. This environment includes the geometry of the guides and the main elements of the elevator affecting the horizontal oscillation: inertial parameters (mass, inertia), stiffness of the roller guides, among others. The present analysis does not take into account the oscillations caused by the traction rope or the movements of the load inside the cabin.

The results of the proposed method show the improvement that can be obtained in the ride quality of the elevator by mapping the geometry of the guide rails and properly using this information for compensating the identified irregularities by active roller guides.

1 INTRODUCTION

Lateral vibration is an important source of discomfort in lifts. As described in [1] and [2], these oscillations are mainly caused by low frequency oscillations from the suspension cables or asymmetric load placing; high frequency oscillations due to the guide rails, aerodynamic turbulence around the car or the movement of the passengers inside the cabin. The present work focuses on reducing the effect of irregularities in the geometry of the guide rails. To do that, a combination of three technologies is proposed: perturbation observers for recognizing the geometry of the guide rails, mapping algorithms for storing it in an efficient way, and active vibration controllers using that information for damping the oscillations.

The estimation of the guide rail geometry is not a new topic and several approaches can be found in the bibliography. [3] describes a method for characterizing the profile of a guide by integrating the information from accelerometers placed on the lift and merging that information with the relative displacements measured at the rolling guides. The further work [4] uses the obtained profile for active vibration control. [5] describes specific procedures for production validation of guide rails, although these techniques are not intended for elevators in normal operation. The proposal in the present paper utilizes the approach described in [6]. It uses stochastic perturbation observers for identifying the irregularities in the guide rail profiles and merges the information in a map. This method allows for a reduction in the amount of data to be stored, and minimizes the number and quality of the sensors as the identification is improved in consecutive measurements.

The information stored in the map is used for compensating the irregularities of the guide rails therefore reducing the lateral oscillations. Other damping techniques in the literature normally lay in one of the following categories: passive, active and semi-active vibration control. The first one relies on the use of passive elements like springs or dampers for modifying the dynamic response of the lift. In contrast to that, active vibration control systems use actuators that can both dissipate and enter power into the system. In the literature interesting active approaches can be found using different technologies: roller guides isolation systems based on magnetic actuators are described in [7], linear actuators are selected for the same sort of application in [8]. Due to their higher cost, the active vibration control systems are currently restricted to high price elevators. Semi-active vibration control technology is an intermediate solution and it is based on modifying in real time the dynamic parameters of the lift, like the effective stiffness or damping [9]. The present paper uses an active vibration control with a feedforward compensation based on a map of the guide rails in combination with a sky-hook feedback.

The present paper is organized as follows: the description of the installation and its mathematical representation is done in the section 2; the proposed architecture appears in section 3; and finally, sections 4 and 5 summarize the results of the virtual validation and the conclusions.

2 DESCRIPTION OF THE REFERENCE INSTALLATION

The algorithms described in the present paper are validated in a virtual model based on the installation available at ITAINNOVA (figure 1) and described in [10].

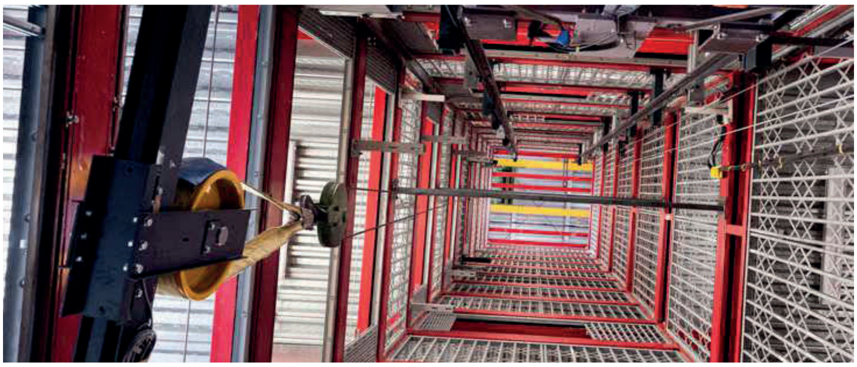

Figure 1. Installation at ITAINNOVA for elevator tests

2.1 Mathematical representation

The following work uses a 2D state-space representation of the installation (figure 2):

$$\dot{x} = Ax + Bu \tag{1}$$

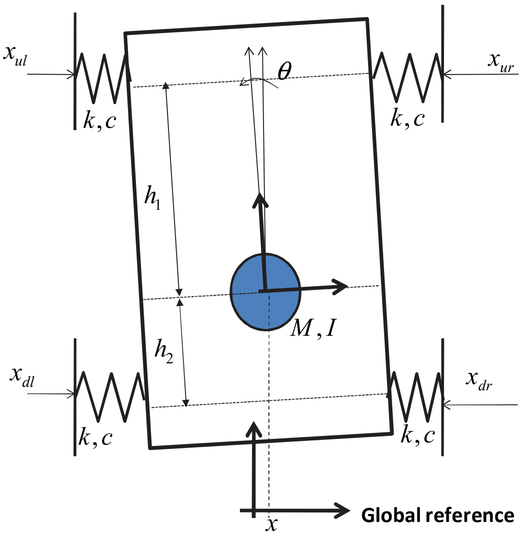

Figure 2. Main parameters of the elevator representation

Where,

$$\boldsymbol{x}=\begin{pmatrix} x \\ \dot{x} \\ \theta \\ \dot{\theta} \\ x_{dl} \\ \dot{x}_{dl} \\ x_{dr} \\ \dot{x}_{dr} \\ x_{ul} \\ \dot{x}_{ul} \\ x_{ur} \\ \dot{x}_{ur} \end{pmatrix};\boldsymbol{u}=\begin{pmatrix} \ddot{x}_{dl} \\ \ddot{x}_{dr} \\ \ddot{x}_{ul} \\ \ddot{x}_{ur} \end{pmatrix};\boldsymbol{B}=\begin{pmatrix} 0&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\\0&0&0&0\\1&0&0&0\\0&0&0&0\\0&1&0&0\\0&0&0&0\\0&0&1&0\\0&0&0&0\\0&0&0&1 \end{pmatrix};\boldsymbol{A}=\begin{pmatrix} \boldsymbol{A}_{11} & \boldsymbol{A}_{12} \\ \boldsymbol{A}_{21} & \boldsymbol{A}_{22} \end{pmatrix}$$

$$\boldsymbol{A}_{11}=\begin{pmatrix} 0 & 1 & 0 & 0 \\ -4k/M & -4c/M & 2k(h_1-h_2)/M & 2c(h_1-h_2)/M \\ 0 & 0 & 0 & 1 \\ 2k(h_1-h_2)/I & 2c(h_1-h_2)/I & -2k(h_1^2+h_2^2)/I & -2c(h_1^2+h_2^2)/I \end{pmatrix}$$

$$\boldsymbol{A}_{12}=\begin{pmatrix} 0&0&0&0&0&0&0&0\\ k/M & c/M & -k/M & -c/M & k/M & c/M & -k/M & -c/M \\ 0&0&0&0&0&0&0&0\\ kh_2/I & ch_2/I & -kh_2/I & -ch_2/I & -kh_1/I & -ch_1/I & kh_1/I & ch_1/I \end{pmatrix}$$

$$A_{21} = \mathbf{0}_{8x4}; A_{22} = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{2}$$

Table 1 contains the main parameters of the representation in (1) and (2).

Table 1. Summary of parameters

M (kg)	I (km.m^2)	h_1 (m)	h_2 (m)	k (N/mm)	c (N.s/m)
1220	200	1.9	0.6	416	1e4

3 ARCHITECTURE

The proposed architecture appears in figure 3. The control system recovers information from the sensors in the elevator and estimates the geometry of the guides storing it in a stochastic map. This information is used by the Active Vibration Control (AVC) for commanding the active rolling guides and damping the oscillations.

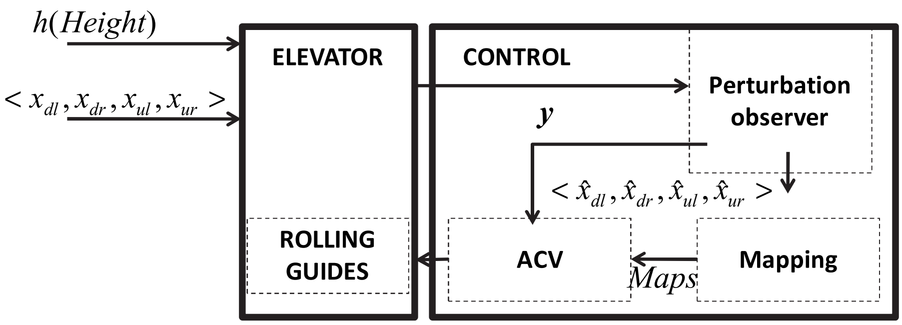

Figure 3. Architecture of the system

The following subsections describe the different modules in the controller.

3.1 Perturbation observer

The perturbation observer identifies the geometry of the guide rails by the sensors installed on the lift (the compression of the rolling guides and the speed at the top and the bottom of the lift). The observer uses a Kalman filter with a discrete representation of the system for predicting the state $\hat{\boldsymbol{x}}_p$ at each instant $k+1$ (sample time τ):

$$\begin{aligned} \hat{\boldsymbol{x}}_{p,k+1} &= (\boldsymbol{I}_{12x12} + \boldsymbol{A}\tau)\hat{\boldsymbol{x}}_k + \boldsymbol{p}_u \\ \boldsymbol{C}_{p,k+1} &= \boldsymbol{A}\boldsymbol{C}_{e,k}\boldsymbol{A}^t + \boldsymbol{C}_u \end{aligned} \tag{3}$$

Where $\boldsymbol{I}_{12x12}$ is the identity matrix of size 12, and $\boldsymbol{p}_u$ is the perturbation vector of mean zero and covariance $\boldsymbol{C}_u$. $\boldsymbol{C}_e$ refers to the uncertainty of the previously estimated state. As observed, the equation (3) does not contemplate the inputs $\boldsymbol{u}$ (second derivative of the guide rail profile in (1)) and therefore assumes a high uncertainty $\boldsymbol{C}_u$ in the prediction. The subindex p makes reference to predicted value, in contrast to the estimated one $\hat{\boldsymbol{x}}_e$ done with the sensor measurements:

$$\begin{aligned}\boldsymbol{K}_{k+1} &= \boldsymbol{C}_{p,k+1}\boldsymbol{C}^t\left(\boldsymbol{C}\boldsymbol{C}_{p,k+1}\boldsymbol{C}^t + \boldsymbol{C}_s\right)^{-1}\\ \hat{\boldsymbol{x}}_{e,k+1} &= \hat{\boldsymbol{x}}_{p,k+1} + \boldsymbol{K}_{k+1}\left(\boldsymbol{y} - \boldsymbol{C}\hat{\boldsymbol{x}}_{p,k+1}\right)\\ \boldsymbol{C}_{e,k+1} &= \left(\boldsymbol{I} - \boldsymbol{K}_{k+1}\boldsymbol{C}\right)\boldsymbol{C}_{p,k+1}\end{aligned} \quad (4)$$

The estimated state $\hat{\boldsymbol{x}}_{e,k+1}$ contains the profile values of the guides as it appears in the equation (2). The matrix $\boldsymbol{C}$ makes reference to the measurement equation associated to the sensors.

- Speeds measured by two accelerometers at the level of the lower and higher rolling guides:

$$\begin{pmatrix}\dot{x}_l\\ \dot{x}_h\end{pmatrix} = \boldsymbol{y}_1 = \begin{pmatrix}0 & 1 & 0 & h_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 1 & 0 & -h_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\end{pmatrix}\boldsymbol{x} = \boldsymbol{C}_1\boldsymbol{x} \quad (5)$$

- Compression in the four rolling guides:

$$\begin{pmatrix}\Delta x_{dl}\\ \Delta x_{dr}\\ \Delta x_{ul}\\ \Delta x_{ur}\end{pmatrix} = \boldsymbol{y}_2 = \begin{pmatrix}-1 & 0 & -h_2 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 1 & 0 & h_2 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0\\ -1 & 0 & h_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0\\ 1 & 0 & -h_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0\end{pmatrix}\boldsymbol{x} = \boldsymbol{C}_2\boldsymbol{x} \quad (6)$$

3.2 Mapping the guide rail geometry

Figure 4 shows the algorithm used for obtaining the map. It is a list of segments characterized by the starting height (h_0), the initial position of the guide (x_0), the slop (m) and the length (l).

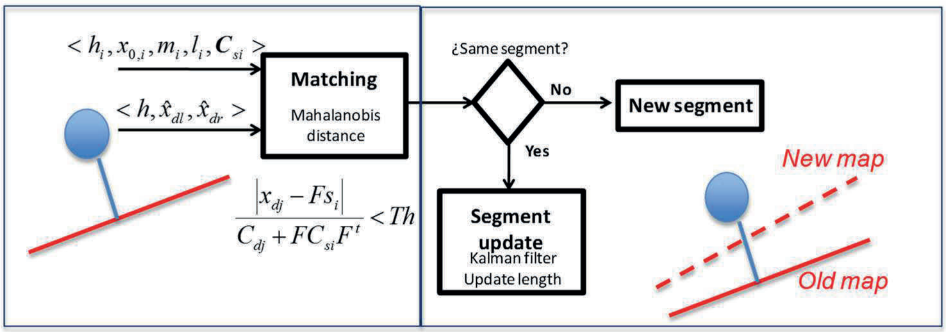

Figure 4. Mapping algorithm

In the following, an example of the mapping process is given. So, given a segment i in the map:

$$x_i = x_{0,1} + m_i\left(h - h_{0i}\right) \quad (7)$$

When a new point of the guide rail profile x_{di} ($j=l,r$) is obtained from the perturbation observer it is decided if it is part of a segment i by using the Mahalanobis distance:

$$\frac{\left|x_{dj} - Fs_i\right|}{C_{dj} + FC_{si}F^t} < Th \quad (8)$$

And by comparing the current height with the length of the segment in the map:

$$((h_{0i} - h > 0)AND(h_{0i} - h < Th_L))OR$$
$$((h - h_{0i} - l_i > 0)AND(h - h_{0i} - l_i < Th_L)) \quad (9)$$

Th_L and Th are positive thresholds. C_{dj} is the uncertainty of the estimation from the perturbation observer (extracted from the covariance $\boldsymbol{C_e}$ in (4)), and C_{si} is the uncertainty of the segment parameters in the map (x_0, m). The measurement function is defined as:

$$\boldsymbol{F} = (1 \quad h - h_{0i})$$
$$\boldsymbol{s}_i = \begin{pmatrix} x_{0i} \\ m_i \end{pmatrix} \quad (10)$$

If the distance is too large, then it is considered as a new segment and it is included in the map list. Otherwise, the segment i is updated with the new point by using a Kalman filter. In this case the estimation at instant k is done with the parameters stored in the map for the segment i $< \boldsymbol{s}_{i,k}, \boldsymbol{C}_{si,k} >$:

$$\hat{\boldsymbol{x}}_{dj,map} = \boldsymbol{F}\boldsymbol{s}_{i,k}$$
$$\boldsymbol{K}_{s,k+1} = \boldsymbol{C}_{si,k}\boldsymbol{F}^t\left(\boldsymbol{F}\boldsymbol{C}_{si,k}\boldsymbol{F}^t + \boldsymbol{C}_{dj}\right)^{-1}$$
$$\boldsymbol{s}_{i,k+1} = \boldsymbol{s}_{i,k} + \boldsymbol{K}_{s,k+1}\left(\hat{\boldsymbol{x}}_{dj,po} - \boldsymbol{F}\boldsymbol{s}_{i,k}\right)$$
$$\boldsymbol{C}_{si,k+1} = \left(\boldsymbol{I} - \boldsymbol{K}_{s,k+1}\boldsymbol{F}\right)\boldsymbol{C}_{si,k} \quad (11)$$

Where, $\hat{\boldsymbol{x}}_{dj,map}$ is the predicted profile from the map.

3.3 Active vibration control

The proposed algorithm for active vibration control appears in figure 5. It has two components:

- The lift position and vertical speed is used for estimating the geometry of the guide rails with the built map (section 3.2). The irregularities are compensated by modifying the preload level at the rolling guides.
- A sky-hook term is added for increasing the damping of the system. It adds a force proportional to the negative value of the elevator lateral speed at each rolling guide.

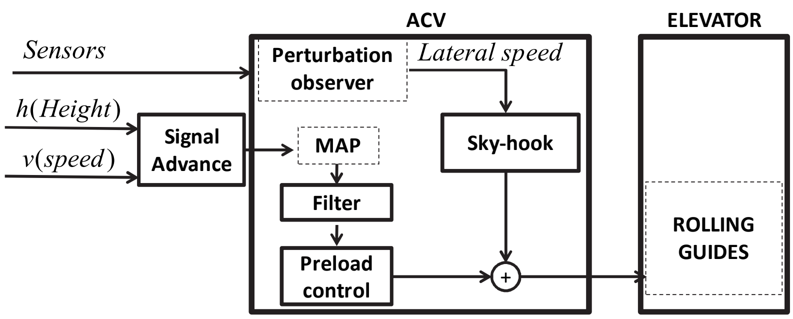

Figure 5. AVC algorithm

The signal advance is used for compensating possible delays in the map representation, which is less and less important as the sampling time of the controller (1kHz in the tests below) or the response time of the elevator to the perturbation increases. The filter is used for avoiding too fast compensation commands that could damage the actuation system or cause impacts.

4 VIRTUAL VALIDATION OF THE SYSTEM

The following test is done at 1 m/s speed in an installation of 18 m height. The lift identifies the map by arranging a cycle upwards and downwards (figure 6). After that, the AVC is activated and the lift arranges other two cycles of lower range.

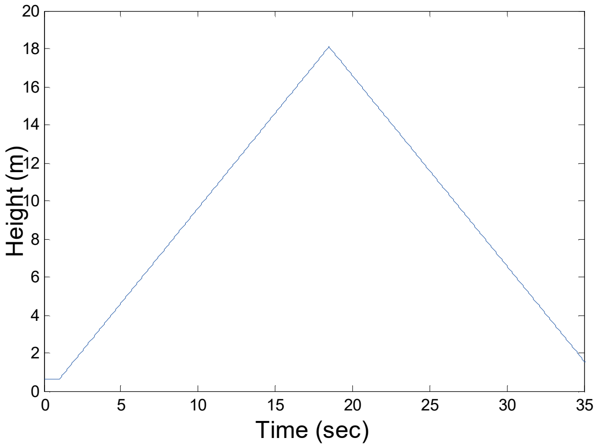

Figure 6. Movement of the lift during the mapping phase

Figure 7 shows the displacement of the lift and the identified geometry of the guide rails.

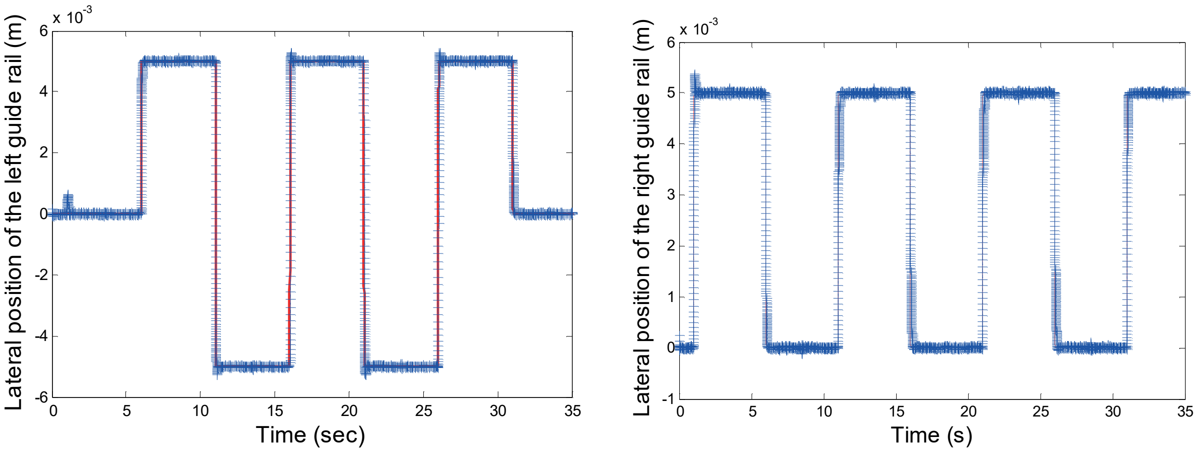

Figure 7. Identified geometry of the guides

At the sight of the results, the perturbation observer obtains a good approximation of the geometry. As the number of points to store is high, the mapping module merges them into a linear representation. Figure 8 shows the result:

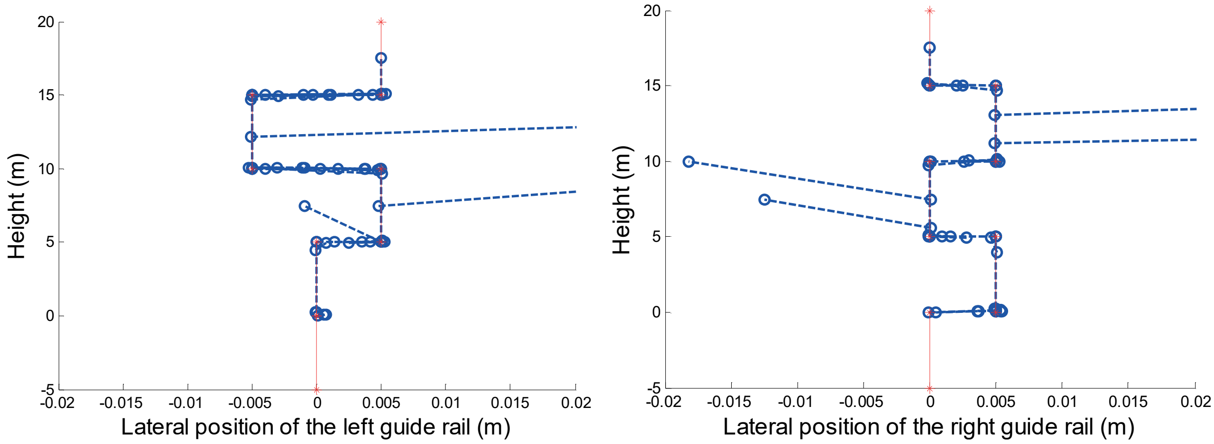

Figure 8. Estimated map (the dashed lines with circles shows the map)

The result shows that the algorithm can merge the geometry in segments with a clear correspondence with the real geometry. As observed in the figures, the map contains some segments without a clear correspondence with the real geometry. This is caused by bad matchings due to noisy measurements. Nevertheless, as there are more segments correctly identified in the region this is not really a problem. Given the high uncertainty of these segments, it is easy to distinguish the good ones from the bad ones. In order to choose the best estimation for the AVC two main approaches have been evaluated:

- The estimation with lowest uncertainty from the different segments in the map is used.
- A weighted estimation considering the uncertainty obtained with the different segments:

$$\hat{x}_{ij} = \frac{\sum_{k=1}^{segments} \frac{1}{C_{ij,k}} \hat{x}_{ij,k}}{\sum_{k=1}^{segments} \frac{1}{C_{ij,k}}} \tag{12}$$

In the final implementation, the first approach is used. Figure 9 shows the matching of the estimation with the real value.

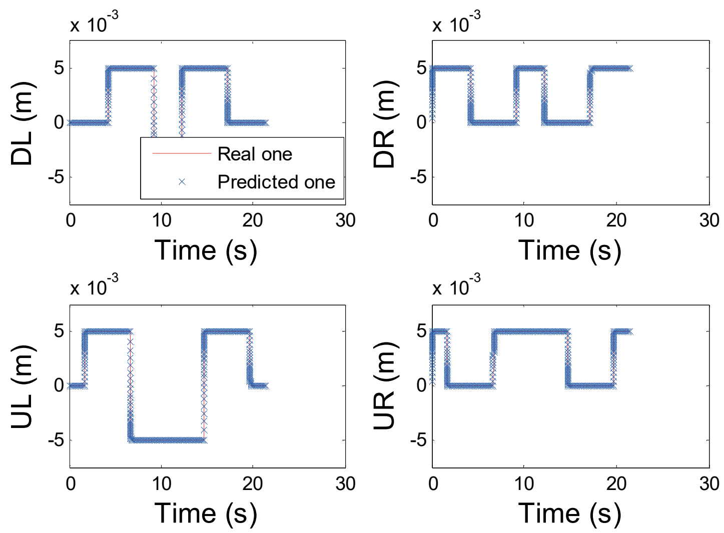

Figure 9. Estimated perturbation in real time using the previously identified map

Figure 10 shows the perturbations at the elevator due to the geometry of the guides in two consecutive cycles of 15 m at 1m/s, first one without AVC and the second one with AVC. As it can be observed, the movement of the active guides compensates the irregularity of the geometry and reduces the perturbation magnitude that arrives at the elevator.

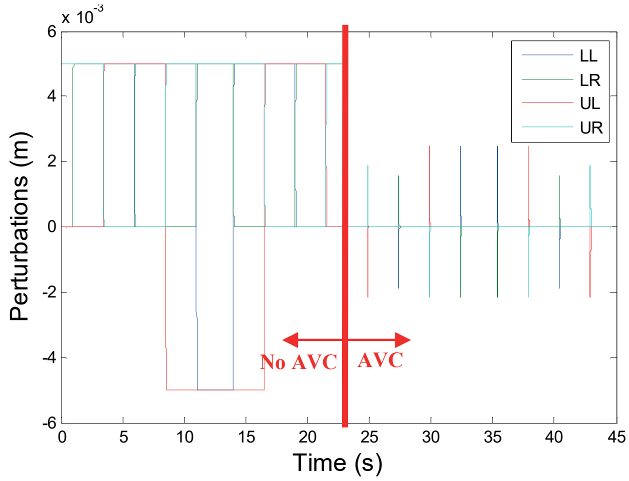

Figure 10. Perturbation entering the system

The resultant damped and short perturbations are well below the response time of the system (figure 11). The use of the proposed AVC results in a clear reduction in the speed levels of oscillation (right), and almost no lateral movement (left):

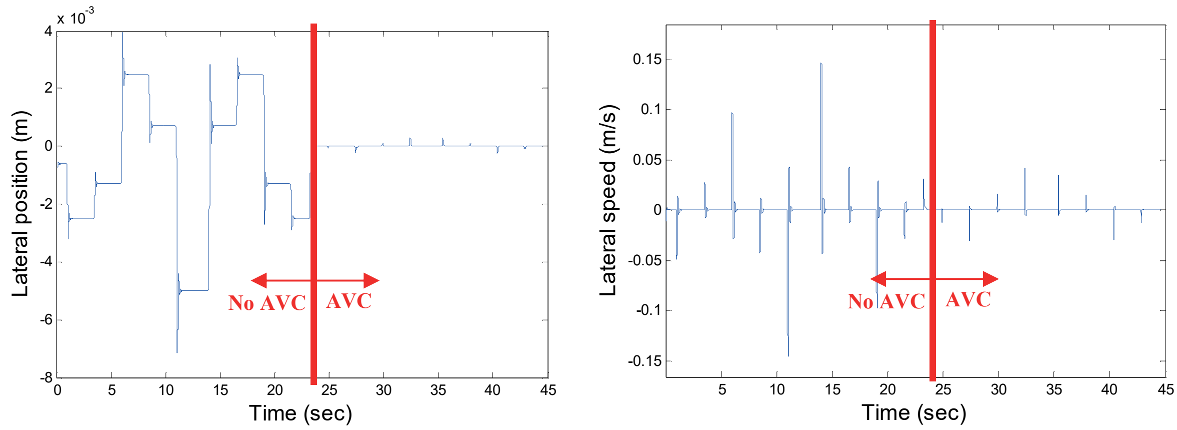

Figure 11. Response of the system when using the AVC

5 CONCLUSIONS

The present paper describes an Active Vibration Controller for compensating the horizontal oscillations caused by irregularities in the guide rails. It continues the work in [6] for mapping the geometry of the guide rails and it uses that algorithm for developing a feedforward command to the preload level at the rolling guides so that it compensates the perturbations that reach the lift. In order to damp the remaining oscillations the controller also includes a sky-hook compensator. The algorithm has been tested by simulation and shows reductions in the maximum speed of around 70%.

The description in the present report represents a proof of concept based on simulation. The results show promising capabilities of the technology and it is expected to implement it in real installations. In order to do that, there are improvements that can still be evaluated, like arranging mapping and compensation at the same time.

6 ACKNOWLEDGEMENTS

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BIOGRAPHICAL DETAILS

Raúl Monge took his degree in Industrial Engineering in 2001 at the University of Zaragoza. He joined ITAINNOVA in 2005 where, among other activities, he has worked on design and experimental validation of different parts for the elevator industry. He is currently project responsible.

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José Manuel Rodríguez obtained his PhD in Informatics and System Engineering from the University of Zaragoza, Spain, in 2012. Previously, he received the MEng and MS degrees in industrial engineering in 2002 and 2007 respectively. He is currently working at ITAINNOVA as R&D engineer and project responsible. His research interests are: nonlinear control algorithms and autonomous navigation.