

# Variable Impedance Actuators: a Review

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## Abstract

Variable Impedance Actuators (VIA) have received increasing attention in recent years as many novel applications involving interactions with an un-known and dynamic environment including humans require actuators with dynamics that are not well-achieved by classical stiff actuators. This paper presents an overview of the different VIAs developed and proposes a classification based on the principles through which the variable stiffness and damping are achieved. The main classes are active impedance by control, inherent compliance and damping actuators, inertial actuators, and combinations of them, which are then further divided into subclasses. This classification allows for designers of new devices to orientate and take inspiration and users of VIA's to be guided in the design and implementation process for their targeted application.

*Keywords:* Variable Impedance Actuators, Variable Stiffness Actuators, Variable Damping Actuators, Compliant Actuators

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## 1 Introduction

Actuators are key enabling components for motion generation and control with properties that greatly impact the overall performance of any mechanical systems. The lack of suitable actuators has hindered the development of

high performance machines with capabilities comparable to humans, especially with respect to motion, safety and energy efficiency of human or other animals. The functional and neuro-mechanical control performances of bio-Preprint submitted to Robotics and Autonomous Systems June 17, 2013\*ManuscriptClick here to view linked Referenceslogical muscle far exceeds that of mechanical devices, with a key difference being the adaptable compliance or variable stiffness found in biological systems; this is very different from the performance of traditional stiff electrical drives used in industrial robotics, which require accurate, reference-trajectory tracking. Recent applications such as robots in close human/robot proximity, legged autonomous robots, and rehabilitation devices and prostheses, set different design specifications, where compliant actuators can have significant advantages over traditional actuation. Variable Impedance Actuators (VIA) are rapidly developing with a wide range of different actuators based on different principles, but as yet there is not “winning” design. Indeed, probably there is no winning actuator, but rather application dependent optimal solutions. To understand this “zoology”, the VIACTORS consortium [1] provides in this paper an overview as well as a categorization, discussing advantages and disadvantages of the different designs. This work is the first of three papers on VIAs, which tries to organize the VIA state of the art, and establish a common language for designers and potential users of VIA technology. Grioli et al. [2] present a Variable Stiffness Actuator (VSA) datasheet as an interface language between designers and users and discuss design procedures and how data generic VSA data may be organized to minimize the engineer’s effort in choosing the actuator type and size. Wolf et al. [3] propose VSA Design Guidelines for R&D engineers facing the challenge of designing new VSA systems and implementing them in use-cases as shock absorbing, stiffness variation, cyclic motions and explosive motions. The development and exploitation of novel actuation technologies will create a new generation of robots that can co-exist and co-operate with people and get much closer to the human levels of manipulation, locomotion and rehabilitation performances.

## 2 Classification of Variable Impedance Actuators

Position control in a task in which a robot interacts with the environment, is not a properly posed problem because the controller is dependent on parameters, which are out of the control potential. Yet, controlling the impedance and the equilibrium position is a well-posed problem that is independent of

the knowledge of the environment, if within certain boundaries. Applications of VIA are consequently found where robots must physically interact with an unknown and dynamic environment and the controlbody-actuator system must have abilities like :

- Efficiency e.g. natural gait generation, adaptation in legged locomotion and prosthetics for lower limbs, explosive motions such as throwing or kicking;
- Robustness to external perturbations and unpredictable model errors (changes) of the environment, of the robot kinematics and dynamics, or of the dynamics of a human interacting with it;
- Adaptability and force accuracy in the interaction with the operator, in applications in which continuous contact and accurate force exchange is necessary, such as in “hands-on” assistive devices, rehabilitation, exoskeletons and haptics;
- Safety to humans (and resilience to self-damage) in operations where the robot has fast, accurate motions, while cooperating, physically interacting or even possibly colliding with the humans and their environment, including other robots.

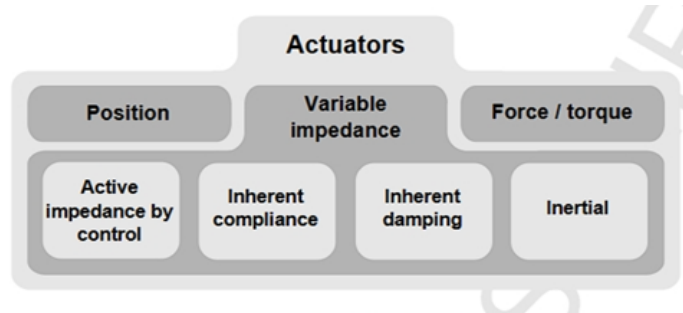


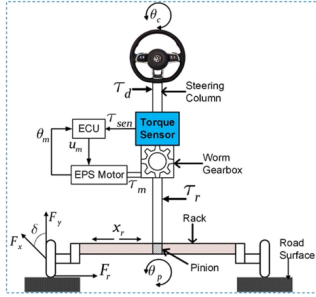
Figure 1: HELLO WORLD

The main classes of VIA are active impedance by control, inherent compliance and damping actuators, inertial actuators, and combinations of them, which are then further divided into subclasses as shown in Fig.2.

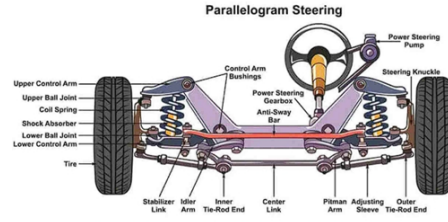
A general VIA is schematically shown in Fig.3a, where the motor drives the load through a transmission and a variable impedance element. The



Figure 2: Overview of Variable Impedance Actuator classification.



(a) Schematic of a general VIA.



(b) Series Elastic Actuator (SEA).

Figure 3: Schematic of a general VIA.

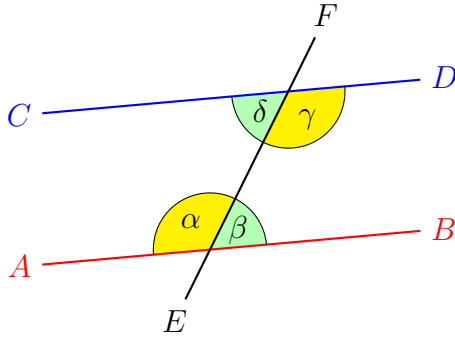
motor can be controlled in position, velocity, torque or impedance. The variable impedance element can be a spring and/or a damper, whose mechanical properties can be changed by an additional mechanism. The load can be a link of a robot or any other mechanical system. A typical example of a VIA is the Series Elastic Actuator (SEA) shown in Fig.3b, where the motor drives the load through a transmission and an elastic element (spring). The motor is usually controlled in position or velocity, while the torque applied to the load is measured by measuring the deflection of the spring. The stiffness of the spring is fixed and cannot be changed during operation. However, by controlling the motor position, the equilibrium position of the spring can be changed, thus changing the effective stiffness of the actuator at low frequencies. SEAs have been widely used in various applications, such as legged robots, prosthetics, and exoskeletons, due to their inherent compliance and ability to store and release energy.

### 3 Principles of Variable Stiffness

Several groups have designed adaptable compliance mechanisms, with elastic elements storing energy, in addition to altering the stiffness. This concept gives intrinsic capabilities (bandwidth, impacts, energy storage) over the joint stiffness range. However, two motors are required: one to control the equilibrium position and the second to control stiffness. In this section, a classification is presented, based on the main principle on which the adaptive stiffness is obtained (see Fig. 2). The different actuators from literature can be classified into three major groups:

- **Spring Preload:** Stiffness is altered by changing the spring preload.
- **Changing transmission between load and spring:** The stiffness is altered by changing the transmission ratio between the output link and the elastic elements.
- **Physical properties of the spring:** The physical structure of the
- **The physical structure of the spring itself is altered.**

Some devices use combinations of these main three mechanical properties.



When we assume that  $AB$  and  $CD$  are parallel, i. e.,  $AB \parallel CD$ , then  $\alpha = \gamma$  and  $\beta = \delta$ .

- 4 Principles of Variable Damping
- 5 Active Impedance Control
- 6 Inherent Compliance and Damping Actuators
- 7 Inertial Actuators
- 8 Combined Approaches
- 9 Design Guidelines
- 10 Applications
- 11 Conclusion

## References

## References

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