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Empirical approach for real-time estimation of air flow rates in a subway station

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ABSTRACT

The EU-funded project called SEAM4US (Sustainable Energy mAnageMent for Underground Stations) is targeted to define advanced control systems for cost-effective management of subway stations, which will be applied to the pilot "Passeig de Gracia" station of the metro network in Barcelona (Spain). To this aim, the environmental conditions of the station must be monitored in real-time. In particular, this paper focuses on the challenge of air flows estimation because this is one of the most critical yet tough variables to be monitored: expensive and intrusive measurement methodologies cannot be used extensively. So a novel methodology, based on the use of ordinary measurement probes and analytical methods and capable of identifying in real-time the intensity and dynamics of ventilation that is taking place, will be suggested. The information deriving from real-time measurements and analyses will be used to dynamically adjust the mechanical ventilation burden, that is currently relying on the station's air supply system, thanks to the adoption of intelligent control systems. Our study is based on both a measurement survey carried out in the aforementioned station and numeric analyses.

1. Introduction

Metro stations are usually serviced by various kinds of equipment involving conditioning, ventilation, safety and security, lighting, vertical transportation and horizontal passenger transfer, gates and ticketing machines, information points and auxiliary systems. The optimal operation of these subsystems would have a big potential impact because, although a relatively small percentage of energy can be saved, it would represent large energy saving in absolute terms. One third of a transportation network's energy is required for operating the subsystems of subway stations and their surroundings. Hence, even a small fraction of non-traction energy savings in underground transportation scenarios would produce relevant energy saving figures in absolute terms (Anderson et al., 2009).

The research step presented in this paper is part of the EU project SEAM4US (Sustainable Energy mAnageMent for Underground Stations) (SEAM4US, 2011), which aims at achieving energy saving in subway stations through automatic control applied to the operation of the station's systems. The SEAM4US control approach will be assessed in the metro station "Passeig de Gracia" (PdG) in Barcelona (Spain). In this paper, the applicability and suitability of cost-effective technologies for real-time measurement of air flow rates are examined, even in the presence of disturbances, in order to support predictive control of the mechanical ventilation system. Such an opportunity derives from the awareness of the station's microclimate context, which might be exploited to avoid unnecessary mechanical air supply, should other sources be available, such as natural ventilation. This feature constitutes one of the sources of alternative energy because one can take advantage of the air exchange determined by such dynamics in order to alleviate the operation of mechanical ventilation. Hence, all the favorable events determined by interactions between indoors and outdoors might be exploited.

For this reason, the SEAM4US approach shall overcome fixed schedules of the operation of equipment pieces based on maximum design occupancy assumptions (Gyalistras et al., 2010), thanks to an integrated predictive and adaptive control (Oldewurtel et al., 2010). This control will work on the basis of a model of the station's dynamics and the solution for an

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Nomenclature

p	air pressure, Pa
P	air pressure after filtering seasonal trend, Pa
f	friction factor
L	length, m
D	hydraulic diameter, m
ρ	density, kg/m^3
v	speed, m/s
ε	roughness, m
Re	Reynolds number
g	acceleration due to gravity, m/s^2
z	elevation above the ground level, m
δ	computational distance from edge, m
μ	frictional velocity, m/s
A	autoregressive matrix with entries α
L	lag operator
r	stochastic error
γ	1D array with coefficients of exogenous vector
y	endogenous variable
x	exogenous variable
p'	air pressure differences, Pa
α	coefficients for endogenous variables
v'	squared air speed, (m/s)^2

Subscripts

tot	total
max	maximum value
t	current time
w	wall

optimization problem to determine the optimal control inputs (Giretti et al., 2012). More specifically, what the Model Predictive Control (MPC) framework SEAM4US is aiming to is shown in Fig. 1. At each control step, presumably equals to 1 h, the "controller unit" will send inputs (array u) to the PdG station, in order to manipulate the parameters (e.g. frequency that drives injector fans in the case of mechanical air supply) affecting indoor comfort levels. The real conditions experienced in the station will be continuously retrieved by means of the output array y, which includes the station's power consumption and indicators for comfort and health that must be controlled in order to reach certain reference levels. The relation between inputs and outputs is also significantly affected by a set of disturbances (d), such as weather, train arrival, passenger flows and fans external to the station: they cannot be manipulated but only "accounted for" by using direct measures, whenever possible, together with a disturbance model. At each control step the controller must evaluate in advance what is the best control policy for the next time step to be applied. To this aim it is supported by a model of the station: the state estimator (or "prediction model"), which receives candidate input sequences (u') picked out by the controller; disturbance predictions come from disturbances models (d') and measured variables (m) from sensors installed inside PdG-L3. These measurements are of huge importance, because they inform the prediction model about the current situation in the station, so as to make its estimation about future states more accurate. Given the listed inputs, the state estimator predicts the output sequence (y') which becomes an input for the controller unit. The optimal control sequence (u) is the outcome of the prediction model and represents that array which minimizes a given cost function while complying with given constraints. Once the optimization problem has been solved, the first step of the optimal sequence is applied as the best control action. The overall procedure is repeated at each step, thus closing

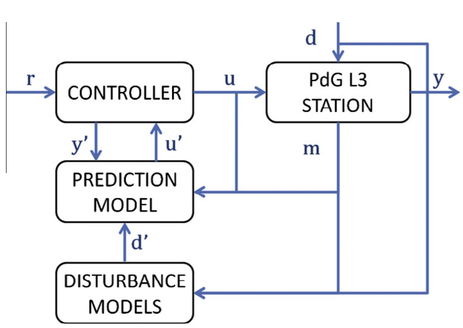

Fig. 1. Control framework in SEAM4US.

the control loop. Hence the implementation of this control framework asks for the development of devices and services:

1. Monitoring systems and intelligent algorithms to estimate current state of PdG station and to interpret occupant's behavior.
2. High-level control systems capable of solving optimization problems in real-time.
3. Accurate and fast dynamic models of buildings' behavior and their systems, necessary to feed the high-level control systems (i.e. to generate the predicted output sequence y').
4. Accurate modelling of disturbances (e.g. occupancy, weather conditions, etc.).

For this reason, the presence of a real-time monitoring layer is critical for the system to be adaptive, that is to say, to adjust its performances according to the actual context, that is the service listed in bullet 1 of the items above. Recently, the availability of pervasive sensor networks made the monitoring of the dynamics of an indoor environment feasible, thus allowing the implementation of complex anticipatory optimal control policies (Mahdavi et al., 2009). Among the environmental variables to be tracked, the estimation of ventilation flows through entrances is very critical and difficult to perform. Indeed, it would help determine at what extent it can relieve the mechanical ventilation burden, which would be an important contribution to energy saving. When dealing with environmental monitoring, there are at least two critical aspects:

- Estimation of "meaningful" environmental parameters which are relevant to infer the physical behavior of the station.
- Installation of non-invasive and cost-effective measurement tools, not interfering with the operation of the subway station.

When the overall air changes must be measured in real-time, few raw measures would not be sufficient, and invasive sensor grids across corridors would not be feasible. So this research suggests that air flow rates can be estimated by intercepting relevant fluxes through duct-shaped rooms, like corridors. This is because air flows through corridors before entering the platform and other crowded rooms. Corridors represent "junctions" linking the several rooms. Furthermore, corridors have a long-limbed layout that generate regular airflows with parallel streamlines, few vortexes and little turbulence. However, during opening hours such measurements are disturbed by the presence of people, the pressure waves