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QUA VADIS MECHANICS
Subjective Point of View

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Abstract: *The paper deals with the subjective point of view on the recent and current development in the area of engineering mechanics. It starts new technologies that have significantly influenced engineering mechanics. Then it discusses the area of structural mechanics in micro, mezzo, macro scale. Then it deals with embedded systems that is basis for mechatronic and controlled mechanical systems. The essential is the control challenges dealing with vibration, motion, control distribution and influence of nonlinearities. It continues with new ways of simulation techniques. Finally, it ends with design challenges and design principles applied to mechanical systems.*

Keywords: Mechanical system, new technologies, structural mechanics, embedded systems, control, simulation, design principles

1. Introduction

This paper deals with subjective point of view on the recent and current developments of mechanics as the basis of design of machines and mechanical engineering generally. This paper provides an overview of innovative concepts of mechanics on which the author participated – this is especially the subjective point of view. Despite of that the described innovative concepts represent results that have been investigated for various applications. This paper in its limited size is just an overview of topics.

2. New technologies

The key development impulses are besides the creativity of human designers and researchers the new technologies that open new possibilities. In mechanics they can be summarized into

- New materials, recently it was carbon fibers leading to composite materials
- 3D printing as a new manufacturing technology
- Embedded systems in general, not only embedded control systems as the basis of mechatronics
- New computing approaches – after recursive formulation of equations, it is parallel computing, AI as LLM models dealing with time series, quantum computing.

To the computing approaches it can be added the creativity as a new computing power. Creativity lies in our subconscious. The subconscious solves everything, and only the subconscious can provide new innovative solutions. Creativity lies in discussion, in dialogue. The key is to ask the right questions; the answers are already there (in the subconscious).

The new technologies always open the question whether machine components and entire machines with significantly improved mechanical properties can be achieved.

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3. Structural mechanics

The structures are the visible applications of new concepts initiated by the application of new technologies. They can be classified into micro, mezzo and macro level. On the micro or mezzo level it is the creation of new materials with deterministic structure. Historically it was composite materials, currently it is metamaterials. These approaches use artificial cell structure creating new materiál with desired properties. A new approach on macro level is the combination of materials (Fig.1). A clamped beam with prescribed stiffness can be manufactured for example from dural only with some weight or from steel only with another weigth. If both materials are combined (1 is dural, 2 is steel) then the resulting structure has lower weight by 5+% than any of previous standalone material choices.

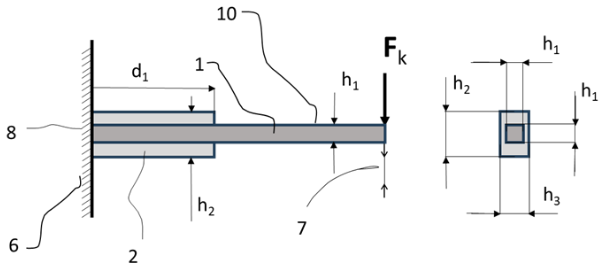

Fig. 1: Combination of materials.

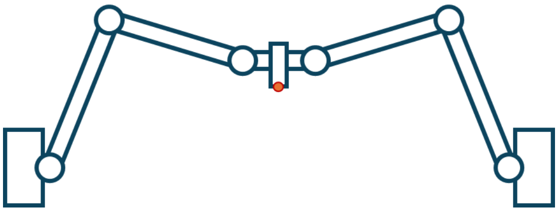

Fig. 2: Vault principle in connected robots.

Very remarkable it is the usage of nonlinearities. The nonlinearity is usually supposed as undesirable property, but it opens new areas of overcoming the limitations derived from linear world. Either the linear extension of influence is limited or the superposition is not happening. Example is the vault principle in Fig. 2. It was expected the addition of stiffness of two robots, but the resulting stiffness of 3.5 times of single robot is the consequence of vault principle. However, the nonlinearity in dynamics and control has larger and more significant influence.

This example of physically connected robots is an example of interconnected subsystems. To these interconnected systems it belongs various systems. They are the parallel kinematice machines, vault structures, mechatronic systems, collaborative robots, redundant measurement and nonlinear structural elements. The transition from serial kinematics of traditional robots through usual parallel kinematice machines to the redundantly actuated parallel kinematics machines is in Fig. 3 where the red arrows are drives. The redundant actuation means that the number of drives is larger than the number of DOFs. The advantage of parallel kinematics is that the drives are placed at the frame only. However, parallel kinematics suffers from singularities.

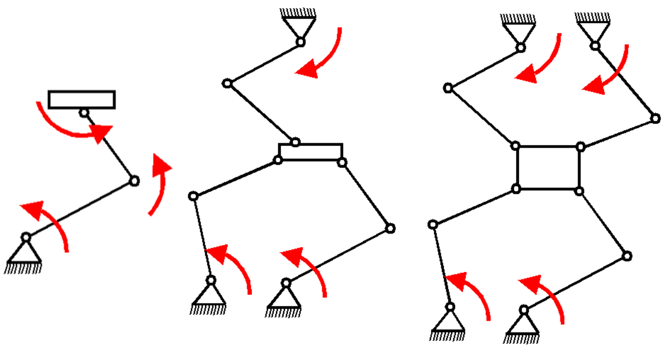

Fig. 3: Serial, parallel and redundant parallel kinematics.

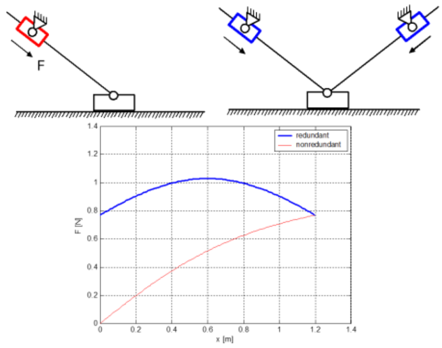

Fig. 4: Singularity removal by redundant actuation.

An example is in Fig. 4 where the actuator with force F moves the horizontal carriage in x direction. If the actuator and the carriage are one above the other then the actuator cannot transmit the force on the carriage. If there are two such drives, then the transmitted force from actuator is always nonzero and is almost uniform as i tis visible from the graph. The examples of redundantly actuated parallel kinematice machines are in Fig. 5. The left one (Sliding Star) has the potential to achieve three times increase of stiffness, eigenfrequencies and dynamics compared to seriál arm structure. The middle one (HexaSphere) enables to achieve +/- 100 degrees orientation capability that is for parallel kinematics exceptional. The right one (DoubleSphere) has the same orientation capability but achieved only with three drives.

The redundantly actuated parallel kinematics are the basis of cable driven robots and machines. Cable driven mechanisms require at least one additional force to the cable forces corresponding to the number of DOFs. Remarkable examples are in Fig. 6. In the figure left it is cable driven HexaSphere. In the middle the cable based mechatronic stiffness for gantry structures of machine tools is depicted. This can be passive as well as active structure. In the right it is the concept of multi-link cable driven robot with mechatronic stiffness. The traditional joints are stiffer (mass/stiffness ratio) than tensegrity structures. The cable based drives are lighter. The cable based mechatronic stiffness is multiplying the mass/stiffness ratio.

A specific redundantly actuated drive is the concept motor-on-motor (Fig. 13) that is capable to remove the dynamic part from the reaction forces in mechanisms.

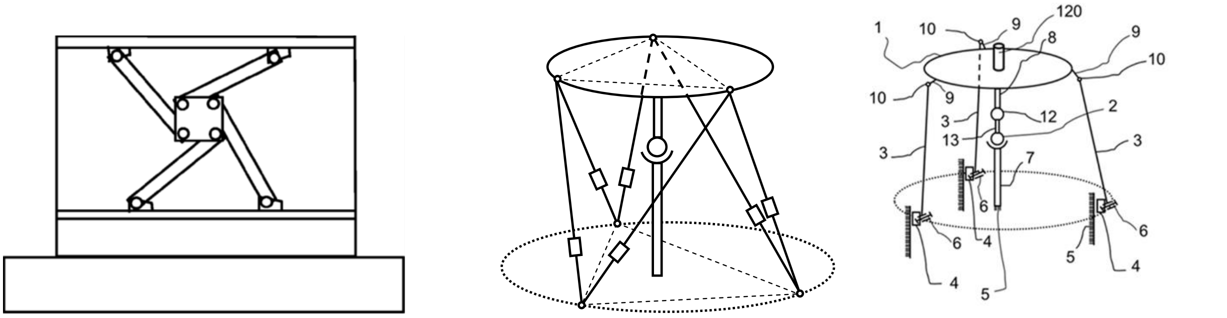

Fig. 5: Concepts of redundantly actuated parallel kinematics: Sliding Star, HexaSphere, Double Sphere.

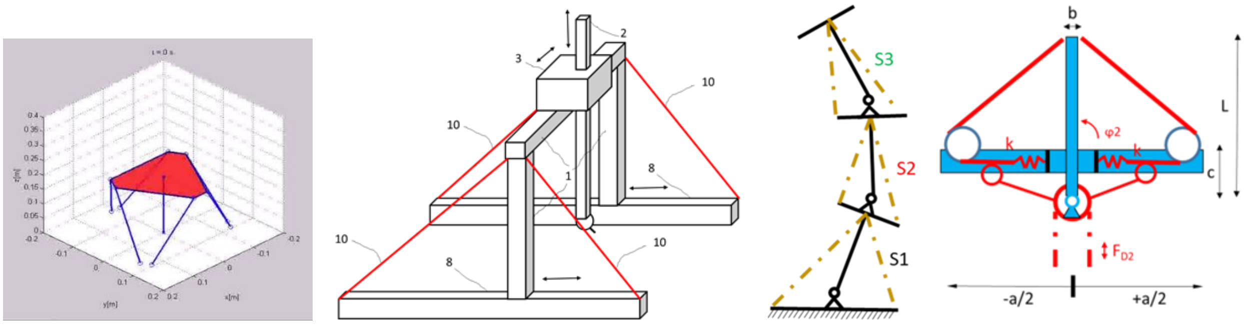

Fig. 6: Cable driven robots and machines.

The vault structures have been detected at connection of two robotic arms, example in Fig. 2. The composition of stiffness of the arms is super-linear.

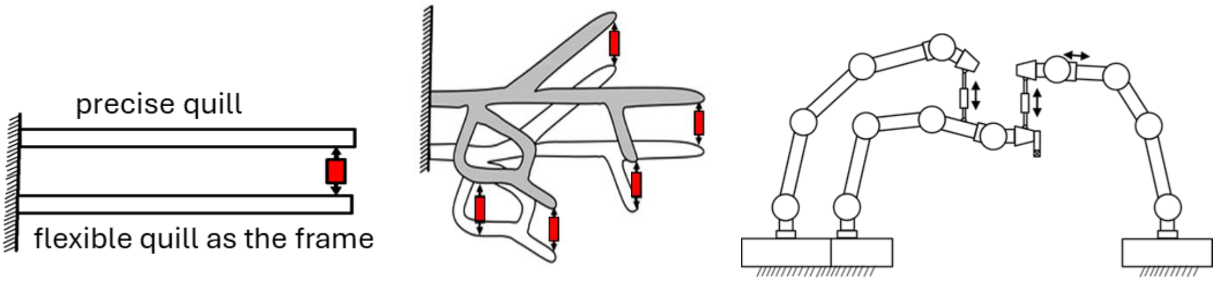

Fig. 7: Mechatronic stiffness.

The concept of mechatronic stiffness is the combination of interconnected substructures and mechatronics (active control). The concept and example are depicted in Fig. 7. Mechanical construction/structure is equipped with concurrent auxiliery structure and both structures are connected in connecting points by one or more actuators that are controlled based on deformation/motion of connecting points. The ratio of disturbance and actuator force is 1 and less. The basis with one actuator is in left figure. The middle figure describes multiple actuators and the right figure is robotic application. Another example of mechatronic system is the active spherical joint for +/- 160 degrees movability. It contains four DOFs from which always one axis must be blocked.

The examples of cooperating (collaborative) robots are in Fig. 2 and Fig. 9. In Fig. 9 left it is the application of connected kinematically redundant robot arms using the vault principle for operating within a cavity with increased stiffness. In Fig. 9 right it is a concept of manipulation with pliable objects, in particular the way how to push a pliable object through a hole. It always requires to use multiple robots.

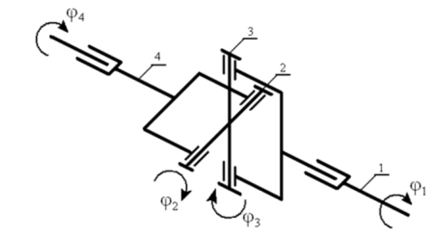

Fig. 8: Active spherical joint.

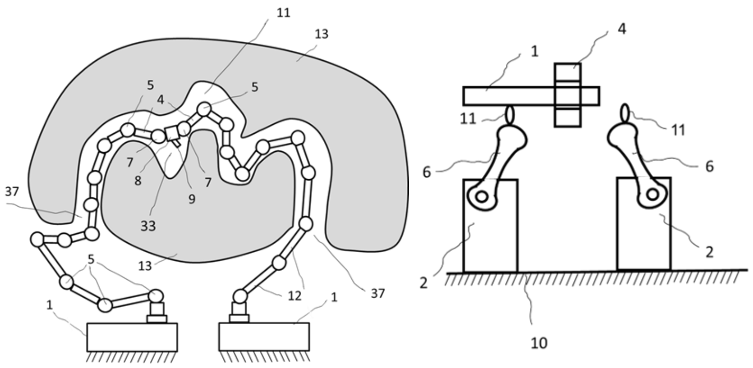

Fig. 9: Cooperating (collaborative) robots.

The consequence of redundant actuation is the redundant measurement. Its principle is in Fig. 10 left upper where instead of repetitive measurement in time the redundant measurements are carried out in the same time instant from various places in the space. The redundant measurement brings the phenomena of self-calibration and avoidance of uncertainty adding by increase of measurement accuracy. The application of this approach as a standalone redundant calibration and measuring machine (ReDCaM) for machine tools or robots is in Fig. 10 right upper. It has been used for mechanical ReDCaM with limited workspace in Fig. 10 left bottom. It has been extended into optical ReDCaM with large workspace in Fig. 10 middle left bottom. Another mechanical ReDCaM with extended workspace is in Fig. 10 right bottom. It has demonstrated the importance of angle measurements. The application of redundant measurement inside parallel kinematics machine (Sliding Star) is in Fig. 10 right bottom. In all cases the increase of accuracy is significant.

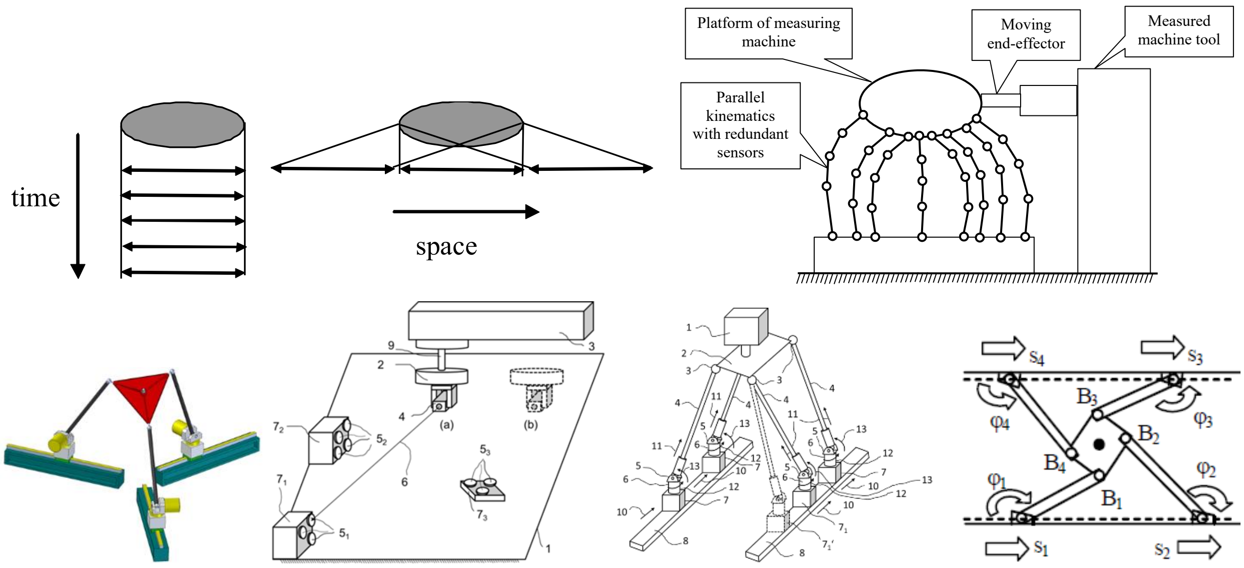

Fig. 10: Redundant measurement.

The development of suitable structural nonlinear elements for mechanical structures and machines is current research topic. Some examples are in Fig. 2, Fig. 6, Fig. 10.

The majority of machines benefits from possibility to modify their structure and parameters according to their state in which they operate. It is achieved by morphing their structure. The application of morphing forces in order to minimize the morphing effort is a challenge of movable structural mechanics. The concept of mechatronic stiffness is leading to favorable demand on the actuator’s capacity. Examples of morphing mechanisms for aircraft wings are in Fig. 11.

The new technology of 3D printing enables to manufacture metamaterials, embedded functional structures and other embedded systems described in next section. The progress of mechanics by 3D printing will be in structures that are otherwise unmanufacturable by traditional technologies. An example of such embedded functional structure is in Fig. 12. It is acoustic barrier with surfaces with both finite curvatures. Another example is heat exchanger.

4. Embedded systems

Embedded systems were traditionally the electronics for control in mechatronic systems. 3D printing can manufacture general embedded systems. The usage of this approach is for manufacture of distributed actuators depicted in Fig. 14. There are four research problems: how to manufacture distributed actuators in material of machines, how to supply them by energy, how to control them and for which purpose use them.

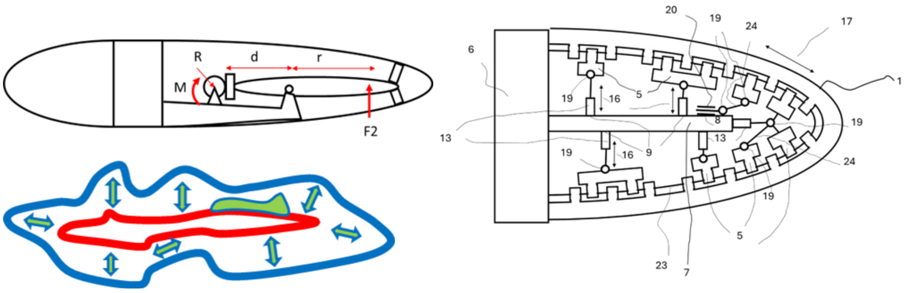

Fig. 11: Morphing of mechanical systems.

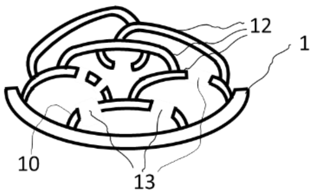

Fig. 12: Acoustic barrier.

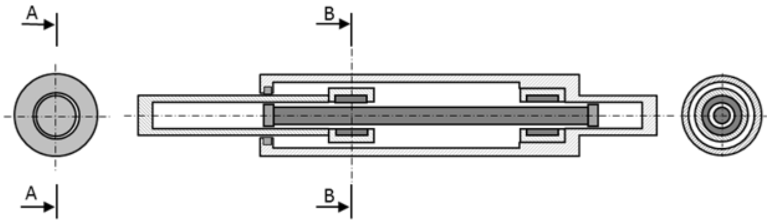

Fig. 13: Concept of motor on motor.

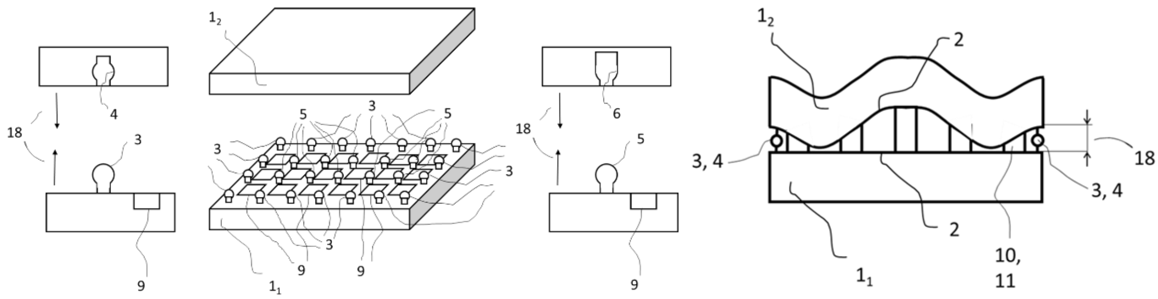

Fig. 14: Distributed actuators.

5. Control challenges

Control is through mechatronics today an important part of mechanical systems. However, the advanced application of control has many challenges. They are related to the stability and the need to know the system model. They are noncollocated vibration suppression – stable and model-free, the control of redundant drives that being deviation-based control leads to inaccuracy and instability, distributed control – stable and model-free, nonlinearity – what is it useful for?

The noncollocated vibration suppression means that the disturbance force Fk, Mk is applied in the place A, its influence is suppressed in the place B and the control actuation is available in the place C (Fig. 15). Interesting possibility to cope with that is the usage of vibration absorber with external control (Fig. 16) that enables to decouple the feedback influence on mechanical system. Another interesting possibility to cope with that is the usage of Wave Based Control (Fig. 17) that is an exceptional control approach without model knowledge.

The control of redundant drives if it is based on deviation feedback suffers from potential instability and inaccuracy. This can be solved by application of Sliding Mode Control (SMC) that does not depend on deviations. Another question is how the redundant measurement can create the system model online.

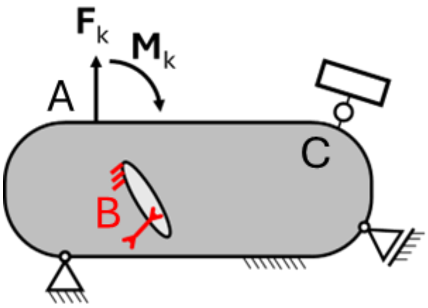

Fig. 15: Noncollocated vibration suppression.

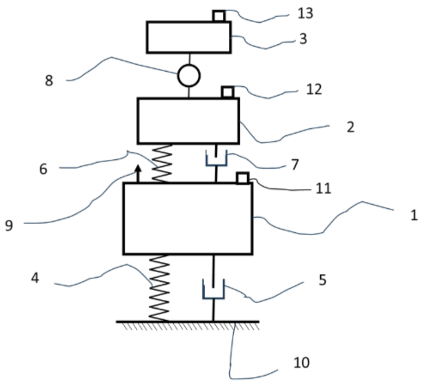

Fig. 16: Vibration absorber with external control.

Relatively new challenge in control of mechanical systems is their distributed control, its stability and requirement on knowledge of their model. A promising approach is the Wave Based Control (WBC) in Fig. 17 that offer stability without knowledge of the model. The difficult challenge in control of mechanical systems is the usage of appropriate nonlinearities. It can be the way how to overcome the limitation of their performance given in Bode sensitivity integral. Another fact is that nonlinearity is essential for the control of underactuated systems.

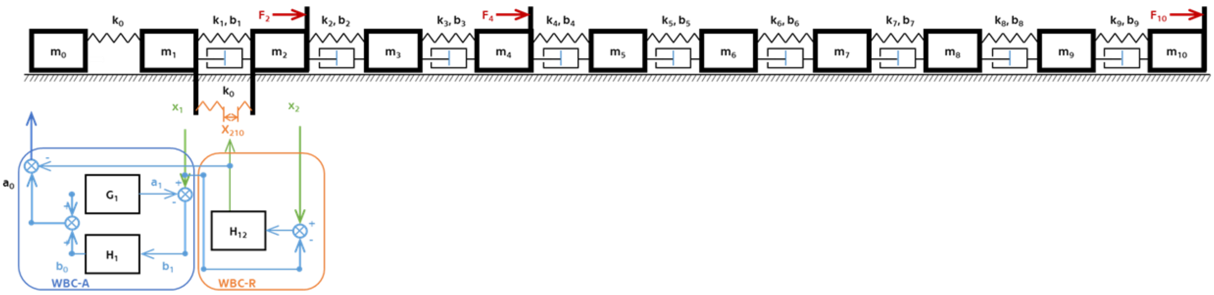

Fig. 17: Wave Based Control.

6. Simulation challenges

The design of mechanical systems requires their effective simulations. There have been developed the recursive algorithms for single computers. The new developments are expected using parallel computers, AI tools and quantum computing. Each of these areas are separate broader areas of interest and results.

7. Design challenges

The mechanical systems that use the above mentioned concepts must be designed into real machines. The design challenge is how to apply these new concepts and/or principles in design practice. The discussed principles are mechatronic stiffness, redundantly driven systems, redundant drives in parallel configuration, redundant measurement, motor-on-motor, externally controlled vibration absorber, nonlinearities.

8. Conclusions

New explored and yet not explored concepts in mechanics as well as the origins of new developments of these concepts have been briefly described. The references can be found at publications on webpage https://fs.cvut.cz/ustavy/sekce-ustav-mechaniky-biomechaniky-a-mechatroniky/ustav-mechaniky-biomechaniky-a-mechatroniky-12105/ustav-12105/lide-12105/?people=20462.