Vuk and Georgi: An Adventure into Active Systems via Mechatronics, Robotics and Manufacturing Engineering

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Abstract—The last century’s ending quarter was marked by an dramatically dynamic development of new technologies and practical realizations of diverse technical constructions in various fields of engineering, in general, and in robotics, in particular. However, such growth of new technological achievements was not accompanied always with the necessary caution steps and protection measures against possible breakdown and destructions, which in specific cases and under certain conditions could be disastrous. In this talk commemorating Academician Vukobratovic and drawing from his endeavors on the so-called active systems and research he shared with me as well as our academic cooperation during the last decade of his active work, while examining some advantages, his merits for the entire field are pointed out to the best author’s abilities. Some active systems such as adaptation for active noise and machine vibration control via active damping by force feedback as well as mobile robotic unmanned air and underwater vehicles as well as platoon of ground vehicles are not considered. Rather focus is put on active controls of earthquake induced vibrations and high-rise structures, manufacturing processes, wheeled mobile manipulators and walking humanoid robots are discussed in more detail while on homing missiles are only mentioned. In due course, some solutions to contact task in dynamic environment that are linked with active systems are also touched upon.

Keywords—Active systems; aerospace engineering; civil engineering; manufacturing engineering; mechanical engineering; robotics and robotic systems.

I. INTRODUCTION

It is very much true that the present day research is focused on topics of human-robot (see Figures 1, 2 and 2) encounters and interactions is things that are close to get transferred from the realm of computer animations and simulations into the real-life and real-world. Crucial roles and tools in these advances have the remarkable achievements within the last two decades in Information Technologies and Computational Intelligence. However, what really is missing in a number of recent publications is the very fact: Robotics and closely related disciplines are sophisticated engineering disciplines of Physical Sciences in the first place [35, 39, 42, 48, 49]. Moreover, the word is about control of complex physical systems [5, 6, 21, 50, 51].
For instance, no controlled stable physical walking happens with observing the law on zero moment point (ZMP), which is one of the fundamental discoveries due to Miomir K. Vukobratovic and his collaborators in the late 1960s and early 1970s [26, 45, 46, 56]. As it is well understood by now (e.g. see works [33, 35, 36]), indeed any applied computing and/or computational intelligence based walking robot controls must observe the ZMP law and its usage to synthesize stable controlled walking. In those days of ZMP discovery, in June 1975 during the Yugoslav ETAN Conference in Ohrid - Macedonia, I met in person Dr Vukobratovic at the Funding Assembly of Yugoslav Section on Robotics and Flexible Automation. Vuk was already so well know across the former S.F.R. Yugoslavia that about 25-30 people, mostly young ones me inclusive, responded to his call and this section was established. Then, a young assistant, I was all but a scared pupil of his. It was not too long before Vuk involved me in studies on flexible automation manufacturing systems. Soon enough, our relationship become so close even the series tragic civil wars in former S.F.R. Yugoslavia could not interrupt it.

Nowadays, in considerable many conference papers and journals articles there appear specific tendencies towards re-defining the discipline of robotics and automation [32], therefore indirectly, also the closely related disciplines of manufacturing engineering and mechatronics engineering. There are no doubts, the relevant signal and information processing play crucial roles. However, the main enabling technologies that make things work, in fact, are the technologies of system control and supervision. Perhaps this could be best appreciated if we recollect our memory of the achievements of the exoskeletons of Vukobratovic and his collaborators [46-48] that paved the way to nowadays research advances into the realm of Humanoid Robotics. In here, this fact is documented by means of the next Figure 4 below.

![Fig. 2 Human-robot interaction: Robot providing to a human customer as per human requirement [65].](image)

![Fig. 3 Real-world physical implementation of wheeled robot PR2 providing service on a supervisory command by a disabled human [9].](image)

It is natural that the human endeavor shall incline and strive to reach something like smooth robot-human encounter, getting acquainted, and learning about each other as shown in Figure 6 further below (one of the current research endeavors), in the next page. The way towards achieving this goal, however, is not via neglecting the physics but via paying deep respect to it because the word is about controlled composite tasks in a dynamic environment before processes of cognition and learning could start. It thus due to the merits of Vukobratovic and his Belgarde School of Robotics, who were among the first in the world to introduce properly system dynamics and control of both manipulation and walking robots (interested reader should consults a set of Springer-Verlag in the 1980s by Vukobratovic and his collaborators).

Yet, rather surprisingly in my opinion (!?), there is no mention of the above unique discoveries of then young Vukobratovic and his collaborators in the recent article [32] on the beginnings of robotic research. The relevant Figure 4 below was taken from there (see p. 73).
II. A PRELIMINARY NOTE

Why in the realm of robotics and robotic systems a need appears to mention engineering constructs called active systems? It should be noted, regardless the category of so-called active systems has practically existed for more than two decades, it seems instrumental to say something more about their physical nature. It is believed so, at least because of the simple fact that in engineering creations in all engineering fields the number of passive (traditional) systems being potential candidates to become active is growing considerably. Moreover, the prospect of engineering and implementation of complex dynamic networks and/or systems-of-systems only gives rise to faster expansion. For, up to fairly recently, active systems have been all but synonymous with active suspension of road and particularly of railway vehicles in transport engineering, and nothing more.

Only in the course of the last couple of decades the idea of active systems spread from mechanical engineering into systems engineering of complex control systems for hybrid complex plants and somewhat earlier constructions of civil engineering. While active systems in vehicles were aimed at adjusting some of the suspension parameters for maintaining the vehicle dynamic
performance, such as motion smoothness (i.e. the ride comfort of the road vehicle), or, maintaining the lateral contact force (wheels - railway tracks) in the permitted range (for the motion safety), the goal of active systems in civil engineering predominantly is to maintain the static performance of civil structures by changing their stiffness in accordance with variable external loads. In contrast, the goal within complex control systems engineering is to enhance modifying the overall system dynamic by combining time-driven evolution with event-driven one by logically integrating them towards wider range of collective adaptation.

Having in mind these remarks, active systems could be defined as the systems which, by automatic adjustment of the characteristic dynamic parameters in a certain range, preserve their dynamic performance, enabling satisfactory functioning of the system under conditions of either internal or, particularly, external perturbations that can even have an extreme character. While there is no need to speak about the advantages of active systems as compared with the passive ones, which in some way participate in the process of adjusting their characteristics to the changed conditions in which the systems (constructions, structures) operate, some of their disadvantages should be still pointed out. Let us mention, for instance, the implementation problem which is technological by its character, so it becomes less important with time, and the other, much more important problem - the maintenance costs, which are inherent and can never be ignored. The active systems must be operative and ready to react in time, and if an extreme situation arose, immediately.

III. OUTLINE OF THE PRESENTATION

1. AN INTRUDUCTION
2. A PRELIMINARY NOTE
3. EARTHQUAKE SUSTAINABLE BUILDINGS: A SAFETY CRITICAL VIBRATION CONTROL SYSTEM
4. ON SOME CONTROL PROBLEMS IN MECHATRONICS
5. ON SOME CONTROL PROBLEMS IN MECHATRONICS UNMANNED MOTION OBJECTS
6. CONCLUDING REMARKS

IV. A SYNOPSIS-LIKE OUTLINE

The second half of the last century was marked by a very dynamic development of new technologies and practical realizations of diverse structures and technical constructions in various fields of engineering. However, such growth of technological achievements was not accompanied by the necessary caution steps and adequate protection measures against possible breakdown and destruction, which in some specific cases and under extreme conditions could be disastrous.

Today, two crucially and extremely sensitive problems can be formulated. The first one is related to the already existing objects and technological systems, and the second is posed ahead of the current and future systems, notably of those constructions, structures and objects that are of the extreme strategic importance in the field of complex electro-energetic systems safety and defense readiness of the regions and countries.

In the first case it is necessary to consider the possible reconstruction and repairs in order to reduce the risk of malfunctioning and destruction. And in the second case, on the grounds of thorough techno-economic analyses, the decision has to be made about the incorporation of some indispensable technical protection mechanisms that increase considerably the probability of the object, structure or the plant system to maintain its performance at a certain level of functionality under severe conditions, which may include strong gales and other high-intensity meteorological occurrences, as well as dangerous seismic ground accelerations. High edifices (tall buildings, cooling or television or towers for telecommunication network nodes, sport halls of large roof spans, etc.), suspension bridges, large water dams, nuclear plants, complex electro-energetic power systems, etc, belong to the class of objects, (plants) constructions and systems of high strategic importance. The reasons for their grave failure can also be diverse in nature. The elements of artificial intelligence should be included into all the mentioned objects (plants) and systems to ensure their active responses, the quality and intensity of which depend on the variable conditions in which these plants and systems should function, and in which they could preserve their basic functionality.
simulators of electro-energetic systems, and other important objects, structures, and systems. In addition to the simulation of the physically realized complete system (object, construction, structure) or its parts (modules), we should mention the most recent technological achievements in the domain of virtual object platform, where the physical modules of different complexity are connected with the simulation display of the scene and/or part of the object. Still, one of the always critical issues – how to capture the uncertainties within this plethora of various systems – remains delicate and ever open to be especially validated.

![Diagram](a1)

![Diagram](b1)

![Diagram](a3)

![Diagram](b3)

Fig. 9. Stabilization performance of the 4-DoF benchmark HRB: The 10kN step-disturbance (into building base) responses of the uncontrolled versus the SMC stabilization controlled displacements at the first and the third storeys in the time domain [12], [14].

The respective physics behind this control performance can be better understood should frequency responses are also examined. Figure VI show the respective frequency responses of both the 1st and the 3rd storeys for uncontrolled and SCM stabilization controlled building, in a superimposed manner, for apparent comparison. The actual ranges of frequency spectra remain very much the same; however frequency response amplitudes are considerably different between the uncontrolled and controlled HRB. Not unexpectedly, the differences in the frequency domain between the cases of PID and SMC controlled building have become rather apparent.

![Diagram](a)

![Diagram](b)

Fig. 10. Stabilization performance of the 4-DoF benchmark HRB: uncontrolled versus SMC controlled displacement responses at the first and the third storeys for 10kN step disturbance to the base in the frequency domain. Remark: Controlled performance under PID and SMC controls.

The criterion on the basis of which the “activation” of a passive construction, leading to a partially or fully active one, is carried out is defined on the basis of the goal to what extent we want to keep the system under control. Thus we arrive at the possibility of controlling the plant system (object or process) under the conditions of malfunction, either by continuing the process of its sufficient (or even minimal) functioning, or by preventing further progress of the malfunctioning, to avoid its higher stages that might have catastrophic consequences to the system and to its narrower or broader environment. Such an active relation towards the potential failure of the plant system or construction structure could yield a more general technical systemic strategy that could be named the “Breakdown Safety Critical Control System”.

The systems whose behavior has to be adjustable to the variable operating conditions, which nowadays are being in a growing demand, should be partially or fully active (Vukobratovic, 2000). Based on the mentioned examples of real or hypothetical active systems in different fields, we can speak about very specific robotized constructions or systemic structures involving different kinds of feedback loops. Thus, we can already speak about the robots of different classes: conventional robots and
unconventional robotized (active) structures, buildings, cooling towers, self-sustained manufacturing plants, driverless vehicles, pilotless air or underwater vehicles, long suspension bridges, etc.

Active response of technical systems and constructions is already becoming a real need in various systems in a broad range of engineering areas (mechanical, electrical and civil engineering). In each of these branches, there is the necessity to maintain the desired system performance under variable working conditions, as well as in the case of external perturbations of different types that could lead to the so-called extreme conditions.

It is a characteristic of the active systems that by adjusting dynamic parameters, their dynamic performance is maintained in different working modes and under variable operating conditions. In the near future, it is quite realistic to expect the widespread realization of active systems and constructions that could lead to an essential improvement of their dynamic performance. Particularly, this would be the case under conditions when the capabilities of traditional (passive) systems (constructions, structures) are exhausted.

Due to the difference from the approach to the synthesis and implementation of active systems, involving the changes of a certain dynamic parameter (inertial, stiffness, and most often damping), it can be additionally proposed that some particular systems and constructions should be designed so as to feature a reconfigurable (varying) geometry in purposeful operating margins (Vukobratovic, 2004; Vukobratovic, 2000; 1998). In this way, one arrives at a new possibility of solving the problems of active systems and structures. Namely, by changing the relevant dynamic parameters it is possible to maintain the requested dynamic performance, while by changing the geometrical parameters, the appropriate distribution of the variable load is achieved in a most direct way and, indirectly, the stiffness of the constructions and structures is adjusted.

For the reasons stated, concerning the constructions, objects, and systems that may suffer from malfunctioning or destruction, we now arrive at the real necessity to highlight a new engineering field, which has already been called safety and prevention engineering. This new field of engineering should combine the efforts and coordinate the activities of the scientists and experts in forming a sufficiently general theory and safety concept for technical objects and systems.

Fig. 11. A snapshot of the animated simulation of the controlled operation an automated flexible manufacturing system [51].

Fig. 12. Communication timings (a) and the operating model based of stochastic Petri nets (b) of the FMS in Fig. 9 [51].
In developing these methods and safety means especially for certain potentially endangered constructions (structures) as well as in implementing and using safety precaution technologies must rely in much better understanding of system dynamics. This activity should be accompanied with promoting a safety culture and spreading it within the society, in which nowadays we face actively and in a different often unforeseen modes various natural (ecological and the others) and technical breakdowns and disasters.

Nonetheless, finally we should not arrive to undisputed conclusion that active systems will always be better and that control system can compensate for a bad design of the plant system as in the above case study of HRB stabilization to sustain earthquake (Figures 8-10). In most cases, a bad design will remain bad, active or not, and an active system engineering solution should normally be considered only after other passive means have been exhausted. One should always bear in mind that feedback control can compensate external disturbances only in a limited frequency band, which is called the bandwidth of the control system. Moreover one should never forget that outside the bandwidth of designed technological systems, most often disturbances are actually amplified by the applied controls.

It appears rather amazing to note how many innovative ideas have been triggered by the actual research studies in legged locomotion, manipulation, and mobile robotics. A considerable number of them have emanated from the efforts to re-think other engineering systems along the lines of either manipulation or legged locomotion robotics.

REFERENCES


[53] Vukobratovic, M. (1998), Contact Tasks of Active Systems Interacting with Dynamic Environment in Different Engineering and Biological Systems. Synopsis of Macedonian Academy Lecture. Private communication, Skopje MKD (Lecture delivered and questions replied on the 18th of June in Amphitheatre MANU during 10:00-12:00 hours).


Appendix: On Parameter-dependent and Multiple Lyapunov and Lyapunov-like Functions in Switched Control Designs

The theory behind these two essentially Lyapunov techniques, albeit not classical (Figures 14, 15, and 16), has been applied to an aerospace illustrative example of the class of switched LPV systems with unstable subsystems. In turn, the respective linear matrix inequalities (LMIs) are solved and the switching law is designed.

That is to say, the relevant theorem was applied first and then the respective computer simulations have been carried out and simulation results produced. The designed switching law guarantees the controlled system state responses converge asymptotically to the steady-state equilibrium.