Proceedings Paper:

Ivanov, V, Augsburg, K, Ruderman, M et al. (2 more authors) (2017) Interdisciplinary design methodology for systems of mechatronic systems focus on highly dynamic environmental applications. In: Proceedings of the 43rd Annual Conference of the IEEE Industrial Electronics Society (IECON 2017). IECON 2017, 29 Oct - 01 Nov 2017, Beijing, China. IEEE , pp. 4062-4067. ISBN 978-1-5386-1127-2

https://doi.org/10.1109/IECON.2017.8216696

Interdisciplinary Design Methodology for Systems of Mechatronic Systems

Focus on Highly Dynamic Environmental Applications

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***Abstract*—This paper discusses a series of research challenges in the design of systems of mechatronic systems. A focus is given to environmental mechatronic applications within the chain "Renewable energy production – Smart grids – Electric vehicles". For the considered mechatronic systems, the main design targets are formulated, the relations to state and parameter estimation, disturbance observation and rejection as well as control algorithms are highlighted. Finally, the study introduces an interdisciplinary design approach based on the intersectoral transfer of knowledge and collaborative experimental activities.**

***Keywords*—mechatronic systems; smart grids, electric vehicles, offshore mechatronics, control systems**

I. Introduction

Development of innovative technologies in all engineering sectors should consider various environmental challenges such as the curb of greenhouse gas emissions and the preferable use of renewable energy. As a result, a series of novel paradigms emerge, which require more complex approaches to the design of eco-friendly technical objects and systems. A paramount example of such eco-friendly objects is the electric vehicle (EV). The following main stages can be distinguished when analyzing the evolution of EV technologies: (i) Only a few decades ago, EVs were developed using traditional methods of automotive engineering with the focus on on-board systems and components; (ii) Further progress in batteries, electric motors and power electronics made the emergence of efficient plug-in charging technologies for EVs possible. Therefore, at the next stage, there is a clear need to explicitly consider electrical grids, such as future "smart" grids, during the EV design process; (iii) An increasingly intensive use of renewable energy sources in grids is not only environmentally positive, but has also a beneficial influence on the increase of the Well-to-Wheel performance (i.e., the energy conversion efficiency) of EVs. The introduced chain "Electric vehicle – Smart grids – Renewable energy production" has all the required characteristics, as described in [1, 2], to be considered as a System of Systems (SoS): ***Operational and managerial independence; Geographical distribution; Emergent behavior; Evolutionary development; Heterogeneity of constituent systems***. This SoS includes a substantial number of mechatronic components lending itself to the concept of ***"System of Mechatronic Systems" (SoMS)***.

The current state of research in SoMS exhibits the following gap: the state-of-the-art of mechatronic, information and communication technologies allows the design and implementation of vehicles, electric power and renewable energy production systems having an extraordinary high dynamic performance, but efficient interconnection of such systems requires new control paradigms. This statement can be illustrated as follows: (i) Despite numerous studies in control methods applied to mechatronic systems in electric surface transportation, clear benchmarking of control approaches and methods for their real-time validation is rarely investigated; (ii) The operation of environmental SoMS is characterized by the presence of many uncertain factors and disturbances. Both are of steady-state, short-term and long-term nature and provide a complex impact on the SoMS performance. Therefore, the development of corresponding disturbance rejection tools explicitly considering different system dynamics is required.

These factors point to the demand on an efficient *methodology in environmental mechatronic control system design relying on multidisciplinary knowledge*. This paper has the main goal to introduce how such a methodology can be developed within the framework of lifelong learning technologies aimed at the acquisition of strong interdisciplinary and product-relevant knowledge. The corresponding case study relates to the project CLOVER (https://clover-project.eu/) within the framework of Marie Skłodowska-Curie Actions established by the European Commission and funded through the Research and Innovation Staff Exchanges scheme between universities and industrial organizations from Germany, Austria, Belgium, Norway, UK, Mexico, and Japan. Within the next sections of the paper, interdisciplinary and intersectoral contents of the related development activities are introduced.

II. Design Framework for Environmental SoMS

The standard procedure for design of mechatronic systems is traditionally described with a V-model [3], where the process is divided on general stages of System Design, Discipline-specific Design and System Integration. Each of these stages can be also separated on various sub-stages depending on the specific design tasks [4]. Considering mechatronic systems within the SoMS framework, more complex models and advanced standards can be used that was thoroughly overviewed by Clark in [5].

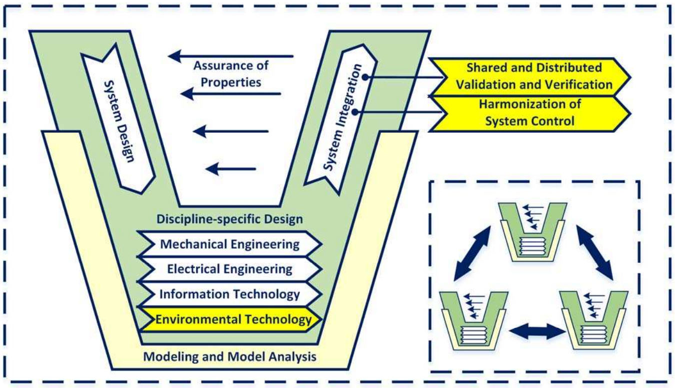

Fig. 1. Variation of V-model for environmental SoMS

For the CLOVER project, the V-model approach is also applied however with embedding of several components as illustrated on Fig. 1. Three main factors should be emphasized here. Firstly, elaboration of a mechatronic system within the environmental SoMS requires inclusion of methods of *Environmental Technology* into the discipline-specific design. It ensures proper evaluation of the expected system impact on diverse environmental factors on this design stage. However, it should be noted that this part of the design framework lies out of scope of the presented paper. Other specific design parts for environmental SoMS are attributed to the System Integration stage. Here, in addition to common sub-stages as the preliminary design or validation, two components can be particularly added. They are conditionally termed *Harmonization of System Control* and *Shared and Distributed Validation and Verification*. The first component deals with unification and benchmarking of control procedures applied in different mechatronic systems within the SoMS to guarantee their reliable real-time collaborative operation. The second component is dedicated to new procedures for testing of complex environmental SoMS. More information about demand on these components and their relation to the CLOVER objectives is provided next.

III. Overview of Control Engineering Problems when Designing Environmental SoMS

The environmental SoMS can be characterized by several typical design factors arising from the development of corresponding controllers both for the whole system and its subsystems. The morphology of these factors is summarized in Table 1. *It should be noted that in the further discussion the off-shore mechatronic systems are selected as one of the key components responsible for renewable energy production*. An analysis of the existing literature in relation to the factors indicated in Table 1 allows the conclusion that some key research problems are valid for all three elements of SoMS and, therefore, unified solutions can be proposed in this regard. As applied to the CLOVER, several areas can be identified with demand for advanced studies that is discussed next.

1) Observation tools for SoMS. Controllers of mechatronic systems widely use virtual sensors (observers). These are dynamic systems, which compute estimates of non-measurable states or parameters like generalized force and motion quantities or other characteristic properties in mechanical systems. They rely on mathematical models of the processes under consideration and use only available measurement data which are often limited. For motion and force controls, the disturbance observer [6] and reaction force observer [7] have been proposed formerly and since then widely used for many mechatronic systems in various industrial sectors. In related methods, disturbance and uncertainty are, in general, lumped together, and an observation mechanism is employed to estimate the total disturbance quantity [8]. To realize a unified approach to the estimation technique for SoMS, the use of observers forming the basis of Fault Detection and Isolation FDI [9] schemes can be proposed. For this purpose, various order sliding mode observers have advantages, since they are insensitive to a wide class of uncertainties and perturbations, and they provide faster convergence (see e.g. in [10], [11]). Such observers can be used to detect and pinpoint faults in highly dynamic SoMS components.

2) Electric vehicle state estimation. State-of-the-art vehicle state estimators rely on methods, which exploit only a limited set of measurements [12] and/or relatively simple models [13, 14]. Such approach does not use all information, which is available in vehicle models and extended sensor sets. It is especially critical for EVs with mechatronic, x-by-wire chassis because they have more degrees-of-freedom than classical vehicles due to an increased number of actuators. Some interesting solutions have recently arisen in this field. Most of them are using information provided by advanced sensor technique as well as dynamic parameters of electric motors [15-17]. As the main estimation tools, traditional approaches as Recursive Least Square estimation and Kalman filtering [16, 18] or H-infinity [19] still are being widely applied for EVs. By considering EVs as components of SoMS, the indirect methods are being applied in the CLOVER project for the vehicle state and parameter estimation with special attention paid to robustness and fail-safe procedures. It concerns new estimators using integration of high-fidelity physical models with sensor fused data. A matter of novelty is also a set of estimators, which are especially proposed for operational conditions of plug-in EVs characterized by limited information space.

3) Smart grid controllers. Current power system operation paradigms are tailored to power grids with bulk fossil-fueled power plants interfaced to the network via synchronous generators [20]. However, future power systems will possess an increasing amount of power electronics equipment (e.g. interfacing renewable sources or HVDC links [20, 21]). This fact combined with the fluctuating nature of most renewable sources leads to higher uncertainties and more volatile dynamics in the system [20, 22]. This requires the development of novel operation strategies for power-electronics-interfaced components. This objective requires developing coordinated robust control strategies for compensation of unbalances and harmonics. Formally, this represents a disturbance rejection / attenuation problem in SoMS. Adaptive and cooperative control strategies for multi-agent systems can be employed here with a focus on active integration of plug-in EVs and wind-park platforms.

TABLE I. EXAMPLES OF DESIGN FACTORS FOR ENVIRONMENTAL SOMS

Design Components	Components of Environmental System of Mechatronic Systems		
	Electric Vehicle	**Grid-Connected Mechatronic Systems in Smart Grids**	**Offshore Mechatronic Systems**
Disturbances			
Steady-state rejection	Route-specific vehicle mass variation	Frequency deviations; voltage deviations; power flow balancing; grid faults	Heave motion; fluid drag; transferable payloads
Short-term rejection	Road profile; road friction conditions	Power quality: voltage and frequency sags, unbalances, harmonics, power factor	Wind a payload transfer; cable break
Long-term rejection	Fading; tribological factors in tyres and brakes	Temporal and spatial load variation; voltage compensation	Cable and structures fatigue; wear; creeping relaxation
Observation and estimation technique			
State estimation	Kinematic parameters of motion (velocity, sideslip angle, …)	Rotor position and speed; phasor measurement units (PMUs)	Relative motion: vessel-to-vessel, vessel-to-ground
Parameter estimation	Road profile and loading modes (mass, road grade and slope)	Line impedance; load impedance; grid frequency and phase angle	Payload masses; drag and friction parameters, cable stiffness and damping
Unknown input estimation	Input torque to the wheel (from the side of the brake system in the case of blended braking control)	Load demand; primary source characteristics (wind speed, solar irradiation); maximum power point	Torque of the winch; impact/contact forces
Controller technique			
Supervisory control	Integrated powertrain / chassis controller	Operational management	Remote operation control
High-level control	Vehicle dynamics controller	Active and reactive power control; control of DC-link voltage	Payload transfer control; heave compensation control
Low-level control	Actuator controllers	Current control; AC voltage control; excitation control; speed control; modulation	Hydraulic/electric motor control; hydraulic cylinder control; proportional valve control
Fail-safe control	Fail-safe controllers of vehicle subsystems	Overcurrent and -voltage protection	Fail-safe control of person and payload transfer, deep-water lifting and lowering control

4) Disturbance attenuation in offshore mechatronic systems. In the offshore and marine industries, the heave motion compensation systems are widely used while distinguishing between passive, active, hybrid passive-active, and wave synchronization systems [23]. These pose high challenges on the underlying control algorithms and equipment, in view of the weakly known environmental dynamics coming from the winds and waves. In harsh sea conditions, the involved crane system must satisfy rigorous requirements in terms of safety and efficiency as shown in [24]. The well-established marine and offshore industry hydraulic systems are mostly space-consuming and require complex power sources and hydraulic circuits, while appearing as only conditionally environmental friendly due to risks related to leakages and openings. Relevant applied control solutions in the CLOVER project consider equally the electric drives for the active heave compensation, which can yield more energy efficient and environmentally friendly approaches for the mechanisms operating on the wind platforms and vessels. The advanced compensation strategies are focused on 3D relative motion compensation while considering complex disturbances aggregated from drag from water, waves, winds and others. A robust observation and estimation of dynamic state quantities can be of interest in view of the sensor limits and inherently restricted state measurements during the operation.

5) Cyber-physical framework. Environmental mechatronic systems, especially in the context of SoMS, belong also to the cyber-physical domain. The cyber-physical properties of mechatronic systems are intensively investigated now in different aspects. For instance, the problems of system architecture [25-27], constraints caused by cyber-physical environment [28], efficient technological processes [29, 30], relevant methods of software design and modelling [31, 32] can be mentioned in this regard. More specific solutions for renewable energy production and environmental systems also received recently attention within the framework of new control design concepts as “Glocal” framework for hierarchical multi-agent networked dynamical systems [33-35]. However, properly addressing the two following cyber-physical topics is of importance during the SoMS design. The first topic relates to overcoming or considerable minimizing communication latency [36] between individual systems composing SoMS to ensure a robust network-based spatial-temporal design process. Some recent studies in this area propose adaptive strategies to compensate communication time delays making distributed and seamless system development possible, e.g. by utilizing an intranet or the internet or by a real-time simulation cloud (see, for example, outcomes of the project ACOSAR [37]). The second topic relates to the creation of an efficient validation and verification testing methodology allowing reduction of the development costs despite high complexity of the systems and their operational environments. This topic is receiving much attention within the CLOVER framework and is explained in the next paragraphs in more details.

6) Testing technologies for environmental SoMS. Designing of SoMS includes testing procedures based on various well-established software- and hardware-in-the-loop approaches with sufficient model fidelity and accuracy. However, there are no apparent procedures for the integrated system testing on the development design stage. Most of the known hardware-in-the-loop applications relate to the cases of development and testing of single subsystem operating in the stand-alone mode that is especially relevant to vehicle systems as indicated in [38, 39]. The complexity of SoMS design requires more advanced approaches, which use integrated testing and co-simulation techniques. The joint application of testing facilities from different physical domains (e.g. test rig-in-the-loop tools as introduced in [40]) is the reasonable research methodology in number of projects. It provides flexibility of experimentation works and gives the open platform for an eventual extension with new devices required for additional tasks by the development of SoMS controllers.

The presented overview allows to formulate a set of key objectives for the design of environmental SoMS. **Research objectives (R)** are focused on: **(R1)** Benchmarking tools for comparative analysis of different control and estimation technique applied to mechatronic systems; **(R2)** Methodological approach for switching between various control strategies under criteria of environmental impact minimization and better energy efficiency; **(R3)** Advanced methods for observers and disturbance rejection / attenuation as applied to highly dynamic mechatronic systems. **Innovation and technological objectives (IT)** are: **(IT1)** Development and real-time hardware-in-the-loop validation of plug-in EV dynamics controller with optimized performance by criteria of energy efficiency, energy harvesting and system safety; **(IT2)** Development and real-time hardware-in-the-loop validation of robust controllers for mechatronic systems operating for and on the wind-park platforms, as smart grid components, and service vessels; **(IT3)** Advancement of open development platform aimed at model-based design of SoMS. The methodological approach for these objectives is introduced in the next section

IV. Methodological Approach

The global approach to the SoMS design in the CLOVER project is based on a consecutive implementation of development activities on three methodological levels (Fig. 2). At the *Control Engineering Level*, a detailed mathematical formulation is required for advanced methods of sliding mode and robust optimal control, which can provide stable operation of highly dynamic systems under influence of uncertain disturbance factors of short-term and long-term nature. These works are being supplemented with the development of distributed observers and disturbance rejection mechanisms. The resulting control engineering tools are then subjected to a practical implementation at the *Mechatronic System Level*. For this purpose, selected critical systems are defined as the network controllers of grid-connected parallel inverters, mechatronic devices for access to and maintenance of the wind-park platforms, and onboard vehicle chassis systems responsible for active safety and driving comfort. To corroborate feasibility of the developed analytical solutions, the methodological approach includes the *Testing Technology Level*, where both mechatronic systems and the prototype of SoMS are subjected to experimental investigations. Here an essential component will comprise the organization and use of remotely connected platforms for testing mechatronic systems from different domains. This methodological approach consists of several components specified next.

Objective R1. The selected methodology consists of two stages. In the first stage, analytic models that capture the fundamental system dynamics should be formulated. The analytic models serve as base for the control design tasks in accordance with Objective R3. In the second stage, software models of higher complexity and real-time applicability are developed. These serve to benchmark the performance of the control algorithms under more practical circumstances and create a natural link to the experimental validation in accordance with objectives IT1 and IT2. For the model derivation of several SoMS components connected in parallel to a smart grid, the theoretical framework of symmetrical components will be used to represent unbalanced electrical quantities in both the analytic and the software model. In line with Objective R1, the methods also include: benchmarking and performance evaluation for the discretized sliding mode controllers and observer algorithms by such criteria as convergence, control action, error bounds, chattering analysis, bandwidth of the feedback loop, rise and settling time, overshoot (peaking phenomenon).

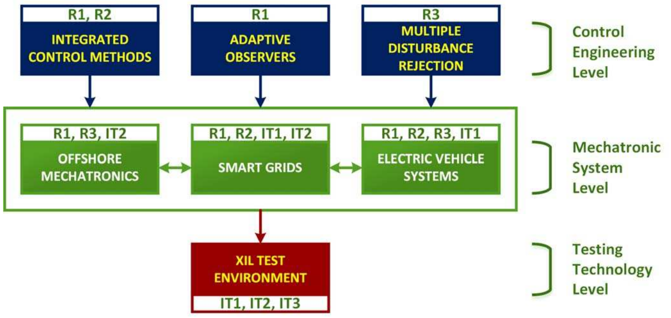

Fig. 2. Methodological levels for SoMS design.

Objective R2. The corresponding methodology covers the development of switching strategies for solving conflicting objectives by means of situation-appropriate control approaches. Switching shall be “bumpless” or smooth enough, with reduction of ringing effects, minimizing control action (for SMC: chattering) for reducing control energy, triggered sensing and actuating only when necessary (event based).

Objective R3. The methodology chosen to achieve the attenuation of electrical grid-side disturbances relies on modern concepts from the areas of adaptive and cooperative control. A focus is on the efficient coordination of several SoMS acting on the electrical grid in parallel. This is crucial to avoid conflicting interactions between individual SoMS. Thereby, a hierarchical control scheme consisting of decentralized low-level controllers and a supervisory distributed control layer can be employed. Further attention is given to robustness with respect to time delays arising from the interaction between digital and analogue components inherent in SoMS. The envisioned procedure is to perform a standard control design on the nominal plant model and subsequently robustify the obtained control with respect to time delays, e.g. by employing tools based on Lyapunov-Krasovskii functionals. Additional elements of the methodology include: observers for distributed parameter systems, distributed observers in networked (ode) systems, solving real-time issues for implementation. Sliding mode methodology can be also used for two principle ways for disturbance rejection: Sliding mode observer disturbance estimation and its compensation; Observation of the system states and sliding mode controller design ensuring theoretically exact uncertainties compensation.

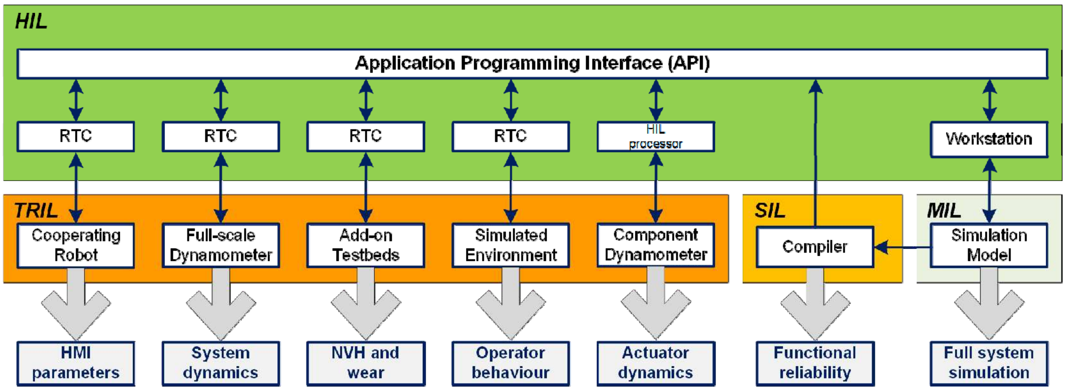

Fig. 3. Variant of XIL-architecture for complex testing of SoMS components. HMI: human-machine-interface; NVH: noise-vibration-harshness; SIL – software-in-the-loop; MIL – model-in-the-loop; TRIL – test rig-in-the-loop; RTC – real-time controller.

Objectives IT1 and IT2. The methodology for real-time HIL validation of controllers for components of SoMS uses the following principle. The controllers with relevant models (vehicle, smart grid, offshore mechatronic devices) should be firstly realized on a software level using a real-time co-simulation interface to ensure the integration of various software (MATLAB/Simulink, dSPACE ASM, LMS et al.), where the dynamics of the whole mechatronic system is being emulated. At this stage, the controllers together with the observers and disturbance rejection tools are also subjected to off-line optimization. After that the corresponding models will be partially replaced with hardware and electronic control units. The further tests will be performed on HIL test rigs. This approach makes possible to investigate stand-alone and cooperative functionality of separate SoMS components.

Objective IT3. The methodology for the objective IT3 is based on advanced X-in-the-loop (XIL) testing approach. This approach is characterized by cooperative experiments using (i) connection of different HIL test platforms in diverse physical locations and (ii) connection of test rigs from different domains (for instance, mechatronic component HIL platform, dynamometric vehicle test rig, and smart grid component HIL platform), Fig. 3. The resulting test environment is open for the plug-in of remote sensors, actuators and test equipment using different communication protocols such as Ethernet, CAN and FlexRay. Test setups in different locations can be coupled, and one host PC will be responsible for co-simulation or integrated control of mechatronic subsystems in real-time modus. In some cases, full real-time integration may not be possible due to bandwidth and physical distance limitations. In these cases, a technique called "simultaneous optimization" can be proposed. This includes a formal gradient-based mathematical optimization technique using (i) the first test platform (HIL) at one physical location to obtain gradient information and (ii) the second test platform (as a reference system) at another location to obtain accurate objective function values. The HIL will give real-time gradient information while the full-scale system tests will give almost instantaneous accurate objective function values that will be used in the optimization algorithms.

The introduced methodology is characterized by a high grade of interdisciplinarity, as visualized in Fig. 4. Hence, the efficient development of environmental SoMS requires different competences and close intersectoral collaboration.

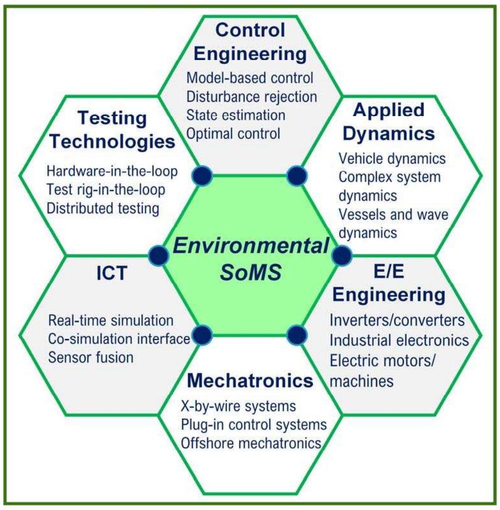

Fig. 4. Interdisciplinarity of SoMS design.

V. Summary: Implementation of Methodology

The concept of SoMS design presented in the previous sections is being elaborated now within the framework of the collaborative project *CLOVER - Robust Control, State Estimation and Disturbance Compensation for Highly Dynamic Environmental Mechatronic Systems*. The project consortium includes partners with competences in different topics of SoMS. Industrial participants are Tenneco Automotive (Belgium), AVL List GmbH (Austria), Red Rock Marine AS (Norway), and Siemens Industry Software (Belgium). Academic partners are TU Ilmenau and FH Kempten (both Germany), Universitetet i Agder (Norway), TU Graz (Austria), University of Leeds (UK), University of Tokyo (Japan), and Universidad Nacional Autónoma de México (Mexico). To design SoMS components, the CLOVER project uses a combination of people-centric and information-centric approaches for knowledge sharing between the partners. This is based on the R&D and training in three interfacing topics: “Mechatronic chassis systems of EVs”, “Mechatronic-based grid-interconnection circuitry”, and “Offshore mechatronics”. For these topics, the following outcomes are being developed under implementation of the described design methodology: (i) Software and middleware for mechatronic systems; (ii) smart grid controllers; (iii) on-board controllers of plug-in electric vehicles; (iv) methods and devices for testing of complex mechatronic systems. The authors intend to introduce corresponding results in subsequent publications.

ACKNOWLEDGMENT

The project leading to this development has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 734832.

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