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Mechatronics in a New Context: a Structuring Conceptual Framework Proposal for MBSE

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***Abstract*—Technological advances are reshaping the world in which we live by enabling the design of systems that are increasingly sophisticated, fast, precise and that assist the human being in all aspects. However, the design of these systems is becoming more and more challenging as they integrate a large number of disciplines that interact synergistically. Current design approaches are therefore reaching their limits and need to be adapted. For this purpose, we propose a conceptual framework to structure current systems. This framework will be the basis for a new design approach that is currently being developed of which we briefly present some broad outlines. An insulin pump system is also used to illustrate the proposed work.**

I. Introduction

While the first systems created by men were inherently mechanical, the need for more accurate and controlled motions implied the progressive introduction of electronics. This is how mechatronic systems first came into being and enhanced the control and operation of systems. Since that time, and thanks to the significant and fast pace technological progress, systems are shifting towards smart, interconnected, communicating and adaptive (self re-configurable) objects and are spreading into very diverse application fields. The new systems are then characterized by the integration of a growing number of disciplines that are more and more sophisticated and increasingly interacting with each other. In addition to the hardware dimension, systems are progressively integrating software and firmware. As a result, concepts such as Cyber-Physical Systems (CPS) and Internet of Things (IoT) have emerged [1] to provide more sophisticated services to humans who are closer (more surrounded by) to systems. The actual context is also characterized by a wild competence in the industrial field and a shortage of available resources. Designers are facing big challenges in designing and developing systems while managing (tackling) their inherent complexity together with diverse constraints.

This paper aims at proposing a new conceptual framework that will guide/support the designers to better tackle the new challenges that they are facing. The proposed framework is also accompanied with some methodological guidelines.

The paper is organized as follows. First the proposed new conceptual framework for mechatronic systems is given in section II. Then, some aspects to integrate in the SE approach are introduced in section III. A case study in presented in section IV in order to illustrate the content/subject/point of this work. The paper is finally concluded in section V.

II. New Conceptual Framework for Mechatronic Systems

Systems today have reached an exceptional level in terms of the functionality provided to the users and consequently in terms of complexity and interconnection. Indeed, thanks to the technological progress, modern man can benefit from assistance in all aspects (all tasks) from transport to medicine to production machines etc. In addition, the development of IT enabled the availability of almost real-time information in several fields. Passengers can have instantaneous real-time traffic information in the streets and on flights and other public transportation. Doctors can remotely perform surgical operations and have follow up information from their patients.

This snapshot demonstrates the shift of our daily life in this beginning of 21st century. Indeed, we can notice that, the cyber dimension is now ubiquitous through the monitoring and processing of data to enhance the management of already existing physical systems and offer more functionality to users. Several research works focus on this shift from mechatronic to cyber-physical systems [2]. This observation has also been underlined in [3] where mechatronic systems are positioned at the interface of the cyber and physical spaces to enable the communication of these distinct worlds.

These progresses aim at providing more services to the humans that closely interact with systems. Indeed, several persons can remotely monitor objects or spaces, be alerted of and resolve potential problems relative to their health, work etc.

The proliferation of systems in use, which are often energy-intensive increased with continuously collecting and processing required data on the one hand, and the shortage in natural resources on the other, make the energy aspect of paramount importance during the design stage.

On the basis of these findings, we may consider that today's world relies on four main pillars:

- *The human dimension*, which denotes that human may be part of the system and contributing to its behavior, or closely interacting with the system, thus strongly contributing to its behavior;
- *The physical dimension*, that allows the system to act on and sense all kind of material and object, static or dynamic, in a 3D physical environment;
- *The informational (cyber) dimension*, that allows the system to deal with internal and external flows of data, information and knowledge, using computing and storage resources, etc.
- *The energetic dimension*, which denotes that the system consumes or/and produces energy to power all its constituents whatever its behavior;

Hence, the human, the physical (both natural and artificial), information and energy form four interdependent and complementary pillars on which our society is based for its current and future needs in artificial systems that are necessary for its existence and harmonious development. Examples include more or less autonomous transport systems, energy smart-grids, industry with the factory of the future (called 4.0), smart medicine, space systems supporting several activities such localisation and communication, the smart house (connected, economical, ecological), large scientific equipment (CERN, LIGO-VIRGO, ESO-MUSE, etc.).

In such context, it is easy to imagine that the design of new systems is a complex activity that requires a formal framework in order to make it intelligible. Thus, as an introduction, and in order to better apprehend this context and the resulting complexity, we believe it is necessary to establish a framework by proposing a set of postulates and hypotheses, in the same way than Lee SMOLIN [4] in his research for new foundations in physics:

"Our strategy will then be to proceed to our goal of inventing a new (fundamental) theory in four steps: first, principles; second, hypotheses (which must satisfy the principles); third, models (which illustrate partial implications of the principles and hypotheses); then last, complete theories".

Thus, in order to settle the new systems context and its consequences, we propose a comprehensive set of postulates and associated hypotheses as follows:

- System Core Postulate:
  A system is based on up to 4 complementary and synergistic domains, namely Physical (P), Cyber/information (C), Energy (E) and Human/social (H) spaces. Like a hub acting as an interface between them, mechatronics enables synergies, relying on a backbone made of sensors, actuators, real-time embedded systems (hardware and software), HSI devices (Human System Interface), etc. as illustrated in Fig. 1.
- Safety Critical System Hypothesis:
  Systems as described in the system core premise, are characterized by a sophisticated structure and a complex behavior, thus they

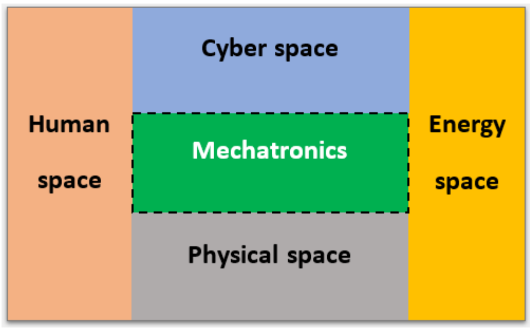

Fig. 1. Mechatonics as a Human-Energy-Cyber-Physical Interface

are potentially safety critical;

- System Rationale Postulate:
A system rationale is to meet a need, by achieving a mission. This need is formalized with a set of requirements, most of them constraining system parameters and variables. The system mission is formalized by operational scenarios that describe the expected behavior, within a specific context, for each phase of the system life cycle;
- Dynamic Requirements and Context Hypothesis:
Requirements continue to evolve during the whole system life cycle, especially within an uncertain and evolving context;
- System Structure and Behavior Postulate:
The mission of a given system can be broken down into a set of interacting functions, each of them being performed by relevant interconnected components. As a result, the system structure (topology) and its global behavior emerge. This emergent behavior of the system has to meet the expected behavior;
- Unintended Behavior Hypothesis:
Interconnection between physical components may lead to unintended behavior generated for instance by multiphysics and geometry interference and interactions, as well as poor or inconsistent interfacing.

III. SE Approach for Mechatronic Systems Design

In order to act as an interface layer between the human space (H), the cyber space (C), the physical space (P) and the energy space (E), Fig. 2 illustrates how the mechatronic backbone relies on:

- Actuators dealing mainly with P and E spaces elements;
- Sensors dealing mainly with P and C spaces elements;
- Embedded systems, with both hardware and software aspects, dealing mainly with C space elements;
- Some Human System Interface (HSI) devices dealing with H space elements;

Based on the conceptual framework described in section II, we will add some guidelines to an existing SysML-based methodology already presented in [5]. This methodology contains two main phases: a black-box phase and a white-box phase. In the first phase, the system is considered from an external perspective (hence as a black box) and is modeled according to different points of view (lifecycle, context, operating modes, use cases and scenarios). The aim of this phase is to collect and capture the requirements that the system must satisfy. In the second phase, the systems is progressively defined (specified, and designed) to respond to the requirements defined in the first phase. This phase begins by the definition of the functional architecture based on the functional requirement identified in the black-box. Then, appropriate components are allocated to the identified functions leading to the component (organic or logical) architecture (the system breakdown as well as the components interconnections). Several alternative solution can be defined and compared at this step. The solution is then further detailed (through the detailed design phase where technological choices are made and the appropriate components are satisfied to satisfy system level requirements.

To better comply with the proposed framework, we suggest the following updates (upgrades, modifications) to this methodology.

- Add attributes to each system model element (requirement, function, components) to define the major and minor dimensions among the four identified dimensions (Informational, Physical, Human, and Energy),
- Define some systematic aspects that the designer must consider for each dimension.

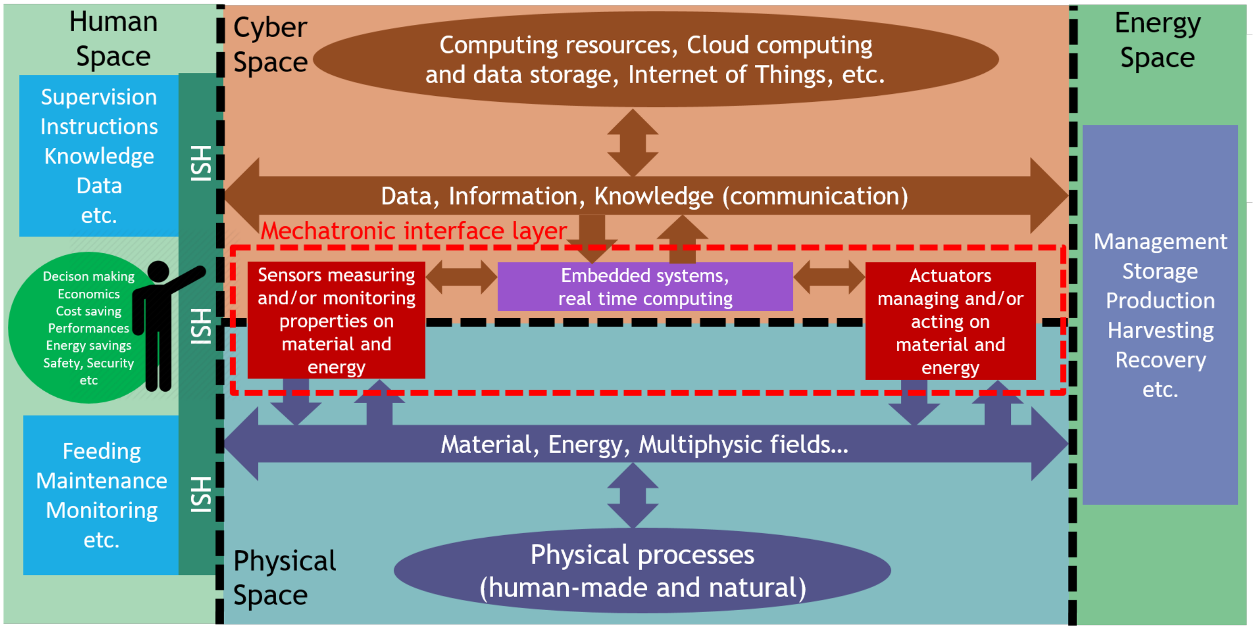

Fig. 2. Mechatronic backbone and Human, Cyber, Physical and Energy spaces

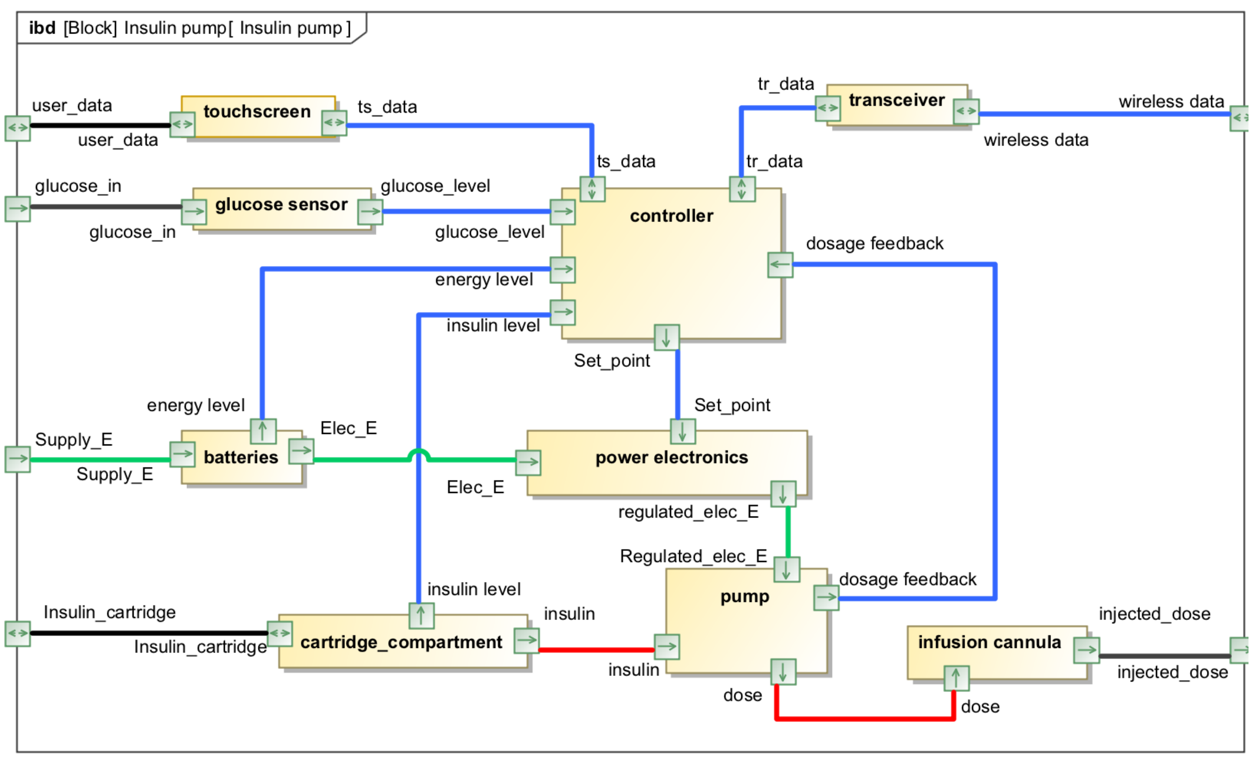

Fig. 3. Insulin pump IBD

Some examples of aspects are:
  - Human dimension: constraints as ergonomics and facility of use shall automatically be considered taking into account the characteristics of the humans in question (age, training, capabilities etc.). Consider the potential errors that can be made by humans and their consequences and add some protection measures if they may have significant impact.
  - Energy dimension: consider potential ways to harvest energy from existing sources (motion, etc.) within the system as well as the integration of low emission and renewable energy; for the choice of components and technologies, give priority to those with lower consumption.
  - Information dimension: consider data protection from malicious individuals by preventing potential accesses and modification (security issues). Shield the supports transmitting data to protect it from surrounding electromagnetic fields.
  - Physical dimension: consider recyclability, the possibility to add required sensors and actuators, and consider potential harm for surrounding elements especially humans, etc.
- Define some verification rules to verify that the different requirements and constraints are correctly traced to elements with similar dimensions.

IV. Case study: Insulin Pump

The insulin pump, also called "artificial pancreas" [6] is a device intended to continuously and automatically provide diabetes patients with required dose of insulin, thus replacing the pancreas in its role of insulin regulator. This device shall therefore continuously sense the glucose rate in the patients' blood, compute the required amount of insulin (if any) and then infuse it into the patient body at the right time. The internal structure of such a medical device is described by an IBD in Fig. 3.

On the human point of view (Fig. 4), the system is directly interfaced with the user via a

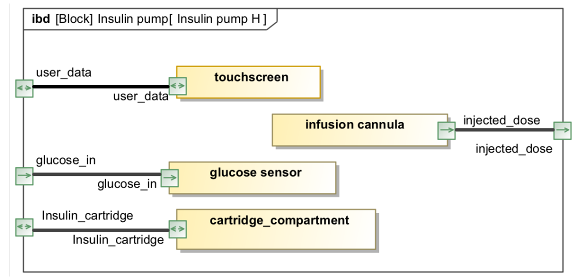

Fig. 4. Insulin pump human point of view

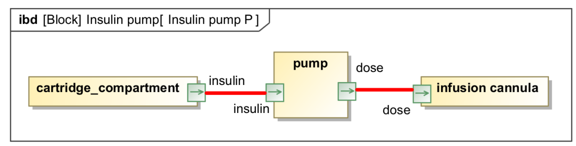

Fig. 5. Insulin pump physical point of view

touchscreen acting as a HSI to perform manual settings and visualize the states and data of the glucose control loop. The system is also interfaced with the user via an infusion cannula and a glucose sensor, both of them being fitted on the user skin. The user has also to fit an insulin cartridge in the relevant compartment.

On the physical point of view (Fig. 5), this insulin cartridge compartment provides the pump with insulin to feed the insulin cannula.

On the cyber point of view (Fig. 6), the glucose control loop algorithms are implemented in a controller driving power electronics. To this end, the controller monitors energy, insulin and glucose levels. A transceiver (e.g. bluetooth) potentially connected to a smartphone or a computer allows remote monitoring by a doctor or the user.

Finally, in order to energize the system (Fig. 7), batteries are used for electricity storage, whatever the way they are charged: external power-pack or even energy harvesting via vibrations or human sweat, etc. Electricity is regulated and driven to the pump by power electronics.

In this medical example, one can remark that the different dimensions (human-social, physical, cyber - information and energy) are closely intertwined, with some components making up a mechatronic backbone (sensors, actuators, etc.). In this work, the different view points have been represented in dedicated complementary IBD gen-

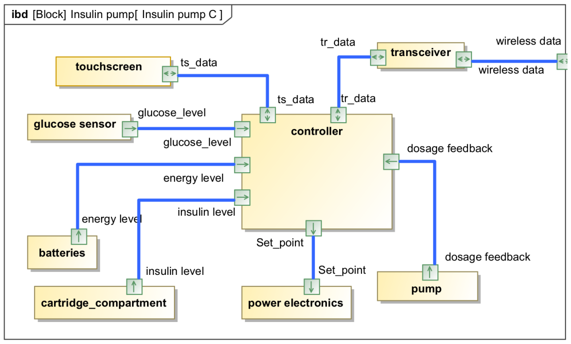

Fig. 6. Insulin pump cyber point of view

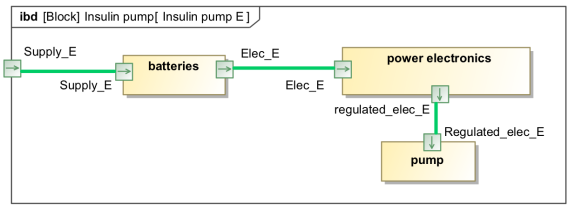

Fig. 7. Insulin pump energy point of view

erated manually.

Thus, the relevance of additional attributes on components, connectors and ports, is obvious and may allow to better identify the four aspects in the system in order to be able to perform dimensioning and requirements verification related to each dimension, allocated to relevant design teams.

V. Conclusion

In this paper, a new conceptual framework was presented for mechatronic systems within the actual context of highly interconnected systems. This framework highlights four dimensions that are essential in the design of such systems i.e. the human, physical, information and energy dimension. On the light of this structuring, design approach can be improved to effectively tackle the above-mentioned dimensions. This paper presented the very first stones of such SE approach. The need for this proposal was illustrated on an insulin pump example. This in an ongoing work and in the near future, the work presented here will be challenged through other case studies to validate the conceptual framework and further develop the approach.

References

[1] P. Hehenberger and D. Bradley, Eds., *Mechatronic Futures: Challenges and Solutions for Mechatronic Systems and their Designers*. Cham: Springer International Publishing, 2016.

[2] O. Penas, R. Plateaux, S. Patalano, and M. Hammadi, "Multi-scale approach from mechatronic to cyber-physical systems for the design of manufacturing systems," *Computers in Industry*, vol. 86, pp. 52 – 69, 2017.

[3] J.-Y. Choley, F. Mhenni, N. Nguyen, and A. Baklouti, "Topology-based safety analysis for safety critical CPS," *Procedia Computer Science*, vol. 95, pp. 32 – 39, 2016, complex Adaptive Systems Los Angeles, CA November 2-4, 2016.

[4] L. Smolin, *Einstein Unfinished Revolution-the Search for what lies Beyond the Quantum*. Penguin Books, 2019.

[5] F. Mhenni, J.-Y. Choley, O. Penas, R. Plateaux, and M. Hammadi, "A SysML-based methodology for mechatronic systems architectural design," *Advanced Engineering Informatics*, vol. 28, no. 3, pp. 218 – 231, 2014, multiview Modeling for Mechatronic Design.

[6] G. Cocha, O. Rodriguez, H. Mazzeo, J. Rapallini, C. Amorena, and C. E. D'Attellis, "Intelligent insulin pump design," in *2018 Congreso Argentino de Ciencias de la Informática y Desarrollos de Investigación (CACIDI)*, 2018, pp. 1–4.