Double Actuation Architectures for Rendering Variable Impedance in Compliant Robots: a Review

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Abstract

Novel compliant actuation systems have been developed in recent years for a variety of possible advantages, such as establishing a safe human-robot interaction, increasing energy efficiency, reducing the effects of impacts and even for the development of neuro-inspired robotic platforms to be used in human motor control studies.

In this rapidly growing and transversal research field, systems involving more than one active element (typically motors) for each actuated degree of freedom are being investigated to allow separate position and impedance regulations. Considering the wide range of applications and the large number of different arrangements deriving from the combination of two active elements and passive elastic components, several actuation architectures have been devised.

This paper reviews state-of-the-art rotary variable impedance units incorporating two separate motors. Existing devices are grouped in three main categories. A critical and comparative analysis of the most relevant features is carried out, also based on most representative prototypes. Recently proposed methodologies and evaluation criteria for design optimization are illustrated and perspectives on potential applications of double actuation systems are presented.

Key words: Double actuation architectures, Variable impedance actuators, Compliant robotics

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1. Introduction

In recent years robotic systems have been more and more conceived for applications where a high level of adaptability is required, in order to interact with the environment and to comply with actions exerted by external agents. New design paradigms [1] and actuation solutions [2] have grown, so to opportunely fulfill the requirements of these scenarios [3] and traditional *stiff robots* [4], with rigid, high-precision behavior, have given way to *soft robots* [5, 6] which operate compliantly.

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In *rehabilitation and assistive robotics*, the physical Human-Robot Interaction (pHRI) is a normal operative condition since users are continuously connected to a machine which guides or assists their movements. In this case a high level of biomechanical compatibility and dynamical adaptability is desirable. These machines have to be as transparent as possible to the active motion of the users and to provide assistance as needed in conditions where they are not able to complete a prescribed motor task [7].

Robotic prostheses are required to restore human functionalities lost due to amputation in a large variety of dynamical conditions. In the case of human locomotion, for example, collision with terrain is managed cyclically and exploited to store energy in elastic tissues, which can be released to reduce the active work produced by the muscles [8]. For this reason, in active prostheses, the necessity of having mechanical properties dynamically varying as a function of gait phase or speed and adapting to terrain shape is crucial to mimic the humans' physiological features [9].

Reproducing passive elastic properties of human and animal joints can also enormously improve the energetic efficiency of *legged robots*, especially in the case of running and hopping machines, as demonstrated in pioneer works in the early 1980s both in simulation and in prototypal implementations [10]. The on-line modification of dynamical properties is also pivotal in bipedal robots using the principles of pseudo-passive locomotion [11] in which a stable limit cycle of the system has to be achieved and possibly modified.

In *neuroscience*, the theories on human sensory-motor control and on learning strategies can be experimentally validated using dedicated robotic platforms [12, 13]. These systems have to reproduce the kinematic, dynamic and functional features of human limbs also with an high level of flexibility to test different kinds of control schemes. One of the main attributes to be replicated is the muscular agonistic/antagonistic actuation arrangement to have the capability of separately regulate joints position and stiffness.

In *industrial robotics* it is crucial to limit the energy exchange with external agents during unwanted collisions and to modulate the level of intervention during human-robot cooperative tasks [3, 14, 15]. The introduction of compliant joints reduces the reflected inertia during human-robot impacts [14, 16]. Moreover, it is possible to *i)* store and release energy, thus achieving link velocities above motor levels if appropriate trajectories are chosen (the sudden release of elastic potential energy makes compliant actuators potentially more dangerous than stiff ones) [17, 18]; *ii)* reduce impact joint torques at high impact speeds, thus protecting robotic joints [18, 19]. Regarding damages to external agents, the Safe Brachistochrone problem aims at finding the minimum time required to move between two fixed configurations such that an unexpected impact would guarantee a defined safety level at any instant. The solution to this optimal control problem suggests the need of adjustable impedance: low stiffness-high speed and high stiffness-low speed movements are required [3, 14].

For a rotational mechanical system the output mechanical impedance can be defined as the torque τ produced in response to a rotation $\theta(t)$. In the Laplace domain the mechanical impedance can be written as the transfer function

$$Z(s) = \frac{\mathrm{T}(s)}{s\,\Theta(s)} \tag{1}$$

in which $T(s)$ and $\Theta(s)$ are the Laplace transforms of τ and θ, respectively.

The simplest solution to render a desired (variable) mechanical impedance, i.e. to provide desired dynamical properties in the interaction with the environment, consists in adopting impedance control schemes to mimick visco-elastic characteristics. In this regards, a torque

$$\tau = k\theta + c\dot{\theta} \tag{2}$$

at the joint level can be commanded to a rigid actuator, being θ, $\dot{\theta}$ joint position and velocity respectively and k, c the parallel spring and damper constants to be virtually rendered. In this case the transfer function corresponding to the mechanical impedance can be written as

$$Z(s) = \left(\frac{k}{s} + c\right) \tag{3}$$

This active control approach is generally implemented on actuators that can be accurately torque controlled. Direct-drive motors can be employed to this aim because there is no amplification of the perceived inertia and friction due to the presence of gears and they can be regarded as ideal torque generators (i.e. with theoretical null intrinsic impedance). Alternatively, geared motors have to be controlled closing loops on torque sensors signals.

On the other hand the introduction of passive mechanical components gives the great advantage of reducing the impedance of robotic systems intrinsically, i.e. across the whole frequency spectrum. The interposition of a compliant element between an actuator and its load was originally presented in [20, 21] in studies on legged locomotion. The proposed prototype, indicated as Series Elastic Actuator (SEA), was a linear actuator but a number of rotary systems have been developed in recent years [22, 23, 24, 25, 26, 27, 28, 29].

This approach provides several advantages:

- intrinsic compliance allows shock tolerance;
- the compliant element protects the motor and gearbox in case of an impact on the output link;
- simple and high fidelity torque/force control can be implemented using as feedback signal the measurement of the elastic element deflection;
- the effects of stiction, friction, backlash and other nonlinearities are reduced;
- work and power output of the actuator can be increased if an appropriate series elasticity is selected according to a specific task;
- in cyclical and/or explosive tasks efficient energy storage/release can be achieved.

Since in SEAs high fidelity torque tracking can be implemented, impedance can be also regulated via active control. Nevertheless, series elasticity causes a degradation of performances in terms of control bandwidth with respect to traditional rigid actuation systems [30]. This limitation can be overcome using elastic elements whose properties can be varied during operation.

The aim of independently regulating motion and impedance field to improve performances as well as to stably controlling robots interaction forces with external agents paved the way to the development of *Variable Stiffness/Impedance Actuators* (*VSA/VIA*), which are achieved by means of redundant actuation solutions, i.e. including a number of active elements higher than the number of actively controlled Degrees Of Freedom (DOFs). The use of more than one active component has the drawback of introducing nonlinearities and a number of design constraints not considered for traditional actuators. For this reason double actuation units benefits can be exploited only if control algorithms are properly employed and redundancy is specifically solved in the target task.

The objective of this paper is to analyze different arrangements deriving from the combination of two active elements, and possibly some passive elastic components, to render variable impedance. Most of the presented configurations can mechanically regulate impedance by means of a single motor or the simultaneous actions of both motors. However, some systems only render desired impedance through active control and the two motors are employed to decouple position and impedance control problems.

Existing devices are grouped in three main categories. A critical and comparative analysis of the most relevant features is carried out and recently proposed novel methodologies for design optimization are presented.

It is worth noticing that the presented analysis will involve also several preliminary works presented in recent international conferences. This choice is motivated by the necessity of reporting about latest activities in the rapidly growing research field of variable impedance actuation.

2. Classification of double actuation units

Reducing the problem to its lowest terms, there are two ways to connect two actuators to a load: in serial or in parallel configurations (Fig. 1). According to the most commonly accepted definition of series and parallel in mechanical systems [31], a configuration is of serial type if the generalized displacement of the output link is obtainable by algebraic sum of the generalized displacements of the two actuators. On the contrary, a configuration is parallel if the torque applied to the output link is obtainable by algebraic sum of the torques applied by the two actuators. These basic possibilities can be varied to achieve a number of profoundly different configurations, by employing different kinds of (nonlinear) transmissions or introducing compliant elements.

Despite the high number of configurations that can be theoretically devised by arranging two motors and some elastic components [32], the focus of the paper will be only on state-of-the-art systems, which have been proved to be effective and relevant.

Two types of serial connections can be achieved: *purely serial* (Fig. 2a-d) and *quasi-antagonistic* [5] (Fig. 2e-f). In the first case the output of one motor is the input for the other one, whose output is connected to the load. Both of them can be *ordinary* (Fig. 2a, c, e), for a direct connection, and *differential* (Fig. 2b, d, f), if the same connectivity between the elements is achieved through a differential transmission. Parallel connections can be classified in: *purely parallel* (Fig. 3a-d) and *agonistic/antagonistic* (Fig. 3e-g). In the first case a *colocated* configuration implies a direct connection of both motors to the load (Fig. 3a, c), while in a *distributed* one the outputs of the motors are coupled and only one of them is directly connected to the load (3b, d). Agonistic/antagonistic architectures can be further distinguished in *simple*, *cross coupled* and *bidirectional* [6] (Fig. 3e, f, g respectively).

Therefore, purely serial and purely parallel solutions can be *elastic* or *rigid* if respectively they use or not compliant components. For elastic implementations a physical impedance regulation is possible while for rigid solutions only software control allows varying impedance.

While in agonistic/antagonistic architectures the two motors (and their series elasticity) are antagonistically coupled, in quasi-antagonistic configuration only the springs are antagonist while the motors are serially coupled. In particular, the simple agonistic/antagonistic arrangement (Fig. 3e) represents the parallel connection of two motors, each of them with nonlinear series elastic components.

This classification is schematically resumed in Fig. 4.

Compliant architectures presented in Fig. 4 are not simply series elastic actuators, but transmission mechanisms and the action of one (for all serial and purely parallel configurations) or both motors (for agonistic/antagonistic configurations) are used to regulate impedance. The necessary nonlinearities for impedance regulations can be introduced either directly in springs characteristics or in transmission mechanisms depending on the specific design choices.

The following sections will be focused on analyzing the different arrangements cited above, and on describing representative prototypes implementing the presented architectures.

Moreover, a third category can be identified, which cannot be properly classified as serial or parallel configurations: *Physically controllable impedance* actuators consists of all systems in which one of the two motors is employed to modify the mechanical properties of a passive elastic element. Possible solutions are exhaustively classified and described in [2] (where a further distinction is made between structure controlled and mechanically controlled impedance) but some examples will be also reported here. Also variable damping actuators will be touched on.

2.1. Serial configuration

In the serial configuration two motors can be used to control the position and the impedance simultaneously and independently [33]. This can be regarded as a direct extension of the SEA concept, which allows to overcome some of the limitations due to a fixed compliance. The drawback of this configuration is that the maximum torque is limited by the smallest motor. As previously remarked, a particular implementation of the serial configuration consists in using a differential mechanism. This principle is also reported in [34] where a rotary SEA is implemented through a Harmonic Drive (HD) gear in differential mode (Differential Elastic Actuator, DEA).

In a differential mechanism the relation among rotations θ and torques τ for the two input shafts (in_1 and in_2) and the output shaft (out) are:

$$\begin{cases} \theta_{out} = \theta_{in_1}/r_{in_1} + \theta_{in_2}/r_{in_2} \\ \tau_{out} = -\tau_{in_1} r_{in_1} = -\tau_{in_2} r_{in_2} \end{cases} \tag{4}$$

being r_{in_1} and r_{in_2} the reduction ratio of the two input shafts with respect to the output. The equivalent output impedance is:

$$Z_{out} = -\frac{r_{in_1}^2 r_{in_2}^2 Z_{in_1} Z_{in_2}}{r_{in_1}^2 Z_{in_1} + r_{in_2}^2 Z_{in_2}} \approx -Z_{in_2} r_{in_2}^2 \tag{5}$$

being Z the impedance of the related shaft. The approximation in (5) is possible if $r_{in_1} \gg r_{in_2}$ and it implies that the output impedance can be modulated by varying only the one of the shaft input 2. Hence, this shaft can be connected to a variable impedance system, while a positioning motor can be placed on the input 1, thus decoupling the two control problems. In the case of a HD, with reduction ratio N and used in differential mode, if the WG (Wave Generator) is considered as input shaft 1, the CS (Circular Spline) as input shaft 2, and the FS (Flexible Spline) as output shaft, equations (4) and (5) are valid for $r_{in_1} = -N$, $r_{in_2} = N/(N+1)$.

In the following sections purely serial and quasi-antagonistic configurations (both of them in an ordinary and differential implementation) will be described through some examples.

2.1.1. Purely serial - ordinary

The Double Actuator Joint (DAJ, [13]) consists of two motors connected in series: one of them commands the equilibrium point of the joint which is connected to (positioning motor) and the other one modulates the joint stiffness (stiffness control motor) via software control. The DAJ represents a *rigid* implementation of the ordinary purely serial configuration. Since no physical compliance is included, typical SEAs advantages (see section 1) cannot be exploited.

The Floating Spring Joint (FSJ, [35]) is an *elastic* version of the ordinary purely serial architecture. In Fig. 5a a conceptual diagram is reported. The Joint Motor (for position regulation) uses a Harmonic Drive (HD) as reduction gear; its output is serially connected to a Variable Stiffness Mechanism (VSM), which is composed by two cam disks separated by cam rollers and connected by a pre-compressed linear spring. The relative rotation of these two disks causes an elastic torque when the joint is passively deflected; the stiffness preset is physically regulated by a Stiffness Motor by modifying the initial relative rotation of the disks.

2.1.2. Purely serial - differential

The SDAU (Serial-type Dual Actuator Unit, [33]) is a rigid implementation of the purely serial differential configuration, where two motors are connected in series via a four-stage planetary gear train. One high-torque low-speed motor (Position Actuator, PA) controls the position and the other low-torque high-speed motor (Stiffness Modulator, SM) regulates the stiffness via software control (as for the DAJ system).

Moreover, the SDAU architecture allows to switch among three operation modes [33]: 'dual actuation' (PA controls the position and SM adjusts the stiffness), 'high torque' (a clutch mechanism locks SM and only PA is activated) and 'high velocity' (both motors play the role of position controller and their velocity can be summed if a small external load is applied).

An elastic implementation of the purely serial differential configuration is presented in [36]. In the VIDA (Variable Impedance Differential Actuator) two motors are connected to a HD in differential mode: the FS is used as output shaft, a rotary impedance-controlled SEA (Impedance Regulator, IR) is connected to the CS while a Position Regulator (PR) is connected to the WG (which has high transmission ratio with respect to the FS). The VIDA system only adds series elasticity with respect to the SDAU but no physical impedance regulation is allowed.

The features of differential HD are also exploited in the VS-Joint (Variable Stiffness Joint) presented in [17] to regulate position and physical stiffness preset separately. In Fig. 6 a conceptual diagram and a picture of the prototype are reported. In the VS-Joint a high power Joint Motor is connected to the WG for position regulation, a VSM is connected to the CS and the output link is connected to the FS. The VSM is composed of four compression springs whose linear deflection is transformed by a cam-based system in a centering torque against the compliant joint deflection. A small Stiffness Motor regulates the springs preload to change the resultant joint stiffness. In case of a passive deflection of the joint the positioning motor does not move and the output impedance is only determined by the VSM. On the other hand, the torque of an active joint movement is transferred to the link directly from the positioning motor to the output without additional friction and inertia of the VSM. Different shapes of the the cam disk profile can be used to provide different stiffness characteristics of the VSM.

2.1.3. Quasi-antagonistic - ordinary

The AMASC (Actuator with Mechanically Adjustable Series Compliance) is presented in [37]. The prototype is depicted in Fig. 7(a). In this actuator two motors are coupled in a quasi-antagonistic configuration, using pulleys and cables. The AMASC system has been specifically designed to adjust the dynamical properties of legged robots. In Fig. 7(b) a schematic overview of the AMASC is given. The springs F_Y are linked to floating pulleys to create a nonlinear spring function ($G(z)$ is the pulley transmission function between the extension of the cable z and the spring deformation y). The link to be actuated (leg) is placed on pulley J_2. One motor controls the rotation θ_1 of pulley J_1 (which corresponds to set the equilibrium position of the system with a constant stiffness) and a second motor controls the displacement x_3 resulting in a deformation of the springs and in the regulation of the output stiffness.

2.1.4. Quasi-antagonistic - differential

The Quasi Antagonistic Joint (QA-Joint, [38]) is similar to the VS-Joint since it employs a HD in differential mode with a VSM connected to the CS. From a comparison between Fig. 8a and Fig. 6a it can be noticed that the VSM of the QA-Joint is composed of two antagonistic nonlinear spring elements, while the one of the VS-Joint has not this antagonistic arrangement.

The compliant system consists of two progressive elastic elements opposing each other with a variable offset. A cam bar is connected to the CS of the HD; two pairs of rocker arms with cam rollers, each pair linked by a linear spring, act on different faces of this cam bar. A pair of rocker arms is fixed to the housing while the other pair is connected to a stiffness motor, which can modify springs pretension. A scheme of the elastic mechanism is reported in Fig. 8b. The use of the cam-roller mechanism allows to achieve different torque/displacement characteristics modifying the shape of the cam profile.

Due to the above-mentioned characteristics of the HD gear, output link position can be changed without implying any motion of the elastic mechanism, thus reducing the moving parts of the joint. It is noticeable that this advantage, already seen for the VS-Joint, is not present in the FSJ where the HD is not used in differential configuration.

2.2. Parallel configuration

Two motors connected in parallel imply that the output torque equals to the algebraic sum of the torque applied by each of the two motors. This can be achieved through two main configurations. The *purely parallel* one is basically used to meet safety and performance demands (as described in the following section) while the *agonistic/antagonistic* one allows a simultaneous regulation of position and stiffness taking inspiration from the working principle of the musculoskeletal system in vertebrates.

Dynamic control of joints stiffness is crucial for animals to produce a wide range of stable movements in accordance to tasks they have to perform, especially in environments where external disturbances are present. Independent stiffness and position regulation are enabled by the antagonistic arrangement of the musculoskeletal system: agonist and antagonist muscles drive one articulation and common-mode actuation, i.e. the co-contraction of both muscles, increases joint stiffness while differential-mode actuation allows position control.

Many robotic actuation solutions have been inspired by biological agonistic/antagonistic setup. This actuation architecture implies two significant drawbacks: the necessity of using complex control algorithms to achieve the desired behaviors and a reduced energetic efficiency. Different configurations have been proposed: *simple*, *cross coupled* and *bidirectional*. Some examples are presented in the following section; more details, also regarding energetic considerations, can be found in [6], where this classification was introduced.

2.2.1. Purely parallel - colocated and distributed

In the purely parallel colocated configuration two motors are directly connected to the load. The *colocated* architecture (see Fig. 3a) does not offer advantages if transmissions are rigid since the same effect can be achieved through a single motor with a higher torque, which would result in a more compact and lightweight design solution.

In [39] a *distributed* approach (see Fig. 3b) was proposed to assure desired interaction forces during constrained motion in robotic manipulators. In particular, a *rigid* macro/micro manipulation system was developed to verify the possibility of reducing impedance and of providing inherently stable behaviors in high bandwidth force control.

The Distributed Elastically Coupled Macro-Mini Parallel Actuator (DECMMA, [16]) adds series elasticity to the one presented in [39] (see Fig. 3d). This architecture was designed to overcome both the safety limitations of torque control [40] and the performance limitations of SEAs [20]. The implementation of joint torque control provides near-zero impedance only within the control bandwidth, thus high-frequency impacts cannot be attenuated. The SEA provides low output impedance across the whole frequency spectrum but with bandwidth limitations that strongly reduce performances with respect to traditional stiff actuators. The DECMMA approach overcomes these limitations using a high torque-low frequency SEA and a low torque-high frequency motor connected in parallel. In this way the torque generation is partitioned into low- and high- frequency contributions with low impedance at all frequencies. The two motors are located in different districts where they are most effective (distributed architecture): the heavy and high torque SEA (the major source of actuation effort) is placed remotely from the manipulator joint so to reduce its reflected weight and inertia while the small low torque motor can be directly connected to the joint through a stiff, low friction transmission to locally improve performance with a reduced amount of additional weight.

The PaCMMA (Parallel-Coupled Micro-Macro Actuator, [41]) is a compact implementation of the DECMMA approach.

2.2.2. Agonistic/antagonistic - simple

The simple agonistic/antagonistic arrangement actually consists of two SEAs connected in parallel to an output shaft (see Fig. 3e). It has to be noticed that, in order to have adaptable stiffness, the two series elastic elements have to be nonlinear [2, 42]. Quadratic springs in an antagonistic configuration, for example, provide a linear relationship between actuator co-contraction and joint stiffness [43]. Due to this nonlinearity a joint displacement under the equilibrium state of low stretching requires small torques while the equilibrium state under high stretching requires large torques to provide the same angular displacement.

If the torques generated by the two motors have different signs and the same magnitude they compensate for each other and no net output torque is generated; however, these opposing torques allow controlling the stiffness of the joint (*pretensioning of the joint* [44]). Therefore, if torques of different magnitude are applied, their difference generates a torque on the load.

Several prototypes have been designed which implement the simple agonistic/antagonistic architecture. Some representative examples are reported in Fig. 9 [45, 46, 47, 48, 49]. These prototypes constitute the elementary implementation of the simple agonistic/antagonistic arrangement; a more complex solution is represented by the Variable Stiffness Joint (VSJ) proposed in [50].

In this system two actuators are connected in parallel and a compliant linkage provides the possibility to vary the output stiffness. The linkage consists of four leaf springs connected to a central axis and four pivots that slide along each spring thanks to rolling elements (Fig. 10). Four 4-bar linkage systems transmit the rotation of two motors to the pivots (Fig. 10); they rotate together with the motors when they move in the same direction and with the same speed. In this case the distance to the axis from the pivots does not change and the stiffness is kept constant. The effective length of the springs changes when the motors rotate in opposite directions, thus varying the joint torsional stiffness.

This symmetric architecture allows to share between both motors the power to move the load or to change the stiffness. Even though the working principle is based on the physical modification of elastic components, the system is classified as agonistic/antagonistic since the net action on the output axis results from the differential contribution of the two parallel motors.

2.2.3. Agonistic/antagonistic - cross coupled

Simple agonistic/antagonistic configuration emulates muscles architecture (see Fig. 3e). Since only pull modality is allowed, the maximum output torque cannot be higher than that of one motor; moreover, no net output torque is available if the maximum stiffness is set ([6, 44]). The elastic couplings existing between different human joints suggest a solution to this limitation: the introduction of a third elastic element (see Fig. 3f) to cross couple the two motors enables setting preload forces and using a fraction of each motor torque in both directions [51].

The VSA (Variable Stiffness Actuator) presented in [52] is an example of the *cross coupled* agonistic/antagonistic configuration. In Fig. 11a a schematic view of the system is reported. The pulleys 2, 3, and 4 are connected by the belt 1. Pulleys 2 and 3 are controlled by two motors, while pulley 4 is connected to the joint shaft. The belt is tensioned by the elastic mechanisms 5, 6, and 7. The linear elastic elements 5 and 6 have a resultant nonlinear characteristic because of the geometric properties of the transmission mechanism. The system 6 keeps the belt in contact with the other two pulleys. When the two motors rotate in opposite directions the stiffness is varied. Starting from the red configuration in Fig. 11b, a clockwise rotation of pulley 3 and a counterclockwise rotation of pulley 2 cause the compression of spring 6 and the elongation of springs 5 and 7, resulting in a more compliant configuration (green in Fig. 11b). When the two motors rotate in the same direction the length of the springs does not change so that only the equilibrium position is varied.

2.2.4. Agonistic/antagonistic - bidirectional

Another solution to overcome the energetic limitations of simple agonistic/antagonistic architecture consists in using the push-pull configuration, i.e. a *bidirectional* connection of the motors to the joint [51] (see Fig. 3g). It has to be noticed that, in order to guarantee that motor continuously apply bidirectional torques to the output joint, the springs have to be constantly pretensioned.

This arrangement, besides allowing the simple antagonism operating mode (as previously described and also indicated as *normal mode*), also enables the motors to support each other increasing torque capability of the system (*helping mode*) [44].

The normal mode assures a broad stiffness adjustment range for low external torques; the helping mode allows the generation of an output torque up to twice the maximum torque of a single motor (in case no pretensioning internal torque is generated), still maintaining stiffness variation capability. Anyhow, the helping mode does not activate if no external torque is applied.

An external load can be shared by the two motors in different ways: output stiffness can be varied by regulating the ratio of the torques applied by the two motors. Therefore, the limitations to the range of allowable stiffness are provided by the following situations: *i)* maximum stiffness is achieved when only one motor completely compensates for the external load, generating its highest allowable torque; *ii)* minimum stiffness is achieved when the load is equally shared between the motors.

The properties of the bidirectional agonistic/antagonistic, with particular regard to the helping mode, are analyzed in detail in [44], where also a method to synthesize stiffness curve to ensure stiffness variation capability in bidirectional mode is reported. Moreover the BAVS (Bidirectional Antagonism with Variable Stiffness) is presented.

The second version of the Variable Stiffness Actuator (VSA-II, [51]) is also an example of *bidirectional* antagonistic arrangement. A picture of the prototype is reported in Fig. 12a. The system is made of two equal halves, each containing a pair of 4-bar elastic mechanisms (each pair is actuated by one motor). The schematic representation of a 4-bar mechanism is depicted in Fig. 12b; the motor is connected in O and its rotation is indicated with θ. A linear torsion spring k is connected in C and β is the transmission angle in A. Because of the nonlinear kinematic constraint between angles θ and β the torsion stiffness opposed to the rotation of axis O is also nonlinear.

The motors torque is distributed in stiffness regulation and net output torque; this distribution is different for the VSA and VSA-II, albeit for both architectures the external load decrease the stiffness range [51]. In the first system a differential torque is required to achieve the minimum stiffness thus reducing the torque available for the motion generation. In the second system the minimum stiffness can be set without generating any differential torque. Moreover, an external torque increases the maximum stiffness in the case of VSA while it decreases the stiffness in the case of VSA-II [51].

2.3. Physically controllable impedance actuators

Solutions which cannot be just considered as serial nor parallel arrangements are described in this section. In *physically controllable impedance* systems one of the two motors is employed to directly modify the properties of a passive elastic element while the other one is in charge of regulating position. A detailed classification and description of these kinds of solutions is reported in [2].

In actuators with *structure controlled stiffness* [2] the physical structure of a spring is modified, for example, varying the length of an elastic beam as for the Mechanical Impedance Adjuster (MIA, [53]) or varying the number of active coils in a helical spring as in [9] or in the Linear adjustable stiffness artificial tendon (LASAT, [54]); in actuators with *mechanically controlled stiffness* [2] the effective physical stiffness of the system is also changed, but the full length of the spring is always used.

In the Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator (MACCEPA, [55]) the stiffness variation is achieved by changing the pretension of a spring. The MACCEPA 2.0 [56]) is an improved version of this prototype.

A profiled disk is placed on the joint and it is directly connected to a linear spring through a wire. A motor rotates the profiled disk and the wire is guided over the profile causing the extension of the spring and the generation of an elastic torque (Fig. 13). A desired (even direction-dependent) torque-angle curve can be achieved opportunely shaping the disk profile. A third version of this system (Wheeled MACCEPA), which enlarges the stiffness range, is presented in [57].

The HDAU (Hybrid-type Dual Actuation Unit, [33]) is based on an adjustable lever arm mechanism. A modified planetary gear train is employed, where the sun gear is replaced with rack gears. The differential action of two motors connected to the inputs of the modified planetary gear train causes the rotation of the joint (position control) and the translation, through rack gears, of linear springs blocks, thus enabling stiffness control by regulating springs engagement point.

A variable spring lever arm system is also used in the AwAS (Actuator with Adjustable Stiffness, [58]) where a linear drive tunes joint stiffness controlling the fixation points of two opposing elastic elements. The working principle is also similar to the one presented in [59] (Adjustable Compliant Series Elastic Actuator, ACSEA).

As reported in Fig. 14 motor M1 controls the position of the joint and it is rigidly connected to an intermediate link; between this intermediate link and the output link two springs are placed. The distance between the center of rotation of the joint and the attachment point of the springs (lever arm) is modified by the motor M2 through a ball screw mechanism (Fig. 14b).

In this system a small amount of energy is needed to change the stiffness: when the output link is in its equilibrium position the force generated by the springs is perpendicular to the direction in which the linear drive acts to modify the lever arm and only friction causes energy dissipation; when the joint is not in the equilibrium position, only a small component of the spring force is parallel to the linear drive motion.

While in the AwAS the lever arm is modified by moving the location of the springs with respect to a fixed pivot, in the AwAS-II, presented in [60], the location of the pivot is changed while the springs are fixed. With this arrangement a wider range of stiffness and a lower regulation time are achieved.

The MESTRAN (MEchanism for varying Stiffness via changing TRasmission ANgle, [61]) is reported in Fig. 15. Link 1 is fixed while Link 2 rotates around O by means of a positioning motor connected to Gear 2. The rotation of Link 2 is converted in a linear motion by a Cam/Follower system. The action of the follower on the Slope-gear causes the Slope-carrier to translate and to compress a linear spring; this results in a perceived elastic torque around the joint O. The stiffness motor modifies through a Worm-gear the angle θ of the Slope-gear thus varying the resultant torsional stiffness of the joint.

2.3.1. Physically controllable dampers

Despite being classified as actuators with physically controllable impedance, the systems described in the previous sections are only employed to regulate stiffness.

Dampers are generally used to attenuate the oscillations induced in robotic systems in which compliance is introduced, especially in the case of interactions with humans [62]. Systems with fixed damping (*passive dampers*) can not adapt their dynamical actions to variations of kinematic configuration or loading conditions. Moreover, impedance control (*active dampers*) is not able to compensate oscillations at frequencies above the closed loop bandwidth. For these reasons *semi-active dampers*, i.e. systems capable of modifying their physical properties with a low amount of power, are being investigated.

Semi-active dampers based on ElectroRheological (ER) fluids or on MagnetoRheological (MR) fluids are presented in [63, 64] and [65, 66, 67] respectively. In these systems, the fluid rheological properties, and the resultant damping capability, are controlled through an applied electric or magnetic field. These solutions have typically drawbacks in terms of bulk, weight and mechanical complexity, which hinder the integration in compact robotic joints. An alternative is constituted by friction dampers, in which the contact between moving components produces frictional forces. Damping can be modulated, for example, modifying the contact of two surfaces through piezoelectric actuators as proposed in the VPDA (Variable Physical Damping actuator, [62]) or compressing a stack of discs as for the WDB (Wafer Disc Brake, [68]) and for the SCA (Series Clutch Actuator, [69]). These systems are clean, lightweight and they can be more easily embedded in compliant joints but they vary their mechanical properties in time due to the wear of the contacting surfaces. The damper proposed in [62] has been integrated in parallel to the compliant element of the rotary SEA presented in [23] in order to regulate oscillations when required. The resultant system (CompAct) has been described in [70].

In [71] a damper based on energy dissipation in a fluid is presented. A rotary joint shaft is connected to a roller, pushed against a silicone tube (closed circuit) filled with mineral oil. An adjustable localized pressure drop produces viscous stresses which generate a resistive torque proportional to the joint angular velocity.

One actuator in which position, stiffness and damping are all separately regulated is the RD-Joint (Redundant Drive Joint, [72]). It consists of a serial connection (achieved through a differential mechanism based on pulleys and wires) of two subsystems: *i)* a motor with a HD gear, which sets the position of the joint; *ii)* an Adjustable Stiffness and Damping Mechanism (ASD-Mechanism), which physically regulates the impedance (both stiffness and damping) of the joint. In the ASD-Mechanism leaf springs and linear air dampers (pistons which forces air through orifices at a controlled rate) are used to provide fixed stiffness and damping; each of them is made variable by controlling the transmission ratio of its connection with the output shaft. This is achieved using two motors which modify the interconnections of linkage mechanisms.

3. Comparison of double actuation units

The main performance characteristics of rotary actuators are torque (peak and maximum continuous) and speed. In the case of VIAs, other fundamental characteristics have to be considered, and in particular [38]: range of impedance (stiffness and/or damping) and impedance regulation time. While an ideal VIA would maintain the torque capacity over the whole impedance range, the actual impedance rendered by a real actuator may depend from the torque (and speed) delivered at specific working points. Therefore, the stiffness-torque characteristics is sometimes reported. In the case of actuators embedding a physical elastic component, also the torque-deflection characteristic, typical of this class of actuators, can be reported. For such actuators, the maximum elastic deflection and the maximum energy stored are also usually reported.

Given the large number of mechanical parameters involved in the description of the performances of VIAs, especially in the case of double actuation units, object of this paper, a straightforward quantitative comparison among proposed devices is not at all trivial, and this justifies recent research efforts aiming at producing standardized data-sheet templates, specifically intended for VIAs [73].

Actuators are usually designed having in mind different and sometimes very specific objectives, which may call for different optimization functions (e.g. mass, impedance range, max deflection, etc.). As an example, specific designs can be adopted to maximize power-to-mass ratio, or to have the impedance range matching that of selected biological components, or to energetically optimize desired dynamic tasks, such as throwing a ball, jumping and running.

Despite the variety of possible design targets, the applications where high power density and minimum actuator mass/volume are required are not at all uncommon, especially in the field of assistive, rehabilitation, industrial, bipedal and biomimetic robotics. The graphs shown in Fig. 16 and Fig. 17 place some of the reviewed double actuation units in the power-mass and power-volume planes. For visualization purposes, in Fig. 16 the nominal power, calculated as the sum of the nominal power of each motor, is reported on a logarithmic scale. The device with the maximum power is the the QA-Joint (320 W). The total mass comprises motors and variable impedance mechanisms. Masses range from 0.5 kg to 5 kg.

The volume (also in logarithmic scale for visualization purposes), calculated on the basis of dimensional information provided by the Authors, corresponds to the volume of the smallest ideal cylinder or box which can be designed around the actuator. Typical volume for double actuation units is in the range 0.7 - 5 l.

In Fig. 17 vertical bars range from nominal to peak torque (in logarithmic scale) for the devices where both values have been provided by Authors. For some devices only one value (nominal (n) or peak (p) torque) is available. The maximum torque is exhibited by the VS-Joint (160 N m) with a mass comparable with other actuators and a volume next to the minimum of volume range.

In Fig. 18 torque-to-mass vs. power-to-mass and torque-to-volume vs. power-to-volume are reported. Torque-to-mass ratio is in the range 2.4 - 22 N m/kg for nominal torques, and in the range 8 - 73 N m/kg for peak torques. Power-to-mass ratio is in the range 15 - 189 W/kg. Torque-to-volume ratio is in the range 0.7 - 40 N m/l for nominal torques, 9 - 86 N m/l for peak torques. Volumetric specific torques increase with power-to-volume ratio (which is in the range 12 - 342 W/l). For many actuators the nominal torque is in the order of 10 N m while the peak torque is about 7 times higher.

Figures 16, 17 and 18 reveal great diversity and actuators of the same category cannot be easily grouped.

The best performances are exhibited by FSJ and QA-Joint (highest torque- and power- to-volume values), which both include custom frameless motors. The mechanical design of the SDAU is not optimized, especially in terms of volume: the mass is smaller than that of the other actuators, but the volume is comparable, with power and torque capabilities much lower. Apparently physically controllable impedance actuators exhibit lower power- to-mass and to-volume ratios with respect to the other categories, that can be due to mechanical complexity of regulation mechanisms (e.g. variable lever arms, as described in section 2.3). Anyhow this conclusion cannot be definitely stated since only few data are reported for the other categories. VSA-HD has the smallest power- to-mass and to-volume ratios because this system has been developed for demonstration purposes (as it will be described in section 4). Nonetheless nominal torque is comparable to that of the most part of the other actuators.

VSA-II and BAVS are example of devices implementing the bidirectional agonistic/antagonistic architecture. The different design solutions adopted greatly impact on specific torque and power. The same consideration is valid for the QA-Joint and the AMASC, which both are quasi-antagonistic systems.

A further comparison can be based on energetic considerations deriving from dynamical modeling of the actuators as in [56]. Specific metrics for comparing energetic performances have been recently proposed in [74]: the port-based modeling framework is used to analyze the power flows in variable stiffness actuators. This approach analyzes energetic efficiency evaluating the power transfer from the internal DOF to the output, independently of the load behavior. In particular, a dynamic measure, based on the ratio between the power captured by the internal elastic components (and cannot be used to produce work on the output) and the total amount of input power, is introduced.

In [74] this mathematical method is applied to the simple agonistic/antagonistic and quasi-antagonistic architectures. For the first architecture it is demonstrated that the energy supplied via the input port is much higher than the kinetic energy on the load, which means that input energy cannot be completely transferred to the output port. A similar result was also achieved for the second architecture. In both cases the power flow ratio is negatively affected by higher springs pretension. This effect increases with the rate of change of the stiffness, and it is more pronounced in the quasi-antagonistic architecture than in the agonistic/antagonistic configuration. This analytical approach is very versatile and can be potentially applied to any class of actuators. Of course, it requires dedicated modeling and it cannot be applied to actuators regulating impedance purely via software.

Very interestingly, the port-based modeling approach has been successfully used not only to analyze the performance of actuators, but also to guide the design of a novel energetically efficient actuator, as it will be briefly reported in section 4.

Common advantages/disadvantages can be identified for the categories presented in this paper, as reported in Table 1.

Serial configurations allow the decoupling of position and stiffness controls; as a drawback, the maximum deliverable torque is limited by the smaller of the two motors.

Moreover, purely parallel configurations allow the partitioning of the generated torque in high- and low-frequency contributions; in this case the use of a SEA for low-frequency/high-torque generation guarantees low intrinsic impedance across the whole frequency spectrum. In the agonistic/antagonistic actuation architectures, complex control laws are required because the motors contemporarily contribute to control position and stiffness. Moreover, the mechanical structure is elaborate and energetic efficiency is often reduced. Nevertheless, they are able to reproduce the working principle of the muscoloskeletal system in vertebrates and they can be successfully used as experimental platforms for neuroscientific studies on motor control or in bioinspired robots.

Although the above-mentioned architectures provide the possibility of regulating stiffness via software or by pre-compressing elastic elements, in actuators with physically controllable impedance the properties of a mechanical component or the way it is connected to the load can be changed. This kind of solution generally implies a complex mechanical structure but it offers the advantage of providing physical mechanical impedance adaptable to different operative conditions and suitable to improve energetic efficiency.

The addition of variable dampers (e.g. ER, MR or friction systems) in actuators with variable stiffness can be useful to improve dynamical performances but it increases the complexity of the mechanical design, as for the system presented in [72] where three motors are used for position, stiffness and damping regulation. For this reason variable dampers are usually employed for joints with a fixed compliance (e.g. in [66, 70]), in traditional robots where flexible components can cause vibrations (e.g. in [63, 64]) or in rehabilitation devices where resistive torques are needed [75, 76, 77].

4. Novel methodologies for dual actuation units design

Because of the growing interest in VIAs, novel design methodologies are currently being investigated. In this section two different approaches will be presented: in [32] a systematic enumeration of possible solutions to use two motors and an analysis of the expected performances are reported (*analytic approach*); in [78] a mathematical framework for modeling variable stiffness actuators and for optimizing efficiency is presented (*synthetic approach*).

The work [32] enumerates all possible arrangements resulting from the combination of two motors, two HD gears, one output shaft and a number of rigid or elastic elements as interconnections between these elements.

A matrix representation is used to express all the possible configurations and an automated algorithm filters out the solutions not responding to the required functional properties. A further filtering process, grouping functionally equivalent systems, highlights 22 resultant architectures, which include many of the actuators already developed and presented in the previous sections.

To verify the mechanical complexity of the layouts selected through the presented enumeration, the Modular Variable Stiffness (MVS) prototype has been developed. MVS is composed of two motors, two HDs, and a modular connection system, which allows to replicate all the connections hypothesized for the enumeration process (rigid beams and linear traction springs with lever arms are employed). Because of its mechanical simplicity, one of the possible 22 layouts has been selected and fabricated as a stand-alone system. In this actuator (VSA-HD, [79]) one of the two HDs has its CS connected to the mechanical frame through nonlinear elastic elements (as for the FS of the second HD), while its FS is connected to the output shaft through a rigid element. Moreover, the two CSs are rigidly coupled. This solution implements a serial connection of the motors.

In [78] a port-based mathematical framework for analyzing and modeling energy efficient variable stiffness actuators is developed. Based on the conditions set by the mathematical framework, the conceptual design of a novel actuator is presented, demonstrating that impedance can be regulated in an efficient way by properly exploiting the internal DOFs. In particular, stiffness can be varied by only modulating the transmission ratio of an ideal transmission without using any energy.

Following this guideline, an actuator, whose functional concept is reported in Fig. 19a, was designed. The working principle is based on a linear spring connected to a lever arm of variable effective length which determines how the stiffness of the spring is felt at the output. The difference with respect to the AwAS, AwAS-II and H-DAU is that, in this case, the locations of the spring and of the pivot are fixed while the point where the end-effector acts is variable [60].

The DOF q_1 controls the transmission ratio from the spring to the end effector while the DOF q_2 directly control the end effector (which has position x). It has been demonstrated that if $\dot{q}_1$ is such that the stiffness varies as desired, and if $\dot{q}_2 = -\sin(\phi)\dot{q}_1$, the stiffness modification does not require energy. A prototype matching the conceptual system of Fig. 19a is reported in Fig. 19b.

5. Conclusions

New actuation solutions have been developed in recent years to establish a safe and effective human-robot interaction in rehabilitation and assistive robotics, to increase energy efficiency in legged robots, to study human motor control in neuro-robotics, and to protect robotic joints during impacts or to improve performances in industrial robots.

In these fields it can be necessary to provide variable impedance at the robotic joints. The advantages of separately controlling position and impedance, according to the different application fields, can be basically resumed as the improvement of systems dynamical performances while preserving safety or as the optimization of energetic exchanges with humans and/or external environment.

Among possible solutions (use of impedance controlled direct-drive motors, geared motors with torque feedback loops or SEAs) architectures involving more than one active element and elastic components are increasingly being investigated. This paper aimed at presenting possible configurations of double actuation units, which can be used to render variable impedance through active control or, for the most part of state-of-the art prototypes, through mechanical regulations.

A classification of rotary double actuation systems has been introduced, including three main categories: *serial*, *parallel* and *physically controllable impedance*. A critical analysis of the most relevant features of each presented architecture has been carried out (see also Table 1). A straightforward comparison among all the presented prototypes is not easy since not all of them are optimized for the same target application, nevertheless some common traits have been identified for the introduced categories. Moreover, a quantitative comparison has been reported based on torque, mass and volume data retrieved from literature. The overview, classification and comparison of these systems can represent a general guideline for future designs of actuators in different application fields.

Factors limiting the use of double actuation systems are inherent to the complexity of the mechanical structure and of the required control algorithms. Moreover, a considerable on-going research effort is currently being devoted to improve power- to-mass and to-volume ratios and energetic efficiency, by exploiting both theoretical design tools and novel technological solutions.

In [78] a mathematical framework has been presented to assess energetic efficiency of VIAs, also demonstrating that a particular class of solutions allows to physically modulate impedance in an energetically conservative way.

Technical choices to improve the overall power-to-mass ratio can include the use of high-performance frameless electromagnetic motors (as in [22, 23, 28, 34]) or the design of custom compliant components to optimize weight and volume (as proposed in [28, 80, 81]). An alternative to electromagnetic motors is constituted by pneumatic artificial muscles (e.g. McKibben muscles [82] or PPAMs (Pleated Pneumatic Artificial Muscles) [83]). These systems provide intrinsic compliance due to gas compressibility and to the flexibility of gas chambers but a considerable drawback is the need of external compressors. As a promising solution, research on novel energy transduction methods is leading to propellant-based chemical actuators able to directly convert chemical energy into mechanical energy [84, 85].

In wearable *assistive/rehabilitative robots*, the requirements on mass/volume are particularly strict. This is the reason why minimal actuation architectures are normally employed, possibly including passive element with fixed compliance [24, 86]. Nevertheless, biomechanical studies clearly demonstrate that the human musculoskeletal system deeply exploits the independent regulation of both position and stiffness in several tasks, including locomotion and manipulation [87, 88, 89]. Ideal actuation solutions for wearable robots should be able to replicate (in the case of *robotic prostheses*) or to harmonically co-exist with (in the case of *active orthoses*) such biomechanical systems. It is expected that in the coming years improvements on key enabling technologies for actuators will allow a widespread diffusion of double actuation architectures in these fields.

In *legged robots* double actuation solutions are currently considered for a decoupled regulation of position and impedance inspired by animals' locomotion and for improving energetic efficiency. In this regards, the adjustment of mechanical properties of the legs can help switching among walking, running and hopping. For pseudo-passive walkers, the modification of the robot natural frequency is even more crucial to elicit stable limit cycles. The use of these actuation systems is expected not to be hindered by requirements on bulk and weight.

In *neuroscience* the use of agonistic/antagonistic architectures, cannot be avoided if the human/animal muscular systems have to be reproduced for motor control investigations. Restrictions on mass and dimensions are not excessively strict for the design of bio-inspired platforms validating neuroscientific hypotheses. Rather, technological solutions are becoming more and more sophisticated to reproduce the cellular array structure of muscles (for example using Shape Memory Alloys (SMA) elements [90]) or to fabricate bio-micro-actuation units using human tissues ([91, 92]). In this sense, a thigh collaboration is expected to be established between neuro-robotics and (bio)material engineering.

In *industrial robotics*, the need of minimizing risks arising from unpredictable collisions and from the interaction during physically shared tasks is primary and cannot completely rely on control software. In this context the widespread adoption of compliant actuation, with adjustable properties for low stiffness-high speed and high stiffness-low speed motion, is likely to happen in the close future.

In general, the current research trend is moving towards the design of actuators with physically controllable impedance, i.e. highly efficient systems physically adaptable to a wide range of dynamic operative conditions. To this aim the most recent works presented in section 4 are devoted to the identification of novel design methodologies where mathematical tools are employed to optimize actuators performances, varying impedance in an energetically efficient way. Despite of that, translating these concepts into practical design is still an open point for future research.

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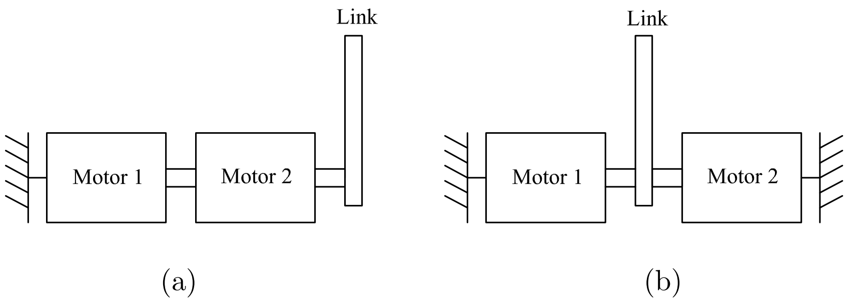


Figure 1: Serial (a) and parallel (b) arrangements of two motors.

Table 1: Characteristics of double actuation architectures.

Actuation architecture			General characteristics	Pros	Cons
Serial	Purely serial	Ordinary	The generalized displacement of the output is obtainable by algebraic sum of the generalized displacements of the two motors.	Decoupling of position and impedance/stiffness controls.	Maximum torque limited by the smallest motor.
		Differential			
	Quasi-antagonistic	Ordinary			Complex mechanical structure.
		Differential			
Parallel	Purely parallel	Colocated	The torque applied to the output is obtainable by algebraic sum of the torques applied by the two motors.	Torque generation can be partitioned into low- and high-frequency contributions to meet safety and performance demands.	Need of a powerful motor for high-torque/ low-frequency torque contribution.
		Distributed			
	Agonistic/ antagonistic	Simple		Simultaneous control of position and stiffness inspired by the muscoloskeletal system.	Complex mechanical structure and control laws. Reduced energetic efficiency.
		Cross coupled			
		Bidirectional			
Physically controllable impedance			One motor is employed to directly modify the properties of a passive elastic element while the other one is in charge of regulating position.	Physical regulation of the impedance. Low power motor for impedance regulation. High energetic efficiency. Decoupling of position and stiffness controls.	Complex mechanical structure.

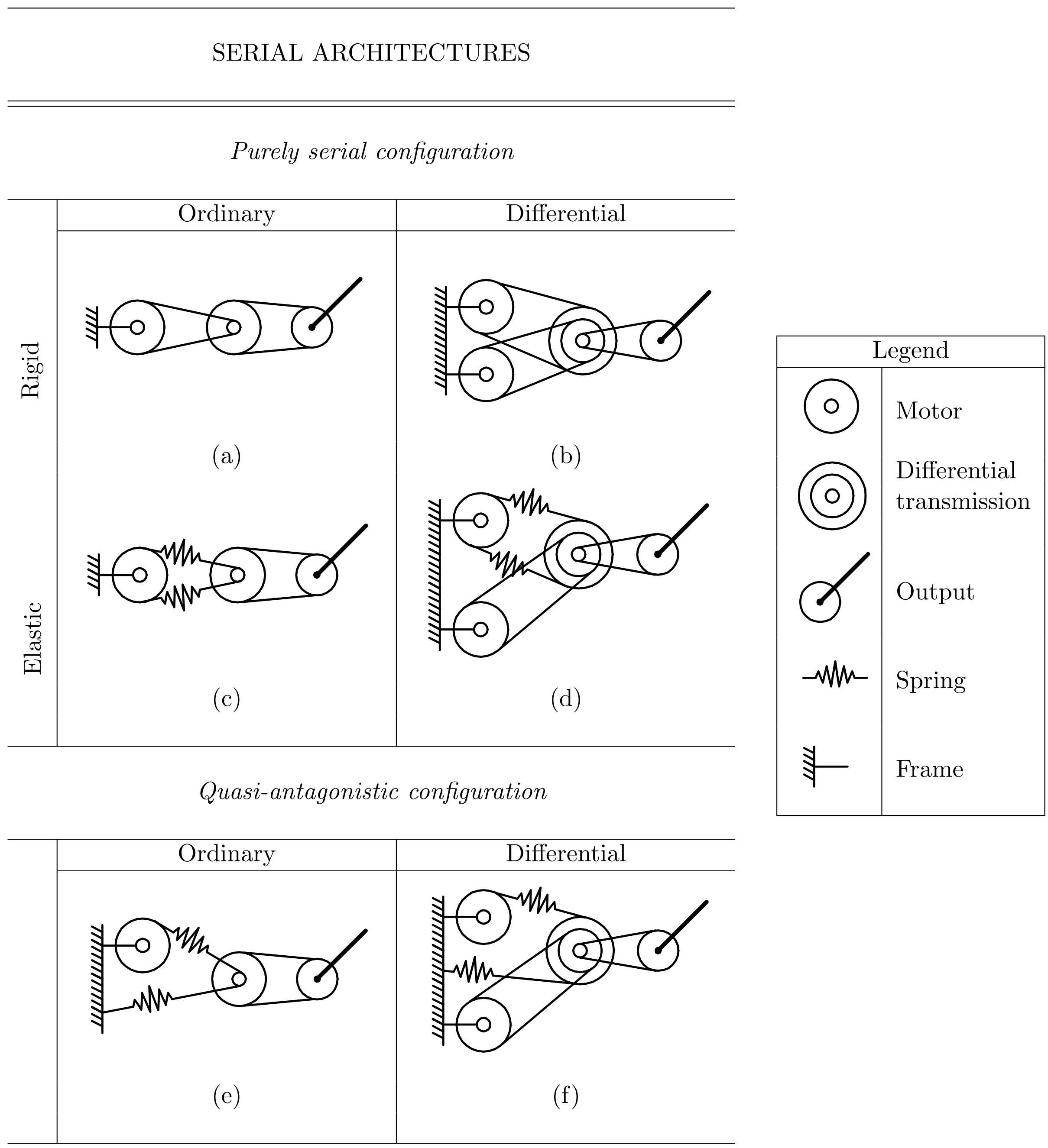


Figure 2: Serial architectures. In the differential transmission symbol the smallest circle is the output while the outer circles are the two inputs. The represented springs are in general nonlinear.

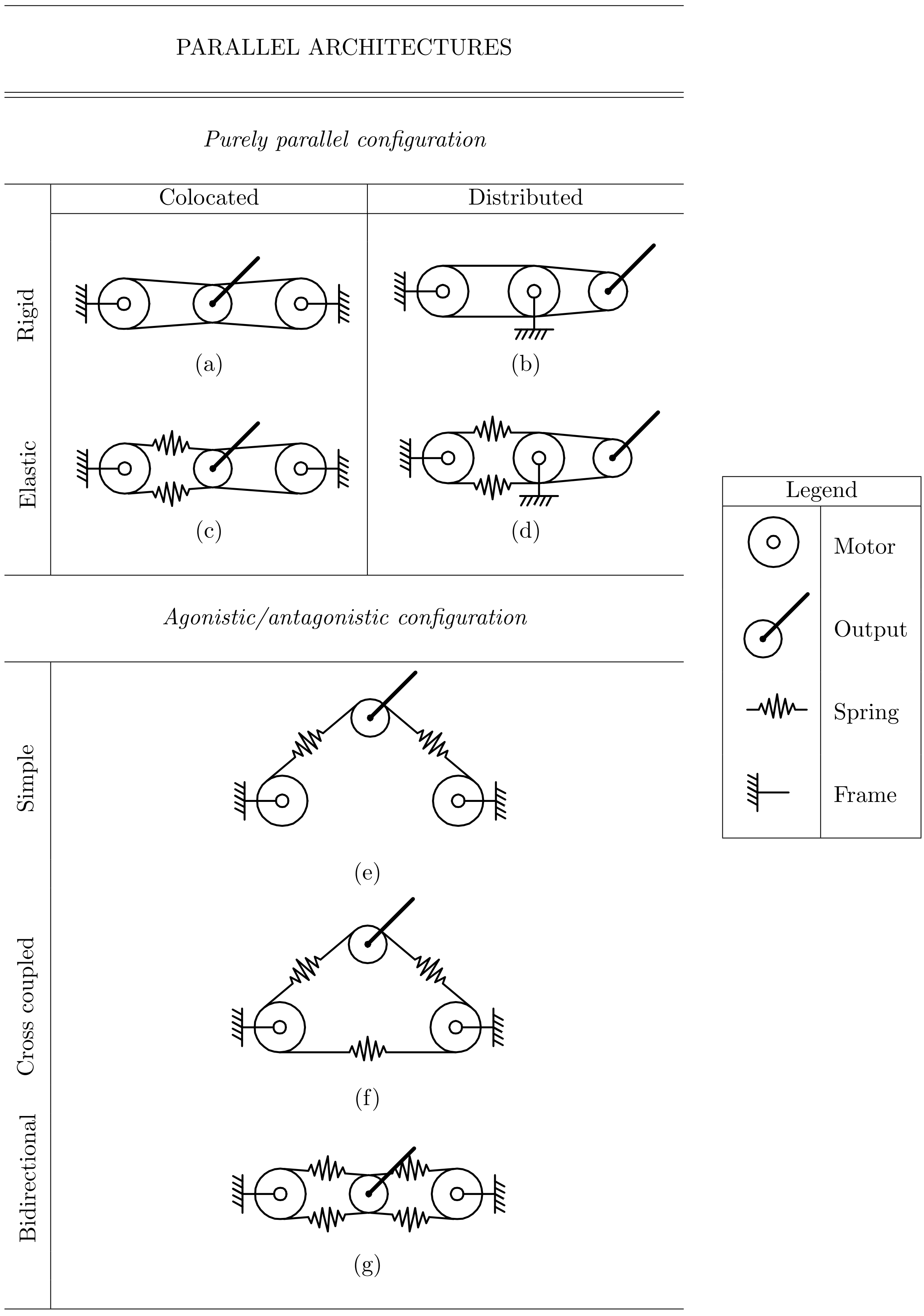


Figure 3: Parallel architectures. The represented springs are in general nonlinear.

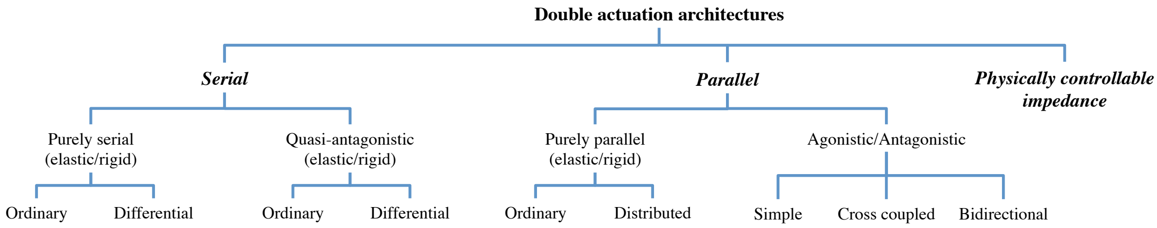
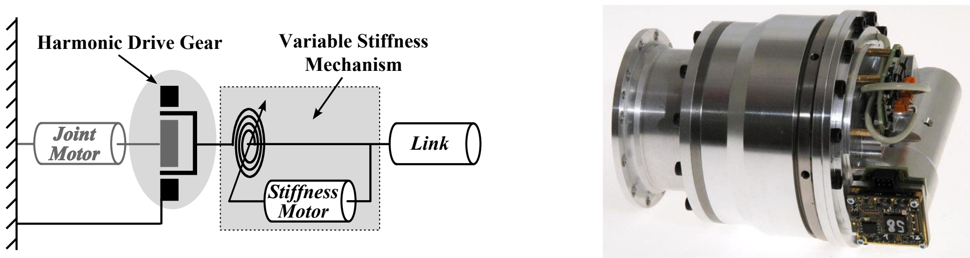
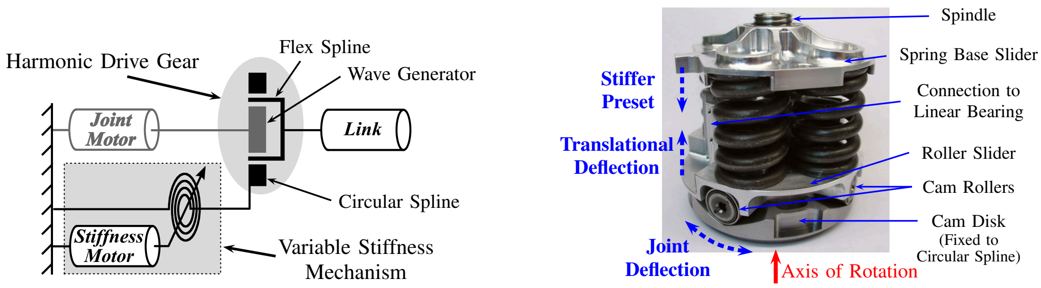


Figure 4: Classification of double actuation architectures.



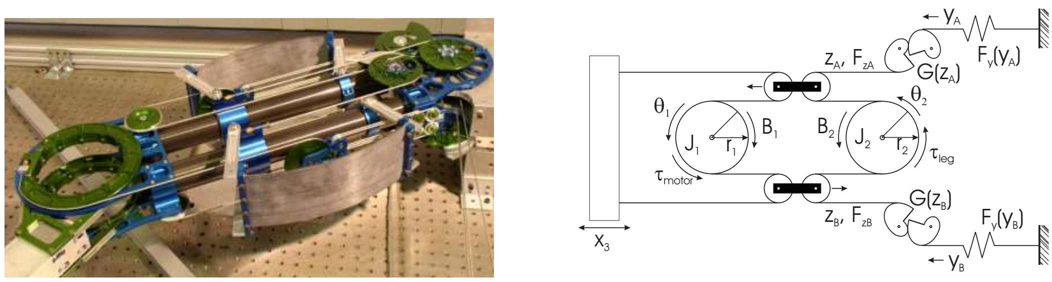
(a) (b)

Figure 5: Conceptual diagram (a) and prototype (b) of the FSJ [35].



(a) (b)

Figure 6: Conceptual diagram (a) and prototype (b) of the VS-Joint [17].



(a) (b)

Figure 7: Prototype (a) and schematic diagram (b) of the AMASC [37].

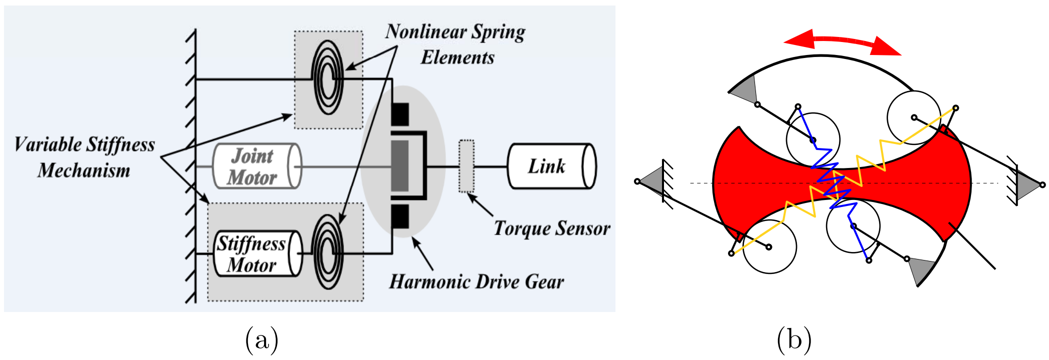


Figure 8: Conceptual diagram of the QA-Joint (a) and working principle of its Variable Stiffness Mechanism (b) [38].

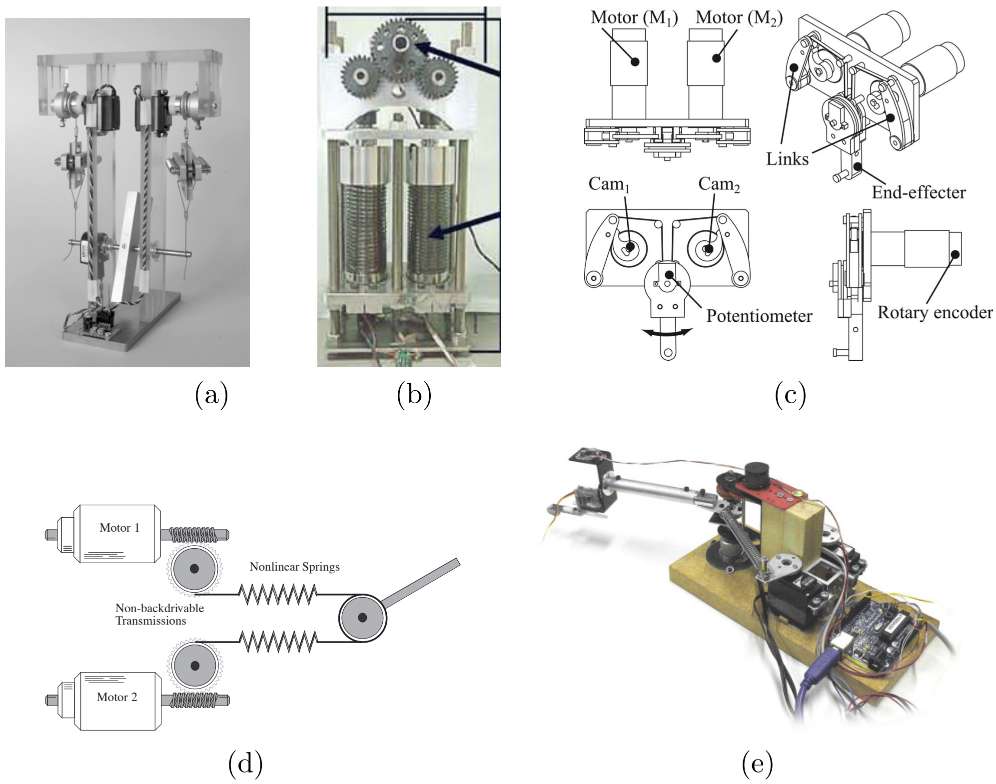


Figure 9: Representative examples of simple agonistic/antagonistic actuation. Prototype of Migliore et al. [45] (a); prototype of the ANLES (Actuator with Non-Linear Elastic System) [46] (b); drawing of the system using KTM (Kinematic Transmission Mechanism) presented in [47] (c); schematic drawing of the system proposed in [48] (d); prototype describe in [49] (e).

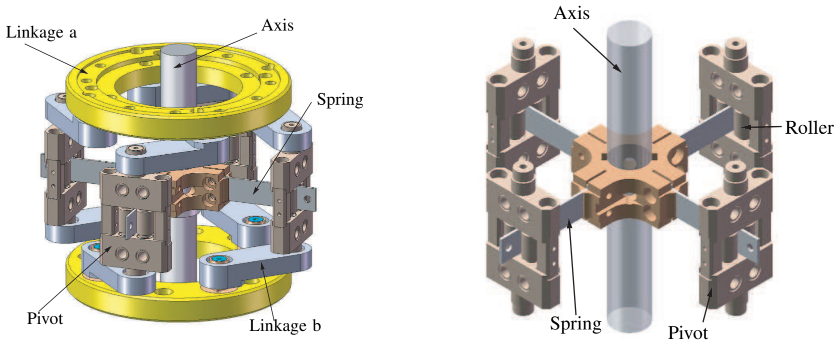
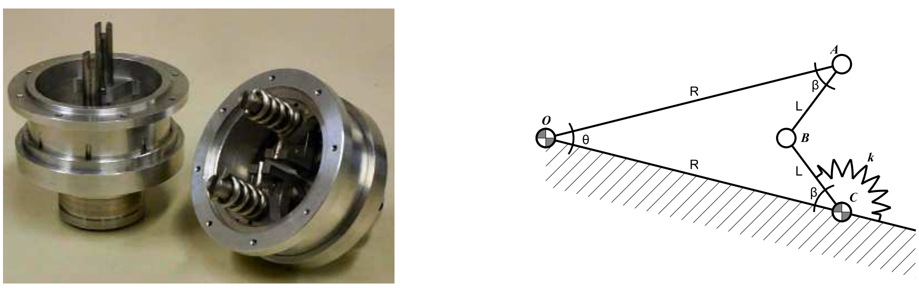


Figure 10: VSJ compliant mechanism [50]. Four leaf springs are attached to a central axis; four pivots sliding along the springs cause a change in stiffness. Four 4-bar linkage systems transmit the motors rotation to the pivots.

(a) (b)

Figure 11: Drawing of the VSA (a) (the motors are connected to pulleys 2 and 3) and detail of the transmission belt and pulleys (b) (the red configuration is stiffer than the green one) [52].



(a) (b)

Figure 12: Open VSA-II prototype (a) and schematic representation of a 4-bar elastic mechanism (b) [51].

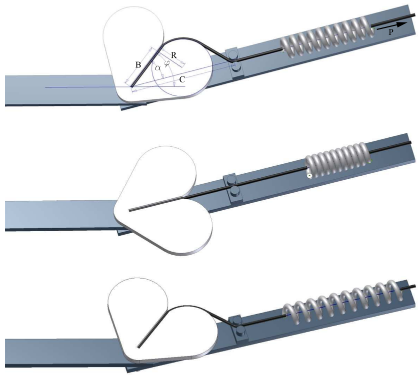
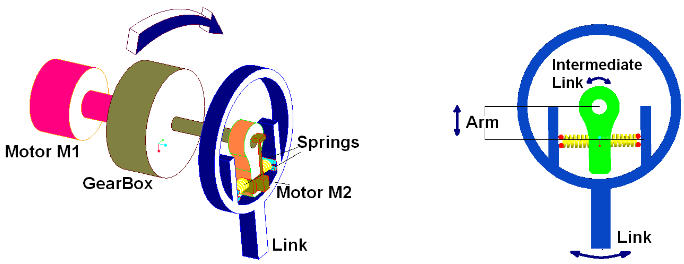


Figure 13: Working principle of the MACCEPA 2.0 [56].



(a) (b)

Figure 14: Conceptual design (a) and working principle (b) of the AwAS [58].

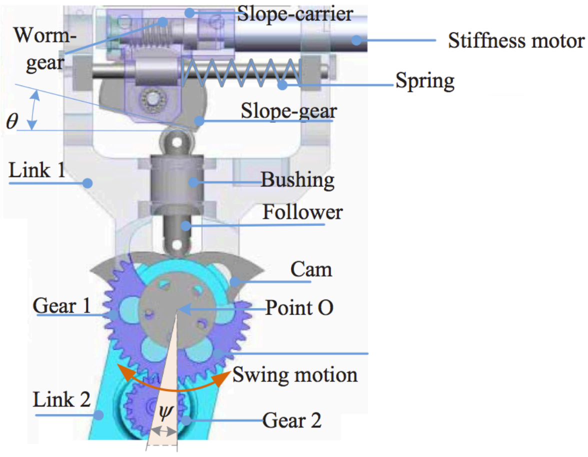


Figure 15: Drawing of the MESTRAN [61].

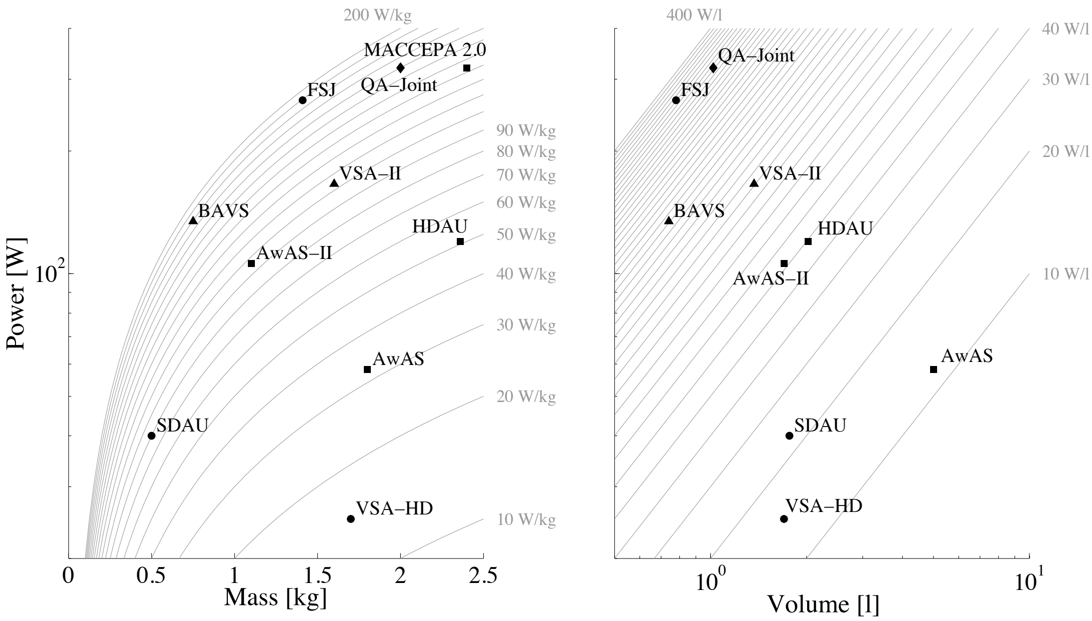


Figure 16: Power vs. mass and power vs. volume for some of the reviewed prototypes. Logarithmic scale is used for power and volume for visualization purposes. Curves at constant power- to-mass and to-volume ratios are reported as reference. *Round marks*: purely serial architectures; *triangular marks*: agonistic/antagonistic architectures; *diamond marks*: quasi-antagonistic architectures; *square marks*: physically controllable impedance actuators.

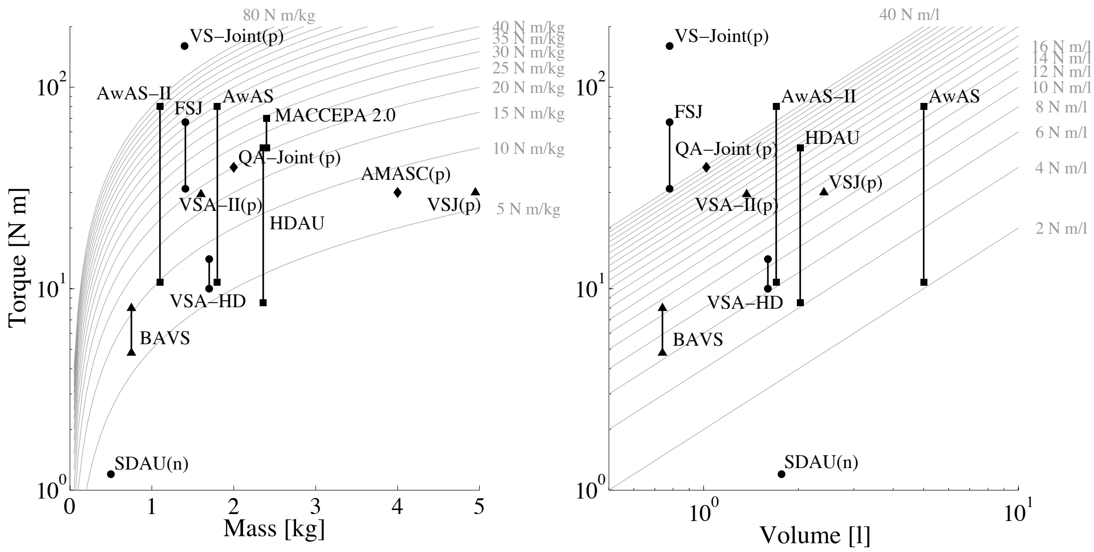


Figure 17: Torque vs. mass and torque vs. volume for some of the reviewed prototypes. Logarithmic scale is used for torque and volume for visualization purposes. Vertical bars range from the nominal torque to the peak torque for each actuator. For some systems only nominal (n) or peak (p) torque is indicated. Curves at constant torque-to-mass and to-volume ratios are reported as reference. *Round marks*: purely serial architectures; *triangular marks*: agonistic/antagonistic architectures; *diamond marks*: quasi-antagonistic architectures; *square marks*: physically controllable impedance actuators.

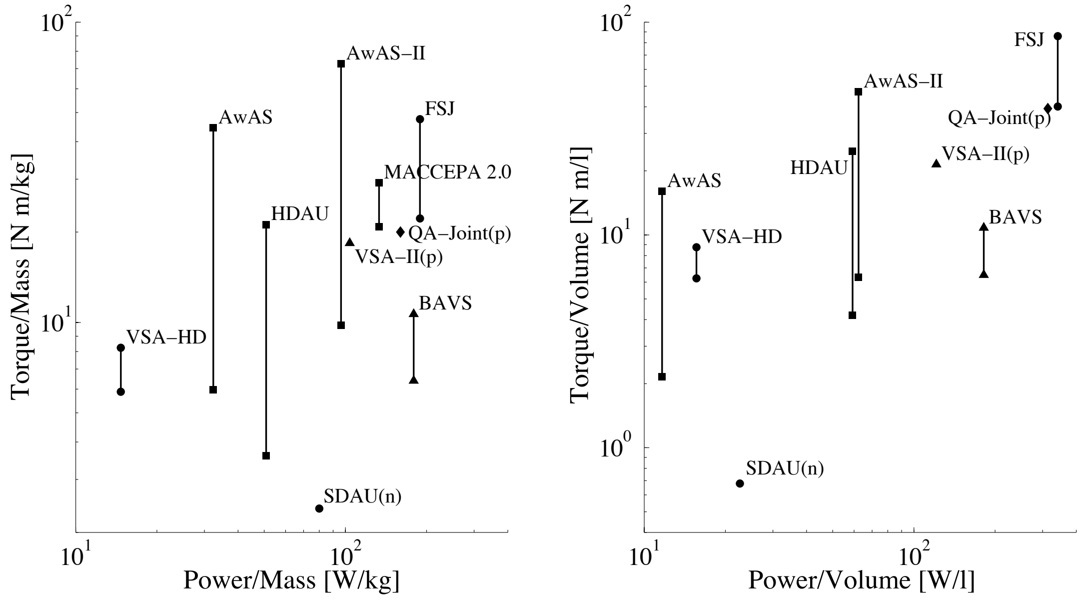


Figure 18: Torque-to-mass ratio vs. power-to-mass ratio and torque-to-volume ratio vs. power-to-volume ratio for some of the reviewed prototypes. Bilogarithmic scales are used for visualization purposes. Vertical bars range from the nominal torque to the peak torque for each actuator. For some systems only nominal (n) or peak (p) torque is indicated. *Round marks*: purely serial architectures; *triangular marks*: agonistic/antagonistic architectures; *diamond marks*: quasi-antagonistic architectures; *square marks*: physically controllable impedance actuators.

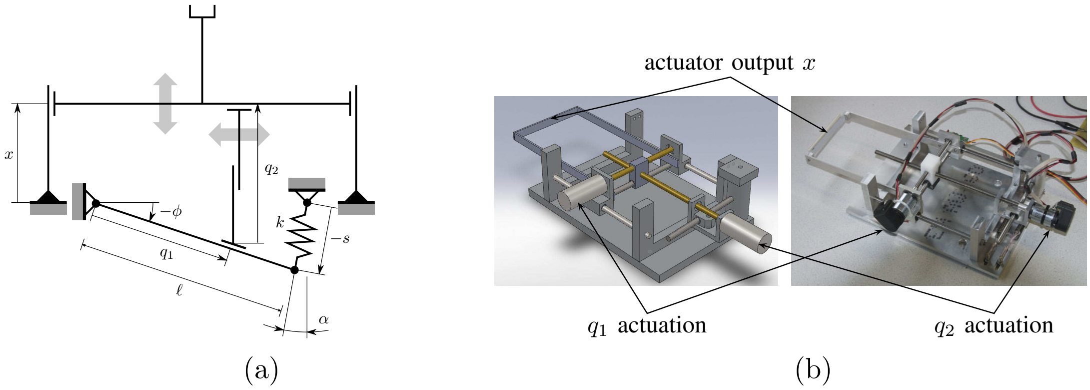


Figure 19: Conceptual design (a) and prototype (b) of the energetic efficient variable stiffness actuator presented in [78].