Examples of actuator uncertainties in environmental systems of mechatronic systems (SoMS)

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The proposed concept of systems of mechatronic systems (SoMS) focuses on a methodology aimed for robust control, state estimation, and disturbance compensation in highly dynamic environmental mechatronic systems. Three interfacing topics – “mechatronic chassis systems of electric vehicles”, “mechatronic-based grid-interconnection circuitry”, and “offshore mechatronics” – have been identified as comprising a series of research challenges in relation to the state and parameter estimation, disturbance observation and attenuation, and robust control design. This paper aims to highlight several examples of actuator uncertainties in environmental SoMS, in particular those used in offshore mechatronics and electric vehicles, and to promote the research activities of the collaborative project CLOVER initiated within European Unions Horizon 2020 framework programme under Marie Sklodowska-Curie actions.

Keywords: Systems of mechatronic systems, motion control, uncertainties, actuators, state estimation, compensators, dead-zone, backlash, offshore mechatronics, hydraulic cylinders, electric vehicle, in-wheel motor technology

1. Introduction

The environmental systems of mechatronic systems can be seen as a broad class of integrated and interconnected environment-friendly technologies, performing in a close proximity with surrounding eco-system and that under criteria of environmental impact minimization and better energy efficiency. An obvious example of environmental mechatronic applications lies within the chain “renewable energy production - smart grids - electric vehicles”. This chain has all the required characteristics to be considered as a system of systems (SoS). To those belong the operational and managerial independence; geographical distribution; emergent behavior; evolutionary development; heterogeneity of constituent systems. In view of the system design and implementation, with related involvement of various technologies, such SoS includes a substantial number of mechatronic components which lends itself to the concept of “System of Mechatronic Systems” (SoMS). The current state of research in SoMS exhibits the following significant gap: state-of-the-art of mechatronic, information, and communication technologies allows one to design and implement the ground vehicles [(1)], grids, and renewable energy production systems. These can have an extraordinary high dynamic performance but require an advancement of the relevant control approaches, so as to ensure operating eco-friendly and energy-efficient and, at the same time, under highly-dynamic and uncertain external conditions.

The operation of environmental SoMS is characterized by variety of uncertain factors and disturbances. Both can be of steady-state, short-term and long-term nature, therefore occurring and acting on different time scales of the system dynamics. The development of robust and reliable methods for detection and estimation of such uncertainties and disturbances constitutes the key part for their attenuation, correspondingly rejection. To be emphasized is that the disturbance estimation and attenuation appear simultaneously, during the operation of a controlled SoMS.

Taking reference to the formulated intensions and start-up activities of the collaborative project CLOVER, this paper addresses several examples of the actuator uncertainties in environmental SoMS. In particularly, the examples are associated with offshore mechatronics, as one of the key technological fields for operation and maintenance of the offshore renewable energy production, and electric cars which pave a way of the future mobility and transportation systems.

2. Framework of collaborative project CLOVER

The following examples relates to the collaborative project CLOVER within the Horizon 2020 framework of Marie Sklodowska-Curie Actions (MSCA) established by the European Commission. The project is funded through the Research and Innovation Staff Exchanges (RISE) scheme between universities and industrial organizations from Germany, Austria, Belgium, Norway, UK, Mexico, and Japan.

Global approach to SoMS in the CLOVER project is based on a consecutive implementation of development activities on three methodological levels as shown in Fig. 1 – Control Engineering; Mechatronic Systems; Testing Technology. The related control engineering problems allows formulating a set of key objectives and that Research (R) objectives and Innovation and technological (IT) objectives.

R1 Benchmarking tools for comparative analysis of differ-

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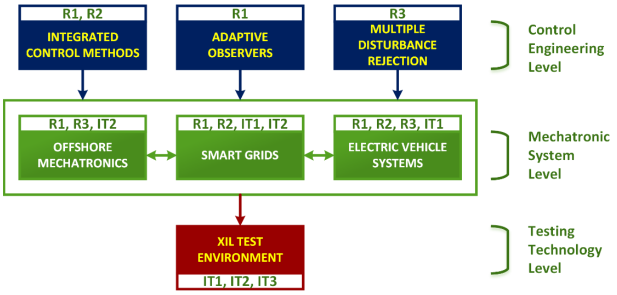

Fig. 1. Research and innovation areas related to the CLOVER project objectives

ent 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;

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 offshore wind-park platforms, as smart grid components, and service vessels;

IT3 Advancement of open development platform aimed at model-based design of SoMS.

The methodology and implementation of the CLOVER project is characterized by a high grade of interdisciplinarity in the research activities as visualized in Fig. 2. Here the involved areas of knowledge and their contribution to the project topics are represented around the core of highly dynamic environmental mechatronic systems. The multidisciplinary character of the CLOVER project aims at providing synergies from different competencies and close intersectoral collaboration between the project partners with their specific expertise and research focus.

3. Actuators in offshore mechatronics

Hydraulic linear-stroke cylinders and hydraulic rotary motors have been, for decades, and yet still remain by far the mostly used actuators in the offshore mechatronics and related maritime applications [2]. This is among others due to a high power density and, consequently, high force-to-mass ratio of hydraulic drives, their robustness when operating in harsh and open-air environments, and required safety against the short-circuits and humidity which, otherwise, appear as critical for the electrically actuated drive systems. Hydraulic actuators exhibit, on the other hand, high level of nonlinearities and heightened uncertainties in view of the nominal parameters and varying operation conditions.

The dead-zone and backlash type nonlinearities, which pose general challenges for the motion control systems, are in addition weakly known and subject to uncertainties when

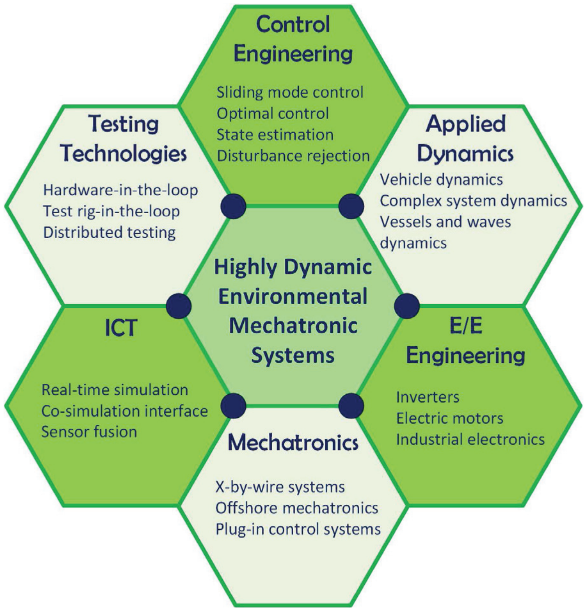

Fig. 2. Inter- and multidisciplinary of CLOVER project

dealing with hydraulic drives and mechanisms. The dead-zones [3][4] appear mainly due to the closed center spool in directional control valves and therefore nearer to the controlled system input. The backlash [5]~[8] type nonlinearities in the couplings and gearing of hydraulic motors connected to winches are rather located in the thick of the drive-trains and therefore more challenging for detection and proper estimation. Furthermore, the open-loop transfer functions of the valve-controlled hydraulic motors and correspondingly hydro-mechanical winch systems [9] exhibit the uncertain and state-varying gain characteristics associated with hydraulic volume displacement, approximated valve constant, not ideally compensated differential pressure over the valve edge, and others. The wire elasticities and varying damping of the wire rolled on the drum constitute additional uncertainties in the open-loop gain of the winch systems to be controlled.

Below, the weakly known dead-zone and varying open-loop gain are addressed in more details as relevant examples of the actuator uncertainties in offshore mechatronic systems.

3.1 Weakly known nonlinearities The dead-zone in the valve-controlled hydraulic cylinders and motors manifests itself as input nonlinearity, for which modeling and identification either the pure static characteristics or those coupled with internal valve dynamics can be pursued. Due to the lack of full-order dynamic modeling and state measurements in the complex chain of energy conversion of the valves, i.e. electric-magnetic-mechanic-hydraulic, the dead-zone nonlinearity appears as often uncertain and state-dependent. The internal spool dynamics with implication on the valve orifices are strongly dependent on the operation conditions, like hydraulic pressure and flow, which in turn can appear as dynamic quantities with uncertainties arising out of elements of hydraulic circuits and mechanical loads.

The experimental setup of hydraulic cylinder to be used for dead-zone analysis and estimation is shown in Fig. 3. The extended measurements of the system include the coil current in electromagnetic solenoid and spool displacement of the directional control valve (DCV), on the one hand, and the

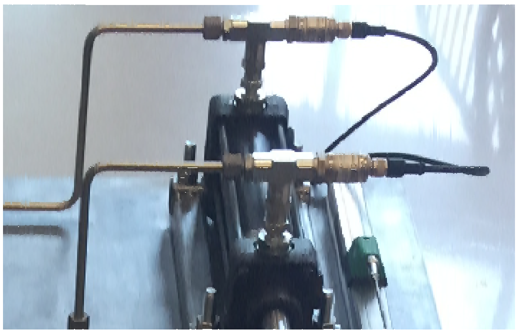

Fig. 3. Experimental setup of valve-controlled hydraulic cylinder with pressure and displacement measurement

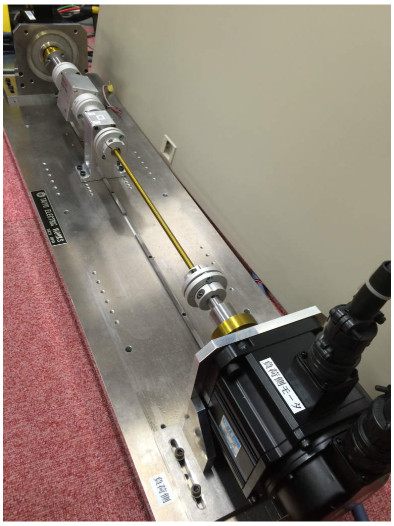

Fig. 4. Experimental setup of two-inertia system

piston stroke and pressure in both chambers of the hydraulic cylinder, on the other hand. Additional measurements of the oil flow within hydraulic loop and temperature on the surface of components in hydraulic circuits, like for example valves, connectors, or cylinder self, provide further operation states which appear significant for analysis and evaluation.

Furthermore, the methods for detection and estimation of the dead-zone and backlash type nonlinearities can be investigated and evaluated on a two-inertia system with exchangeable couplings and both-side encoders which provide an exact reference value of incorporated nonlinearities [10]. The experimental setup consists of two surface permanent magnet synchronous motors with 20 bits high resolution encoders as shown in Fig. 4. To evaluate the robustness of control methods against model uncertainties, flexible joints with various torsional rigidity and inertia weights can be equipped. By replacing a flexible coupling with a gear coupling, backlash can be added and removed easily. The backlash width can be directly evaluated by using two high resolution encoders.

3.2 Varying open-loop gain The hydro-mechanical systems, like for example winches actuated by hydraulic motors [9], are often modeled through linearizing the continuity equations of hydraulic flow and approximating the hydraulic motor volumetric displacement, valve gain, and other operation states by the constant values. During the operation, the assumed constants are subject to uncertainties, therefore resulting in a varying open-loop gain – differing from that determined by the measured frequency response functions at the stage of system identification. Furthermore, the varying drum radius, which depends on the state of the rolled-on wire, and structural and contact damping of the winch bring additional uncertainties into the open-loop gain of system under control. The weakly known leakage coefficient and total volume of hydraulic pipes and motor displacement equally fall into the scope of varying gain characteristics when considering the open-loop transfer function of the actuated hydro-mechanical winch system. For the quite similar reasons as above, another types of hydraulic actuators like linear-stroke cylinders, but also any other complex drive-trains irrespective of hydraulic or electric actuation principles, are subject to uncertain and condition-based variations of the open-loop gain characteristics. For designing robust and efficient feedforward and feedback control systems the methods for estimating and coping with varying system gains are required.

4. In-wheel motor control of electric vehicle

Electric vehicles can demonstrate higher motion performance than internal combustion engine vehicles thanks to the following three advantages: 1) torque responses of electric motors are more than hundred times faster as that of internal combustion engines; 2) distributed arrangement of multiple motors makes torque vectoring possible; 3) motors can measure the output torque from their current sensors. Wheel slip control is required to achieve high vehicle motion performance. In electric vehicles, wheel slip control with high control bandwidth can be realized thanks to the three aforementioned advantages [11].

To realize advanced motion control by precisely controlling traction force, control methods using wheel angular velocity and acceleration have been proposed [12]. Angular velocity and acceleration are usually calculated by angles of resolvers equipped on motors. Wheels are connected to motors with drive shafts and reduction gears, which introduce model uncertainties such as low resonance modes, backlash, and friction [13]. It appears as not realistic to estimate load-side (wheel-side) information from the motor-side resolvers with gears' nonlinearities [14] and unknown environmental disturbances. Therefore, the research group at the University of Tokyo has developed an in-wheel motor electric vehicle with load-side encoders. Fig. 5 shows an electric vehicle setup and Fig. 6 shows an in-wheel motor unit with a load-side encoder. As shown in Fig. 6, there is an output shaft between the load and the load-side encoder through the hollow motor, and the motor-side encoder and the load-side encoder are equipped side by side. The load-side encoder enables to obtain precisely the wheel-side information without influences of the gears' nonlinearities.

Precise slip ratio estimation based on a high-resolution encoder has been already evaluated experimentally with on the setup [15]. High-resolution encoders can reduce quantization errors of the angular velocity and acceleration which are calculated by the angle information. The setup is to be used for further advanced research, with aim to improve the motion performance under gears' nonlinearities and unknown environmental disturbances.

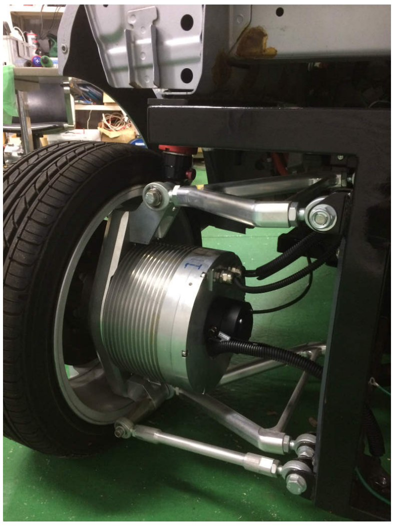

Fig. 5. In-wheel motor electric vehicle with load-side encoders

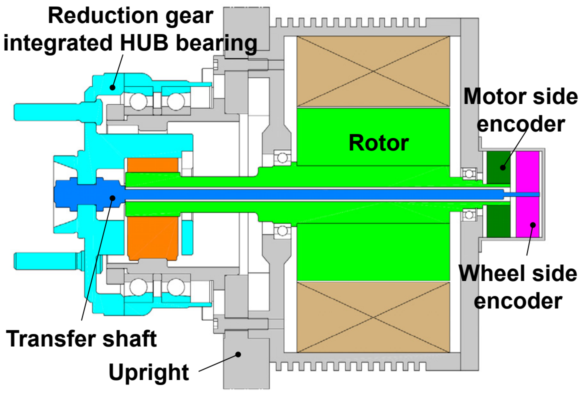

Fig. 6. In-wheel motor unit with load-side encoder

5. Summary

The multidisciplinary concept of highly dynamic environmental applications allows addressing the topical problems of uncertainties and disturbance rejection / attenuation in complex systems of mechatronic systems (SoMS). The framework of the collaborative project "CLOVER - Robust Control, State Estimation and Disturbance Compensation for Highly Dynamic Environmental Mechatronic Systems" has identified a number of theoretical and technological issues that requires intensive research and innovation staff exchange between the networked project partners. The project consortium includes partners with competencies in different domains 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 Autnoma de Mexico (Mexico). To guarantee a strong focus of the project activities on real-world problems, the CLOVER concept is based on the R&D and training in three interfacing topics: "mechatronic chassis systems of electric vehicles", "mechatronic-based grid-interconnection circuitry", and "offshore mechatronics".

In this paper, the following examples of the actuator uncertainties in environmental systems of mechatronic systems have been addressed. For the load and person transfer systems, which are widely used in offshore mechatronics and mostly equipped with hydraulic type actuators, the uncertain and state-varying dead-zone nonlinearities and open-loop gains have been considered. For electric vehicles, which are required to work under unknown disturbances, the gear's nonlinearity in the drivetrain has been addressed with applying a high-resolution encoder at the load side.

The authors intend to introduce corresponding results in the subsequent publications.

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References

(1) V. Ivanov and D. Savitski, "Systematization of integrated motion control of ground vehicles," *IEEE ACCESS*, vol. 3, pp. 2080–2099, 2015.

(2) J. Woodacre, R. Bauer, and R. Irani, "A review of vertical motion heave compensation systems," *Ocean Engineering*, vol. 104, pp. 140–154, 2015.

(3) X.-S. Wang, H. Hong, and C.-Y. Su, "Model reference adaptive control of continuous-time systems with an unknown input dead-zone," *IEE Proceedings-Control Theory and Applications*, vol. 150, no. 3, pp. 261–266, 2003.

(4) C. Vázquez, S. Aranovskiy, and L. B. Freidovich, "Input nonlinearity compensation and chattering reduction in a mobile hydraulic forestry crane," *E & I Elektrotechnik und Informationstechnik*, vol. 133, no. 6, pp. 248–252, 2016.

(5) M. Nordin and P.-O. Gutman, "Controlling mechanical systems with backlash – a survey," *Automatica*, vol. 38, no. 10, pp. 1633–1649, 2002.

(6) R. Merzouki and J. Cadiou, "Estimation of backlash phenomenon in the electromechanical actuator," *Control Engineering Practice*, vol. 13, no. 8, pp. 973–983, 2005.

(7) S. Villwock and M. Pacas, "Time-domain identification method for detecting mechanical backlash in electrical drives," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 2, pp. 568–573, 2009.

(8) M. Ruderman, F. Hoffmann, and T. Bertram, "Modeling and identification of elastic robot joints with hysteresis and backlash," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 10, pp. 3840–3847, 2009.

(9) M. B. Kjelland and M. R. Hansen, "Offshore Wind Payload Transfer Using Flexible Mobile Crane," *Modeling, Identification and Control*, vol. 36, no. 1, pp. 1–9, 2015.

(10) S. Yamada and H. Fujimoto, "Proposal of high back-drivable control using load-side encoder and backlash," in *IEEE 42nd Annual Conference of the IEEE Industrial Electronics Society*, 2016, p. pp.

(11) V. Ivanov, D. Savitski, and B. Shyrokau, "A survey of traction control and antilock braking systems of full electric vehicles with individually controlled electric motors," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 9, pp. 3878–3896, 2015.

(12) K. Maeda, H. Fujimoto, and Y. Hori, "Four-wheel driving-force distribution method for instantaneous or split slippery roads for electric vehicle," *Automatika - Journal for Control, Measurement, Electronics, Computing and Communications*, vol. 54, no. 1, pp. 103–113, 2013.

(13) M. Ruderman and M. Iwasaki, "Observer of nonlinear friction dynamics for motion control," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 9, pp. 5941–5949, 2015.

(14) M. Ruderman, T. Bertram, and M. Iwasaki, "Modeling, observation, and control of hysteresis torsion in elastic robot joints," *Mechatronics*, vol. 24, no. 5, pp. 407–415, 2014.

(15) T. Emmei, H. Fujimoto, Y. Hori, K. Omata, and D. Gunji, "Slip ratio estimation for in-wheel motors with reduction gears using load-side high resolution encoders," in *IEEJ Industry Applications Society Conference*, vol. in Japanese, 2016, p. pp.