Contribution to the field of motion control

Prof Vukosavic has during more than 40 years provided significant contributions to the theory and practice in electronic controlled, electrical motor driven motion control systems applied in industry automation and in all branches of robotics. His distinctive contributions include development of innovative digital control algorithms for electrical drives and power electronic converters. He was the first to discover time-optimal, strictly aperiodic control algorithms for light-weight, flexible joint robots, and apply created solutions in modular multi-axis servo drives. Modern production machines, industrial robots as well as robots in military, agricultural and medical applications are built so that their total weight is as low as possible, with the aim of reducing metal consumption and reducing energy consumption during operation. Due to reduced stiffness of mechanical couplings, the operation is accompanied by mechanical and torsional oscillations that threaten stability and accuracy in position and speed control. Prof. Vukosavić developed a new, original methodology for the design of speed and position servo systems that enable the achievement of a strictly aperiodic response that suppresses force, velocity and position oscillations and guarantees time-optimal response, that is, the fastest response that can be reached within given system limitations. The methodology has found wide industrial application.

Evidence

Prof. Vukosavić worked on establishing the Vickers-Electric R/D group (later on MOOG-Electric) for development of digital motion control products for industrial robots and processes, with the customer base mostly focused on major European car manufacturers. While conducting the research and development, and while working to expand the research team and augment their competence, he also worked on the development of a new concept of digital motion control. The outcome is characterized by compactness of the characteristic polynomial similar to the parameter-sensitive dead-time solutions, but with multiple poles in the z plane shifted to the positive part of the real axis and with enhanced robustness. The new methodology guarantees strict aperiodicity, time optimality and insensitivity to parameter changes proven by significant vector margin. Design methodology and engineering foundations of this approach are given in monograph [1], which summarizes contributions from several journal and conference papers. The monograph introduces theoretical support and practical solutions for designing and tuning motion controllers. Theoretical developments within [1] result in control structures and parameter setting procedures which secure strictly-aperiodic force, speed and position response with the maximum speed. By considering the transport delays and the feedback acquisition processes through direct digital design approach, proposed methods provide the motion controllers which make the most of the given mechanical subsystem and provide the best feasible bandwidth and precision. Solutions published in [1] were advantageously used in industrial multi-axis motion control, trajectory generation and compliance control, featuring an unprecedented performances. He also introduced widely accepted control means for the suppression of torsional oscillations and mechanical resonance [2], designed for the systems with elastically coupled masses which establish mechanical resonators, the resonant frequencies of which are comparable with the desired bandwidth, thus jeopardizing the desired performances. Conventional anti-resonant compensators were sensitive to parameter changes, and their proper setting required the knowledge of temperature-sensitive viscous friction. Moreover, conventional notch-type IIR compensators with exceptionally low damping of the poles and zeros are sensitive to the finite-wordlength issues and generate considerable noise. Methodology of [2] provides robust, FIR-based suppression of torsional oscillations in industrial robots which does not require the viscous friction parameters and does not depend on the remaining parameters. It can be re-tuned on-line in accordance to the outputs of identification routines. The approach of [2] is mostly used in industrial robots at EU car manufacturers, but also in other applications worldwide.

Industrial impact

The results of [1] were used to build the motion products DBM, DBS, DS2000, DMS and DM2020 that are used by European automotive sector, with more than 80,000 installations until 2002, and they helped to reduce the cycle time of industrial robots. His motion control algorithms with anti-resonant features enabled considerable increase in speed, precision and robustness of flexible industrial robots with fixed- and variable-compliance actuators. The above discoveries were always boldly implemented in the industrial environment, and they were installed at a number of world-renowned car manufacturers, used in injection moulding machines, medical and agriculture robots, laser and water cutting machines and military applications. The key features of his industrial motion products include robust, DSP-based algorithms for on-line efficiency optimization [3], on-line identification of key parameters in ac spindle drives [4] and other advanced diagnostic and monitoring methods for electrical machines and power converters used within industrial robots. He also introduced the first robust, noise-free feedback acquisition systems for industrial environment that were implemented on contemporary DSP-platforms. Relying on automated oversampling and decimation, his robust digital controllers achieved the best bandwidth for the given PWM frequency [5]. The above DSP-based solutions are nowadays widely used in industry.

Evidence on industrial impact

The significance and long-term impact of the results of prof. Vukosavić in the field of digital motion control to be evaluated through the practical industrial use of DBM, DBS, DS2000, DMS and DM2020 products, designed on the basis of his methodology, concept and algorithms. According to several executives of Vickers-Electric/Moog and the company documents, the relevant motion control products developed by prof. Vukosavic were the first multi-axis servo-drives for digital motion control of light-weight industrial robots, targeted at car manufacturers and their production lines for automated assembly. Their use worldwide started during the last decade of 20th century, at times when prof. Vukosavic worked on establishing the R&D group in Vickers-Electric and has been the lead designer and inventor of the IGBT inverters, control hardware, and software for these product families, and it proceeds as well nowadays. The total volume of the products sold on the European automotive market alone exceeds 80,000 with the value of over US$70 million. In the field of industrial, manufacturing robots, the most significant applications are within the production lines of the companies Renault-Automation, Fiat, Peugeot, Michelin, Comau-Robotics and Systemrobot, where the application of the prof. Vukosavic algorithms increased the accuracy in tracking the trajectories of tools and work pieces and enabled cycle shortening. Results achieved by manufacturers of metal and non-metal machine tools, including Risco, Card Monroe, Protti, Steiger, Jobs JO-TECH, Mapos, Axis, Jones&Shipman, WEG, Whitney Automatex, Behrens and Bihler, indicate a significant increase in accuracy, which proved to be particularly significant when cutting with a water jet or laser. Strict aperiodicity and time optimality improved the performance of machines for cutting and processing glass, stone, arcopal and leather. Among the most important users are the companies Verrerie Cristalerie d'Arc, Incimar and Atom. Precise tracking of trajectories is particularly important for machines that produce plastic parts by casting and injection under high pressure, as well as for machines that process metal by cutting and bending. Among the constructors who used the results provided by prof. Vukosavic are Klockner-Ferromatic (Malterdingen, Germany); Cincinnati Millacron (USA), as well as Italian constructors Salvagnini, Omes, FICEP, and BHS-Torino. Finally, DBM devices were used in gantry cranes with bridge-like overhead structures, where the algorithms developed by prof. Vukosavic significantly improved the performance of the "electric shaft" control structure. Among the constructors who have widely used the device are JOBS, Salvagnini and Michelin-Imeca.

[1] S. N. Vukosavic, “Digital Control of Electrical Drives“, Springer, New York-USA, 2007, ISBN 978 0-387-25985-7, 352 pages.

[2] S. N. Vukosavic, M. R. Stojic, "Suppression of torsional oscillations in a high-performance speed servo drive," IEEE Trans. Ind. Electron., 45(1), pp.108-117, 1998.

[3] S. N. Vukosavic, E. Levi, “Robust DSP-based efficiency optimization of a variable speed induction motor drive,” IEEE Trans. Ind. Electron., 50(3), pp.560-570, 2003.

[4] S. N. Vukosavic, M. R. Stojic, “On-line tuning of the rotor time constant for vector-controlled induction motor in position control applications,” IEEE Trans. Ind. Electronics, 40(1), pp.130-138, 1993.

[5] S. N. Vukosavic, Lj. S. Peric, E. Levi, "AC current controller with error-free feedback acquisition system," IEEE Trans. Energy Conversion, 31(1), pp.381-391, 2016.