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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 unknown 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.

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 biological 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 no "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.

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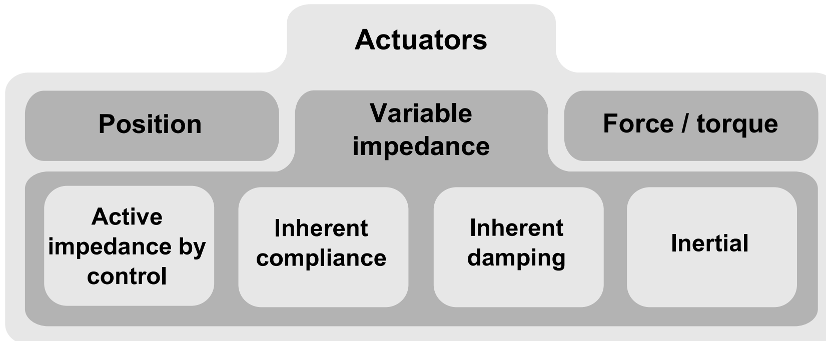

Fig. 1. Main categorization of actuators.

1. What is a Variable Impedance Actuator?

To define what a Variable Impedance Actuator (VIA) is, it is useful to start by defining a non-VIA (traditional stiff) actuator. A stiff actuator is a device, able to move to a specific position or track a predefined trajectory. Once a position is reached, the actuator will hold this position, (ideally) whatever the external forces (within the force limits of the device). It is a position source, i.e. a system with a very high (ideally infinite) mechanical impedance. This behavior is obtained when a motor has a high gear ratio (e.g. servomotors) aiming to be as stiff as possible [4]. Such actuators have excellent trajectory tracking with a high bandwidth and high accuracy. They are common in industrial robots. A VIA in contrast deviates from its set equilibrium position, depending on the external forces and the mechanical properties of the actuator (mostly inertia, stiffness and damping factors). Equilibrium is defined as the position where the actuator generates zero force or torque (also called virtual position by Hogan [5]). This concept is specific to VIA actuators, since it does not exist for stiff actuators. An extreme case is where the impedance is zero and the actuator forms a force/torque source or transparent actuator, e.g. gravity is a force source. Examples where a force/torque source are approached are direct drive motors [6] or constant torque springs.

VIAs are important in Embodied Intelligence. Pfeifer and Bongard [7] state that adaptive behavior is not just control and computation, but it emerges from the complex and dynamic interaction between the robot's morphology, sensory-motor control, and environment. Through smart design of the body and the actuators, part of the computational intelligence can be outsourced to the embodied intelligence making many tasks become simpler.

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 [8,9]. 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 were robots must physically interact with an unknown and dynamic environment and the control body-actuator system must have abilities like [10]:

- 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 co-operating, physically interacting or even possibly colliding with humans and their environment, including other robots.

Variable Impedance Actuators will be categorized depending on how their stiffness and damping can be achieved, Fig. 1. This is a revision of the work by Van Ham et al. [11]. A first division can be made between active impedance by control, inherent compliance and damping actuators, inertial and a combination of them.

In this section the terms impedance, admittance, compliance, stiffness and damping are introduced and a relationship between them is provided. Mechanical interaction between two systems *A* and *B* can be modeled looking at the dynamic relation between the variables which characterize the energy exchange and interaction behavior between the two systems. The resulting interaction force and motion between *A* and *B* cannot be attributed solely to one of the systems but is the combination of an intrinsic property (behavior) of *A* and an intrinsic property (behavior) of *B*. These intrinsic behaviors are referred to as impedance and admittance. If the system *A* is modeled as an impedance, system *B* must be modeled as an admittance to complement the other. Mechanical impedance is a dynamic relation which generates a force (in time) as a function of a displacement (in time). This differential relation can be linear (modellable usually with Laplace methods) or nonlinear (modellable with nonlinear functional analysis tools, such as e.g. jet bundles). Admittance is the complement of impedance. Stiffness is the differential relation between infinitesimal differences in force and position. Compliance is the inverse. Stiffness and compliance are related to elastic energy storage. Damping is a differential relation between infinitesimal changes in force and velocity, and is related to irreversible transduction of mechanical energy to heat and as such takes energy out of the systems.

2. Active impedance by control

Active impedance by control is when an actuator mimics the impedance behavior using software control [12]. Based on the measured output state, a correction is calculated by the controller and set by the (stiff) actuator. This type of VIA has an actuator, sensor and controller that are fast enough for the application, but no energy can be stored and due to the limited bandwidth of the controller no shock can be absorbed (e.g. hitting with a bat will not be handled by the system with the desired impedance setting). Similarly, exploiting energy efficient natural dynamics (cf. passive walkers [13]), is not possible since energy is required to move. Also the impedance controller is quite complex and requires accurate system dynamics models. An advantage of controlled impedance is that it can adapt both the damping and stiffness (contributing to the impedance of the system) online and this in a theoretical