Extending the 4-Variable Approach to Cyber-Physical Systems: A Practical Experience

Leo Ordinez[1], Omar Alimenti[1], Emilia Rinland[2], Marisa Gómez[2], Jorge Marchetti[3]

[1] Dpto. de Ing. Eléctrica y de Computadoras
Universidad Nacional del Sur
IIIE - CONICET
lordinez@uns.edu.ar, iealimen@criba.edu.ar
[2] Dpto. de Agronomía
Universidad Nacional del Sur
CERZOS - CONICET
merinland@cerzos-conicet.gob.ar, marisa.gomez@uns.edu.ar
[3] Dpto. de Física
Universidad Nacional del Sur
IFISUR - CONICET
jmarchetti@uns.edu.ar

Abstract. Cyber-physical systems are a new research discipline that involves many areas. The key concept behind this discipline has to do with a strong interaction between the physical world and a computing system, which should be transparent to an external observer. Thus, it cannot be determined whether the system's behavior is due to the influence of the environment or the actions of the computing system. In this paper, a requirement analysis approach for these systems is presented. It is called 3D Approach and it is based on the well-known 4-Variable Model. The 3D Approach came out as the result of systematizing practical experiences taken from the design of a biodigester.

1 Motivation

Renewable energies utilization is of great importance for contemporary society, due to seek for independence from oil and oil derivatives. The rising prices for crude oil and environmental damages have marked the necessity of having a sustainable and renewable energy. Furthermore, the ecological advantages of renewable energies, such as diminishing greenhouse effect gases, make them a very valuable fuel. Likewise, problems associated with organic waste such as household garbage, animal manure, harvest residues, etc., requires solutions that minimize the environmental impact, maximizing its potential benefit.
The cultivated onion area in the Patagonian Protected Region varies annually between 8500 and 12000 hectares. According to statistics of Fresh Onions Certification program carried out by Zoophytosanitary Patagonian Foundation Barrier (FunBaPa) [1], during the first five months of

2008, onion exports from that region reached 156410 tons. The problem of the final disposal of residues left in fields, such as those from packhouses, is a major concern for farmers and residents of Patagonian Protected Region.

Biodigesters are devices that enhance organic matter degradation trough anaerobic digestion [2]. This technology allows a sustainable production of methane gas.However, anaerobic digestion process is extremely sensitive. This aspect makes necessary to control different variables in order to achieve not only efficiency but for the process to actually work. In this sense, it was decided to model the biodigester and anaerobic digestion process, along with an electronic system for monitoring and control of it, as a cyber-physical system.

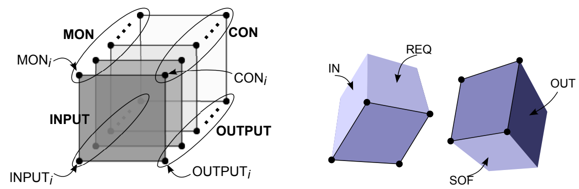
Cyber-physical systems (CPS) represent the intersection between the computational world and the physical environment [3].

In this paper, a requirement analysis approach for CPS is presented. The approach is based on the well-known 4-Variable Model, but it introduces some extensions and adaptations to be used in CPS. The proposed approach is centered in the environmental aspects and the way in which they are affected by the computing system. This is a key aspect when dealing with CPS, that is the vision of the complete system as a domain co-managed by the physical laws and the computer system. It is worth noting that the proposed adaptation is based on matters that came out from practical experience. Thus, the paper emphasizes the practical aspects taken from a real-world experience, along with the needed extension.

2 Extending the Model: a 3D Approach

The proposed extension, called 3D Approach, is depicted in Figure 1(a). This new model maintains the same basic sets of variables and their relationships (*i.e.*, MON, CON, INPUT and OUTPUT; and NAT, REQ, IN, OUT and SOF, respectively). However, it expands them to several planes, each of which constituted by a particular case of the original 4-Variable Model. Consequently, forming a three-dimensional body. The key idea behind this is to express the different physical laws involved in a process by means of simpler ones. In addition, this viewpoint allows to establish relationships between control laws (and hence between software requirements) and to have a clearer vision of the system at the time of implementing it.

From a geometric point of view, in this new scheme, the sets MON, CON, INPUT and OUTPUT are not just corners in a rectangle, but edges. Additionally, relationships REQ, IN, OUT and SOF are no longer lines, but planes. Figure 1(b) shows those planes. This new formulation eases the separation of concerns in the sense of splitting the different components of the systems in terms of their particular functionalities. This is, the separation of concerns is done on the basis of the purposes of the system, which are expressed as control laws. Moreover, within each plane, a subset of related lines can be grouped together, constituting a subgroup of relationships. Despite pursuing a distinct purpose, each relationship



(a) 3D Approach. (b) 3D Planes.

Fig. 1.

in this subgroup of relationships share a common aspect or characteristic. They are related in some way. This feature can be exploited to infer communications within the system.

3 Practical Application

$$\mathsf{MON} = \left\{ \begin{array}{ll} \texttt{temp} & \text{Temperature inside the digester} \\ \texttt{ch4} & \text{Level of biogas generated} \\ \texttt{pH} & \text{Level of pH} \\ \texttt{orp} & \text{Level of redox potential} \\ \texttt{ts} & \text{Total solids of the feedstock} \\ \texttt{vs} & \text{Volatile solids of the feedstock} \end{array} \right\}$$

$$\mathsf{CON} = \left\{ \begin{array}{ll} \texttt{temp} & \text{Temperature inside the digester} \\ \texttt{hrt} & \text{Hydraulic retention time} \\ \texttt{srt} & \text{Solids retention time} \end{array} \right\}$$

Once determined the physical variables, different requirements relationships are established. It is worth noting that this process is not done sequentially, but in parallel, and that sometimes the variables determine the relationships and some others in reverse.

$$\mathsf{REQ}_1 \begin{cases} \mathsf{MON}_1 = \{\texttt{temp}, \texttt{pH}, \texttt{ch4}\} \\ \mathsf{CON}_1 = \{\texttt{temp}\} \end{cases} \quad \mathsf{REQ}_2 \begin{cases} \mathsf{MON}_2 = \{\texttt{temp}, \texttt{orp}, \texttt{ch4}\} \\ \mathsf{CON}_2 = \{\texttt{hrt}, \texttt{srt}\} \end{cases}$$

$$\mathsf{REQ}_3 \begin{cases} \mathsf{MON}_3 = \{\texttt{ts}, \texttt{vs}\} \\ \mathsf{CON}_3 = \{\texttt{hrt}, \texttt{srt}\} \end{cases} \quad \mathsf{REQ}_4 \begin{cases} \mathsf{MON}_4 = \{\texttt{temp}, \texttt{ch4}\} \\ \mathsf{CON}_4 = \{\texttt{temp}, \texttt{hrt}, \texttt{srt}\} \end{cases}$$

$$\mathsf{REQ} = \{\mathsf{REQ}_1, \mathsf{REQ}_2, \mathsf{REQ}_3, \mathsf{REQ}_4\}$$

According to the previously stated definition of the requirement relationships, each of them should be expressed as a control law. In this case, only their inputs and outputs are shown, since the inclusion of them would be out of the paper's scope. Moreover, the interactions between the control laws is a topic not easily approachable and that requires the physicochemical modeling of the anaerobic digestion process [4].
In the computing system side, the identified variables are named with a prefix indicating whether they are inputs or output (*i.e.*, in_ or out_).

$\mathsf{INPUT} = \{\texttt{in\_temp}, \texttt{in\_ch4}, \texttt{in\_pH}, \texttt{in\_orp}, \texttt{in\_ts}, \texttt{in\_vs}\}$
$\mathsf{OUTPUT} = \{\texttt{out\_temp}, \texttt{out\_hrt}, \texttt{out\_srt}\}$

Following, the planes that serve as interface between the physical and computational world are summarized.

$$\mathsf{IN} = \left\{ \begin{array}{ll} \texttt{temp} & \rightarrow \texttt{in\_temp} \\ \texttt{ch4} & \rightarrow \texttt{in\_ch4} \\ \texttt{pH} & \rightarrow \texttt{in\_pH} \\ \texttt{orp} & \rightarrow \texttt{in\_orp} \\ \texttt{ts} & \rightarrow \texttt{in\_ts} \\ \texttt{vs} & \rightarrow \texttt{in\_vs} \end{array} \right\} \mathsf{OUT} = \left\{ \begin{array}{ll} \texttt{temp} & \rightarrow \texttt{out\_temp} \\ \texttt{hrt} & \rightarrow \texttt{srt\_ch4} \\ \texttt{srt} & \rightarrow \texttt{srt\_pH} \end{array} \right\}$$

4 Conclusions and Future Work

Cyber-physical systems are an emerging research discipline that settle their foundations in well-known ones such as control theory, real-time embedded systems, communication networks, software engineering and electronics. Nevertheless the key aspect of this new discipline is its very close relationship with the physical world. This impose the necessity to deal with both worlds in parallel when developing an application.
In this paper, some outcomes from the practical experience of designing a CPS where exposed. The chosen application was a biodigester, which is a device that allows and favors the anaerobic digestion process of organic matter. The biodigester was meant to work in an autonomous way, with almost any human intervention. As a consequence, the requirements elicited were related to physicochemical characteristics of the anaerobic digestion process. This led the development of a new model, called the 3D Approach. The most relevant aspect of the 3D Approach is the separation of concerns based on the physical laws that governs the process. In this manner, the features of a CPS can be easily distinguished and tackled.
Future works have to do with formalizing the method and systematically describing its usage. Finally, in order to complete the approach a special effort will be put in analyzing non-functional requirements, which are a fundamental issue in CPS.

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