# Adaptive Robotic Mechanical Systems: A Design Paradigm

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*This paper aims at developing a general framework for the use of the concept of adaptive mechanical system in the design of advanced robotic devices. The concept of adaptive mechanical system is first formalized. A design methodology is then proposed in order to formulate the associated design paradigm, based on the fundamental principles of mechanics. Finally, examples of adaptive robotic mechanical systems taken from the literature are presented in order to illustrate the application of the general design methodology.* [DOI: 10.1115/1.2120781]

## 1 Introduction

A little more than half a century ago, mechanisms were used to calculate trigonometric functions in computers, to simulate differential equations, to keep the time in clocks, to provide switching in telephone networks and many other similar tasks [1]. For example, the variable speed mechanism shown in Fig. 1—taken from [2]—was used in mechanical analog computers to provide mathematical differentiation. Such mechanical computers were at the core of the preeminence of the fire-control capabilities of the U.S. Navy for a period of over 40 years in the beginning of the twentieth century [3].

In all the above mentioned applications, mechanical systems have later been superseded by electronic devices which provided better, more accurate, cheaper and faster means of performing the tasks. This evolution was inevitable since none of these applications requires, by essence, the use of a mechanical system. Indeed, these applications are purely computational or logical.

On the other hand, many applications (e.g., in robotics), are mechanical by nature. They involve mechanical systems and possibly their interaction with the environment. In such systems, mechanics is at the core of the function to be performed and should be a very important component of the engineering solutions. However, the trend in the development of robotic systems has very often been to confine mechanical systems to the execution of motion/forces under the command of high-level complex controllers. Although intelligent controllers are essential in modern advanced robotic systems, the best designs are usually attained if the mechanical aspect of the system is considered as one of the key elements in the synthesis and design process.

In this paper, the concept of adaptive mechanical system is first formalized. Then, a design methodology is proposed in order to provide designers with general guidelines that can be used in a practical context of synthesis and design. Finally, examples of adaptive robotic mechanical systems taken from the literature are presented in order to illustrate the concept. For each example, the connection with the variables defined in the methodology is clearly explained.

Clearly, the aim of this paper is not to present new robotic mechanisms but rather to point out the commonality between existing robotic systems which can be viewed as adaptive robotic mechanical systems. It is hoped that the methodology and the observations provided in this paper will shed some light on the challenges to be faced by robotics engineers and will pave the way for the development of new high-performance robotic devices.

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## 2 Adaptive Robotic Mechanical Systems

From the broad perspective of intelligent systems, an adaptive system may be defined as follows [4]:

Definition 1 Adaptive System. *A system is said to be adaptive if it has a capacity for adaptation, i.e., the ability to respond successfully to a new situation.*

A system can, therefore, be said to be adaptive if it can respond to different situations in the performance of a task.

Although adaptive systems and artificial intelligence are usually associated with computer systems, the purpose of the present paper is to develop the concept of *adaptive (robotic) mechanical system*. Therefore, the following definition is proposed:

Definition 2 Adaptive (Robotic) Mechanical System. *An adaptive (robotic) mechanical system is an adaptive system in which the ability to adapt to new external situations relies strictly on mechanical properties.*

In other words, an adaptive mechanical system is one in which some form of intelligence is embedded into the mechanics. In such a system, no sensors or complex controllers are required to perform the main task since the mechanical system itself will provide the required adaptive behavior. Such systems are also sometimes referred to as Mechanically Intelligent Systems [5]. In practice, adaptive robotic mechanical systems are usually coupled to intelligent mechatronic systems, thereby allowing the strength of both to be exploited.

Several examples of adaptive robotic mechanical systems satisfying the above definition can be found in the literature, as will be seen in the last section of this paper. However, before introducing the examples, a design methodology must be rigorously defined in order to clearly outline the commonality between the different adaptive mechanical systems as well as to provide the designers with a clear formulation that can be applied to other systems.

## 3 Design Methodology

The design of adaptive robotic mechanical systems can be approached using the general formulation now proposed. This methodology is based on the use of the basic principles of mechanics, i.e., the fundamental laws of statics, Newton's laws of mechanics—including their extension to rotating bodies (Euler's equations)—as well as energy-based formulations of these principles. The methodology can be divided into four main steps.

**3.1 Step 1: Definition of the Variables.** The first step is to analyze the robotic mechanical system under study in order to determine the configuration variables and the design parameters. The vector of configuration variables, noted $\boldsymbol{\theta}$ contains the motion variables (joint variables or Cartesian variables) used to describe the motion of the mechanical system. These variables may be limited to a given range, i.e., there may be constraints, written as

  

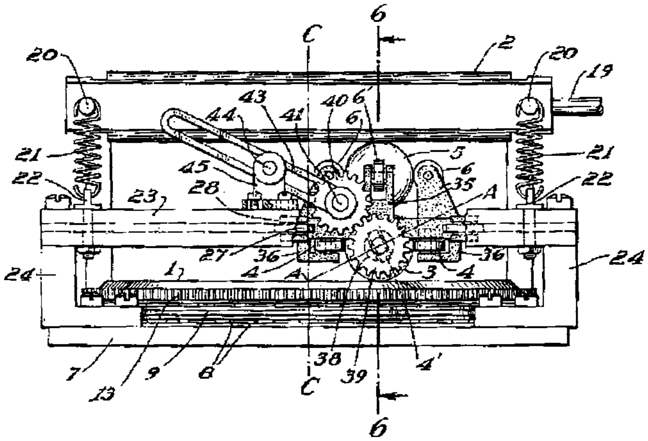

Fig. 1 Variable speed mechanism (1935) used in analog mechanical computers (from [2])

$$\boldsymbol{\theta} \in [\boldsymbol{\theta}_{\min}, \boldsymbol{\theta}_{\max}] \tag{1}$$

The vector of design parameters, noted $\mathbf{k}$, contains the set of dimensional and inertial parameters used to represent a given design of the mechanical system. Once a design is chosen, these parameters remain constant.

**3.2 Step 2: Mathematical Expression of the Fundamental Mechanical Properties.** Once the vector of configuration variables and the vector of design parameters are defined, it is possible to use them to develop the mathematical expression(s) associated with the mechanical properties that represent the adaptiveness of the mechanical system. If these mechanical properties involve the laws of statics, the expression(s) will take the following form:

$$\mathbf{F}(\boldsymbol{\theta}, \mathbf{k}) = \mathbf{0}. \tag{2}$$

On the other hand, if dynamic properties are involved, the expression will generally take the following form:

$$\mathbf{F}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}, \ddot{\boldsymbol{\theta}}, \mathbf{k}) = \mathbf{0}. \tag{3}$$

**3.3 Step 3: Derivation of the Conditions for Adaptiveness.** Using the mathematical expression developed in the preceding step, it is now possible to derive the conditions under which the desired properties can be achieved for *any value of the configuration variables*. In general, these conditions will take the following form:

$$\frac{\partial \mathbf{F}}{\partial \boldsymbol{\theta}} \equiv \mathbf{0}, \quad \text{for all } \boldsymbol{\theta} \in [\boldsymbol{\theta}_{\min}, \boldsymbol{\theta}_{\max}] \tag{4}$$

with possibly the following additional conditions:

$$\frac{\partial \mathbf{F}}{\partial \dot{\boldsymbol{\theta}}} \equiv \mathbf{0}, \quad \frac{\partial \mathbf{F}}{\partial \ddot{\boldsymbol{\theta}}} \equiv \mathbf{0}. \tag{5}$$

**3.4 Step 4: Derivation of the Design Rules.** The conditions written in Eq. (4) [and possibly Eq. (5)] are usually independent from the configuration variables and their time derivatives. When this is not the case, it may still be possible to find sufficient conditions that are independent from the configuration variables and which guarantee that Eq. (4) [and possibly Eq. (5)] is(are) satisfied. The conditions finally obtained are of the following form:

$$\mathbf{G}(\mathbf{k}) = \mathbf{0}. \tag{6}$$

The latter equation is a function of the design parameters only. Therefore, based on Eq. (6), design rules can be derived. In general, Eq. (6) can be thought of as a set of constraints which define a subspace of the design space in which the mechanical properties that provide the adaptiveness of the system are ensured. In other words, all designs chosen within this subspace will be adaptive in the sense defined in step 2 of the procedure.

In the next section, examples of adaptive robotic mechanical systems taken from the literature are presented in order to illustrate the concept. For each of the examples provided, the application of the procedure defined above is outlined, and the adaptive solutions proposed are exposed. Observations on how the adaptiveness of the systems is exhibited are also provided.

## 4 Examples

**4.1 Adaptive Robotic Hands.** In many robotic applications, the manipulation of objects with very complex mechanical hands [6–8] is not essential and grasping devices are sufficient. However, simple grippers [9] are not appropriate in most cases because they are not capable of adapting to the shape of different objects. Hence, the development of versatile robotic hands which are capable of grasping a wide variety of objects with a very simple control structure is of great interest for many applications. In such applications, robotic grippers which can mechanically adapt to the shape of a broad variety of objects by a mere redistribution of the forces—and not by direct control—represent a very promising avenue. It is clear that robot hands based on the latter principle are adaptive mechanical systems since they can adapt to the shape of the objects simply by the mechanical action of their components. Since this behaviour implies that motion takes place without control actions, underactuation must be introduced.

An *underactuated mechanism* is one which has fewer actuators than degrees of freedom (dof)s. When applied to mechanical fingers, the concept of underactuation leads to mechanical adaptiveness. Mechanically adaptive fingers envelope the objects to be grasped and automatically adapt to their shape with a limited number of actuators—usually one—and without complex control strategies.

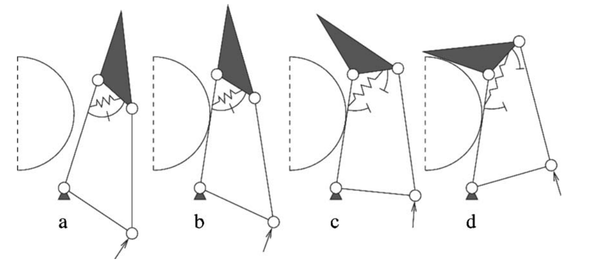


Fig. 2 Closing sequence of an underactuated two-dof finger

As an example, the closing sequence of an underactuated two-dof finger is shown in Fig. 2 in order to clearly illustrate the concept of underactuation. The finger is actuated through the lower link, as shown by the arrow in the figure. Since there are two dofs and one actuator, one (two minus one) elastic element must be used. In the present example, an extension spring is used which tends to maintain the finger fully extended. A mechanical limit is used to keep the phalanges aligned under the action of this spring when no external forces are applied on the phalanges. It should be noted that the sequence occurs with a continuous motion of the actuator. In Fig. 2(*a*), the finger is in its initial configuration and no external forces are present. The finger behaves as a single rigid body undergoing rotation about a fixed pivot. In Fig. 2(*b*), the proximal phalanx makes contact with the object. In Fig. 2(*c*), the second phalanx is moving with respect to the first one—the second phalanx is moving away from the mechanical limit—and the finger is closing on the object since the proximal phalanx is constrained by the object. Finally, in Fig. 2(*d*), both phalanges are in contact with the object and the finger has completed the shape adaptation phase. The actuator force is distributed among the two phalanges in contact with the object.

Based on the principle described above and on engineering intuition, a few (mechanically intelligent) underactuated fingers have been proposed in the literature. Some of them are based on linkages while others are based on tendon-driven mechanisms. Examples of underactuated hands based on tendons are given in Refs. [10–12]. The latter reference introduced—almost 30 years ago—the *Soft Gripper*, a pioneer design which involved tentacle-like fingers composed of several phalanges. The video demonstrations of the prototypes of the Soft Gripper clearly illustrated the mechanical adaptiveness (or intelligence) of the system.

Tendon systems are generally limited to rather small grasping forces and are therefore ideal when lightweight objects are to be manipulated. However, for applications in which large grasping forces are expected, linkage mechanisms are usually preferred. Examples of underactuated hands based on linkages are given in Refs. [13,14].

An alternative form of underactuation was proposed in Refs. [15,5],[1] and [16]. It consists in using brakes or clutches in order to sequentially drive the different dofs with a single actuator. The mechanical action of the forces acts as a commuting device which directs the motion of the actuator to the proper joints, thereby providing mechanical adaptiveness.

The main challenge in the design of underactuated hands is to determine the design parameters that will lead to stable grasps for a very broad variety of shapes of objects, i.e., to maximize the adaptiveness of the mechanical fingers, as first understood in Ref. [17]. It is possible to address this challenge using the general methodology introduced in the preceding section as follows:

1. Definition of the variables (see Sec. 3.1): First, it is readily observed that the configuration variables, vector $\boldsymbol{\theta}$ can be defined as a set of independent joint variables that describe completely the configuration of the finger. For instance, in the finger illustrated in Fig. 2, two joint variables would be used.
2. Fundamental mechanical properties (see Sec. 3.2): The fundamental principle of mechanics used to characterize the system is simply the equations of static equilibrium applied to the finger in an arbitrary configuration. These equations can be written in the form given in Eq. (2), where $\mathbf{k}$ denotes here the vector containing the dimensional parameters (link lengths and angles) describing the geometry of the finger.
3. Conditions for adaptiveness (see Sec. 3.3): In the third step of the procedure, it is observed here that grasping stability will occur when the contact forces at the phalanges are all positive (all phalanges pushing on the object). These conditions can be clearly illustrated using the *grasp-state plane* formalism introduced in Ref. [18]. Using this formalism, the conditions for adaptiveness can be written as
$$\mathbf{H}(\boldsymbol{\theta},\mathbf{k}) \geqslant \mathbf{0}, \quad \text{for } \boldsymbol{\theta} \in [\boldsymbol{\theta}_{\min}, \boldsymbol{\theta}_{\max}]. \tag{7}$$
i.e., the forces on the phalanges should be positive within the range of motion of the joints allowed by the mechanical limits.
4. Design rules (see Sec. 3.4): Finally, the use of the above conditions and the grasp-state plane allow the derivation of design rules which generally take the form of inequalities, i.e.,
$$\mathbf{G}(\mathbf{k}) \geqslant \mathbf{0}. \tag{8}$$
It should also be pointed out that other criteria can be used to obtain design rules, such as a uniform distribution of the forces among the phalanges.

Using this approach, several prototypes of mechanically adaptive underactuated robotic hands have been developed in the Robotics Laboratory at Laval University [19,20]. The Laval mechanically intelligent robotic hands are composed of three underactuated fingers, each finger having three phalanges. The use of three fingers is thought to be an effective compromise for grasping since it is the minimum number of fingers required to accomplish stable grasps. Each of the three identical fingers is mounted on an additional revolute joint whose axis is located on the vertex of an equilateral triangle and oriented normal to the plane of the triangle. With these additional revolute joints, the hands can be reconfigured by modifying the orientation of the fingers in order to adapt to the general geometry of the object to be grasped. One of the prototypes—the MARS hand—is shown in Fig. 3, where the adaptiveness to the shape of the grasped objects is clearly illustrated. Because the adaptiveness of the system is embedded in the mechanics, the fingers are driven simply by high level commands such as "open" or "close" and the motion of the individual joints associated with the phalanges is dictated by the distribution of the forces, i.e., by the shape of the object being grasped.

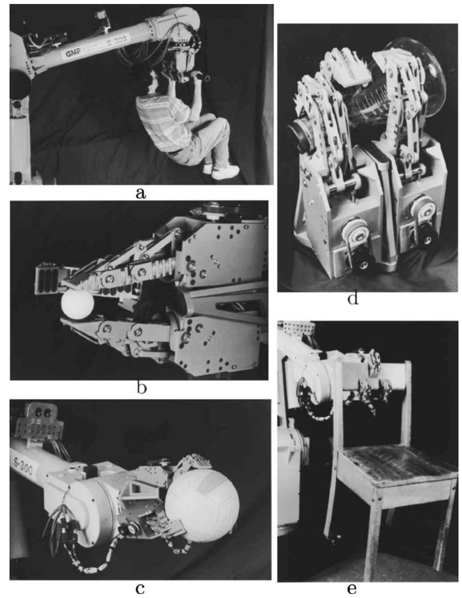


**Fig. 3 Examples of grasps performed with the MARS hand: (*a*) Person, (*b*) golf ball, (*c*) volleyball (*d*) flask, and (*e*) chair**

**4.2 Gravity-Compensated Robotic Systems.** Another area where adaptive mechanical systems can be used effectively is in the development of gravity compensated multi-dof robotic systems. A robotic mechanism is said to be *gravity compensated* if the weight of the links of the mechanism does not produce any torque (or force) at the actuators under static conditions, for *any* configuration of the mechanism within its workspace.

Gravity-compensated serial mechanisms have been designed in Refs. [21–26] using counterweights, springs and sometimes cams and/or pulleys. The adaptiveness of the proposed designs is readily observed: Whatever the configuration in which the mechanisms are placed, they will automatically adapt and ensure that no torque or force is required at the actuators to maintain the system in static equilibrium.

A hybrid direct-drive gravity-compensated manipulator has also been developed in Ref. [27]. Moreover, a general approach for the static balancing of linkages—including but not limited to gravity compensation—has been presented in Ref. [28]. The latter reference is definitely one of the most complete works on this topic.

Similarly to the case of the mechanically adaptive robotic hands, the design of gravity compensated mechanisms can be formulated using the approach described in the preceding section.

[1]This reference is one of the rare publication in which the term "Mechanically intelligent" is explicitly used.

1. Definition of the variables (see Sec. 3.1): Let a general spatial $n$-degree-of-freedom mechanism be composed of $n_b$ moving bodies and one fixed link. Moreover, let the position vector of the center of mass of each moving body with respect to a fixed reference frame be noted $\mathbf{c}_i$ and let the mass of the $i$th moving body be noted $m_i$. The vector of configuration variables $\boldsymbol{\theta}$ is defined here as the vector comprising all the joint coordinates of the mechanism while the vector of design parameters $\mathbf{k}$ is the vector containing the masses of the moving bodies as well as all the geometric parameters required to define the assembly and the positions of the centers of mass on the bodies. In gravity compensated systems, means of storing elastic potential energy—such as springs—are often used. In this case, the undeformed length and the stiffness of the springs are also included in the vector of design parameters.
2. Fundamental mechanical properties (see Sec. 3.2): A simple and effective tool to study gravity compensation is the total potential energy in the mechanism. This quantity can be written as:

$$F = F(\boldsymbol{\theta},\mathbf{k}) = g\mathbf{e}_z^T\sum_{i=1}^{n_b} m_i\mathbf{c}_i + \frac{1}{2}\sum_{j=1}^{n_s} k_j(s_j - s_j^o)^2 \tag{9}$$

where $g$ is the magnitude of the gravitational acceleration, $\mathbf{e}_z$ is a unit (upward) vector oriented in the direction of gravity, $m_i$ and $\mathbf{c}_i$ are as defined above, $n_s$ is the number of linear elastic elements in the system, $k_j$ is the stiffness of the $j$th elastic element, $s_j$ is the length of the $j$th elastic element and $s_j^o$ is its undeformed length. The first term of the right-hand side of the equation is the gravitational potential energy while the second term is the elastic potential energy. As expressed in this equation, the total potential energy is a function of the configuration variables as well as the design parameters.
3. Conditions for adaptiveness (see Sec. 3.3): A sufficient condition for a mechanism to be statically balanced is that the total potential energy be constant, for any value of the configuration variables within the allowed range, i.e.,

$$\frac{\partial F}{\partial \boldsymbol{\theta}} = \mathbf{0}, \quad \text{for all } \boldsymbol{\theta} \in [\boldsymbol{\theta}_{\min}, \boldsymbol{\theta}_{\max}]. \tag{10}$$

4. Design rules (see Sec. 3.4): Finally, by inspection of Eq. (10), it is possible to obtain a set of constraints on the design parameters that will ensure that the total potential energy in the system is constant, for all configurations. A set of constraints of the type given in Eq. (6) is obtained.

*4.2.1 Planar 1-dof Illustrative Example*. The concept of gravity compensation using elastic energy-storage elements can be illustrated using the simple one-dof example shown in Fig. 4. In the latter system, a single link of mass $m$ is rotating in a vertical plane, as illustrated in the figure. The center of mass of the link is located at a distance $c$ from the pivot and a spring is attached to the fixed link along the vertical axis, at a distance $h$ from the pivot, as well as to the rotating link, at a distance $l$ from the pivot. The only configuration variable in the system is the angle $\theta$ associated with the single degree of freedom of the mechanism. The vector of design parameters $\mathbf{k}$ can be written as follows:

$$\mathbf{k} = [m,c,h,l,s^o,k]^T \tag{11}$$

where $s_0$ is the undeformed length of the spring and $\mathbf{k}$ is its stiffness.

Using Eq. (9), the total potential energy in the system can be written as

$$F(\theta,\mathbf{k}) = mgc\cos\theta + \tfrac{1}{2}k(s - s^o)^2 \tag{12}$$

where $s$ is the length of the spring. From the law of cosines, one can write

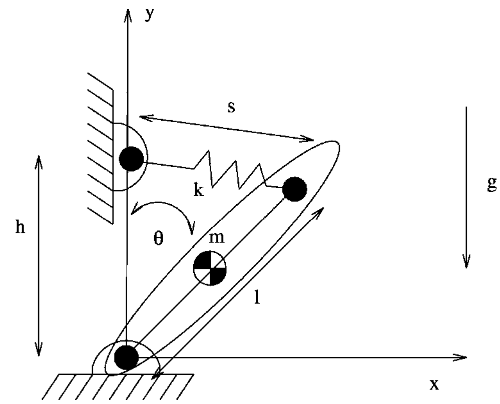


**Fig. 4 Simple one-degree-of-freedom statically balanced system**

$$s^2 = h^2 + l^2 - 2hl\cos\theta \tag{13}$$

Moreover, if the undeformed length of the spring is equal to zero, i.e.,

$$s^o = 0 \tag{14}$$

then, Eq. (13) can be substituted directly into Eq. (12), which leads to

$$F(\theta,\mathbf{k}) = (mgc - khl)\cos\theta + \tfrac{1}{2}k(h^2 + l^2). \tag{15}$$

Following the general procedure derived in the preceding section, we can now write the condition for the potential energy to be constant, i.e.,

$$\frac{\partial F}{\partial \theta} = -(mgc - khl)\sin\theta = 0. \tag{16}$$

From the above equation, it is clear that the total potential energy of the system will be constant for any value of $\theta$ if and only if one has

$$mgc = khl \tag{17}$$

or, in other words, if the stiffness of the spring is chosen such that

$$k = \frac{mgc}{hl} \tag{18}$$

The resulting statically balanced system will, therefore, be in static equilibrium for *any* configuration, as long as the orientation of the base of the mechanism with respect to the gravity field is not changed. The mechanism can adapt to any change of configuration and still maintain the static equilibrium.

*4.2.2 Application to Multi-dof Robotic Mechanisms*. The above analysis can be applied to robotic mechanisms with several degrees of freedom. For instance, in Ref. [29], the gravity compensation of 6-dof parallel mechanisms with revolute actuators was presented. General expressions for the balancing conditions were obtained and examples of gravity-compensated 6-dof parallel mechanisms were given.

Following this work, a prototype of 6-dof gravity-compensated parallel mechanism was developed and built at Laval University. The prototype is shown in Fig. 5. The platform of the mechanism is in static equilibrium in any configuration within its 6-dof workspace, with zero torques at the actuators. Indeed, since the total potential energy in the system is constant, all configurations are equilibrium configurations.

Gravity-compensated robotic mechanisms are mechanically adaptive systems since any change in the posture—and hence any change in the gravitational potential energy—is automatically compensated for by an equivalent change in the elastic potential energy, thereby maintaining the system in equilibrium. This reac-

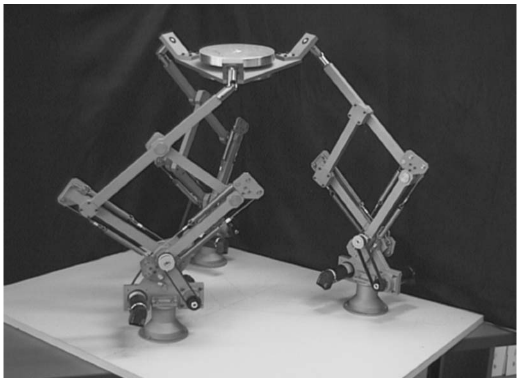

**Fig. 5 Prototype of a gravity-compensated 6-dof parallel mechanism**

tion of the system is embedded in its mechanical design and hence occurs without resorting to a high-level mechatronic controller.

**4.3 Reactionless (Dynamically Balanced) Robotic Mechanisms.** The concept of adaptive mechanical system can also be used for the control of the reaction forces and moments at the base of a robotic mechanism.

A mechanism is said to be *reactionless or dynamically balanced* if, for any motion of the mechanism, there is no reaction force (excluding gravity) and moment at its base at all times. This property is crucial in space robotics (free-floating devices) in order to preserve the momentum of the moving base—space vehicle, satellite or space station—while a robot mounted on this base is performing tasks. In advanced telescopes, dynamically balanced mechanisms are also required to avoid exciting the structure of the telescope while moving the mirrors at high frequencies in order to correct for atmospheric disturbances. Additionally, in industrial applications involving parallel manipulators performing high-speed motions, eliminating or reducing the reactions on the base of the robot would also significantly improve the general performance by reducing vibrations and thereby improving the accuracy.

The balancing of mechanisms has been an important research topic for several decades [30–32]. Extensive studies on the dynamic balancing of planar linkages as well as some research work related to the complete balancing of spatial linkages with one degree of freedom have been presented in the literature. However, because of the complexity of the problem, the dynamic balancing of multi-degree-of-freedom parallel mechanisms has not been addressed until very recently [33]. Alternatively, some authors have addressed the trajectory planning of manipulators in order to generate reactionless trajectories or minimize disturbances (see, for instance, Ref. [34]). However, the approaches based on trajectory planning are relying on the ability of the controller to reproduce computed trajectories (positions, velocities, and accelerations) very precisely. Clearly, such approaches consist in concentrating the intelligence of the system in the controller. In the context of adaptive mechanical systems, it is rather desirable to attain the reactionless property by embedding it into the mechanics of the system. The reactionless property is then ensured for any trajectory and is independent from the ability of the controller to generate accurate trajectories.

The design of reactionless robotic systems can be addressed using the procedure proposed in the preceding section.

1. Definition of the variables (see Sec. 3.1): Consider a $n$-dof mechanism whose joint coordinates are represented by vector $\boldsymbol{\theta}$. Since the dynamics of the mechanism must be considered, the vector of design parameters, $\mathbf{k}$ includes the dimensional parameters, the mass of the links, the position of the center of mass of the links and the inertia of the links.
2. Fundamental mechanical properties (see Sec. 3.2): For a system with constant mass, the resultant of the external forces acting on the system equals the time rate of change of the linear momentum of the system, while the resultant of the external moments with respect to a fixed point $O$ (or the center of mass of the system) equals the time rate of change of the angular momentum about the same point, namely,
$$\Sigma\mathbf{F} = m\dot{\mathbf{v}} \tag{19}$$
$$\Sigma\mathbf{M} = \dot{\mathbf{h}} \tag{20}$$
where $\Sigma\mathbf{F}$ is the vector sum of the external forces, $m$ is the total mass, $\mathbf{v}$ is the velocity of the center of mass of the system, $\Sigma\mathbf{M}$ is the vector sum of the external moments about a fixed reference point $O$ and $\mathbf{h}$ is the total angular momentum of the system about the same point.
3. Conditions for adaptiveness (see Sec. 3.3): The opposites of the terms on the right-hand side of Eqs. (19) and (20) are actually the so-called shaking force and shaking moment respectively due to the moving masses and inertia. Clearly, from Eqs. (19) and (20), if the linear momentum ($m\mathbf{v}$) and the total angular momentum ($\mathbf{h}$) of the system remain constant for any motion at all times the shaking force and shaking moment will vanish. Usually, the state of rest will be included in the possible set of motions of the mechanism, in which case both linear and angular momentum are zero. Therefore, in practical situations, the conditions for dynamic balancing are that for *any* motion of the mechanism the center of mass of the system should remain stationary and the total angular momentum must be zero at all times. Hence, two constraints have to be satisfied for a mechanism to be reactionless, namely, the center of mass of the mechanism should remain fixed (stationary) and the total angular momentum must remain constant (zero) with respect to a fixed point at all times for arbitrary trajectories of the end-effector [35], i.e.,
$$\frac{d\mathbf{r}}{dt} = 0 \tag{21}$$
$$\frac{d\mathbf{h}_o}{dt} = 0 \tag{22}$$
where $\mathbf{r}$ is the position vector of the center of mass and $\mathbf{h}_o$ is the total angular momentum of the mechanism relative to a fixed point $O$. Equations (21) and (22) are necessary and sufficient conditions for a mechanism to be dynamically balanced, i.e., reactionless. More specifically, (21) implies force balancing—eliminating the shaking force—whereas (22) implies moment balancing—eliminating the shaking moment.
4. Design rules (see Sec. 3.4): Finally, using the above equations—Eqs. (21) and (22)—it is in principle possible to obtain necessary and sufficient conditions for the dynamic balancing of multi-degree-of-freedom robotic mechanisms. However, in practice, obtaining Eqs. (21) and (22) as functions of a set of independent configuration variables (joint variables or Cartesian variables) is very challenging. Therefore, dynamic balancing conditions obtained for robotic mechanisms are usually sufficient conditions only. In other words, it is generally possible to find families of dynamically balanced designs but it is extremely difficult to obtain the complete set of balanced designs. In fact, this issue is still open, except for very simple linkages—such as the planar four-bar linkage.

By deriving necessary and sufficient conditions on a four-bar planar mechanism, Ricard and Gosselin [35] obtained the complete set of dynamically balanced four-bar mechanisms that do not require additional counter-rotations. Three families of mechanisms were found. In each case, there are no separate counter-

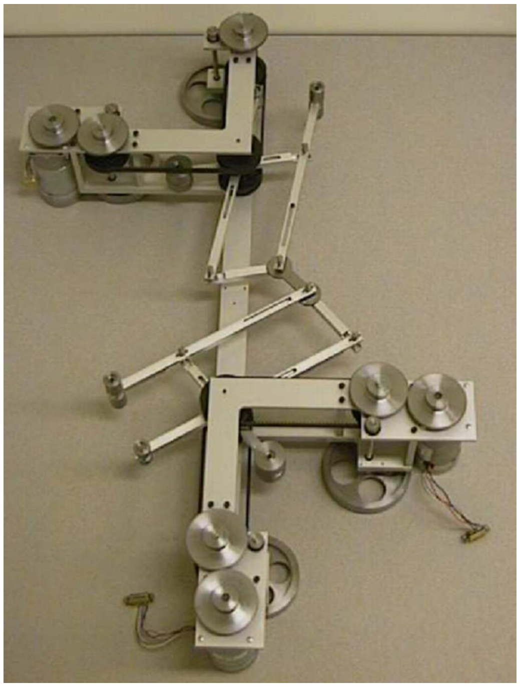

Fig. 6 Prototype of a reactionless planar 3-DOF parallel mechanism

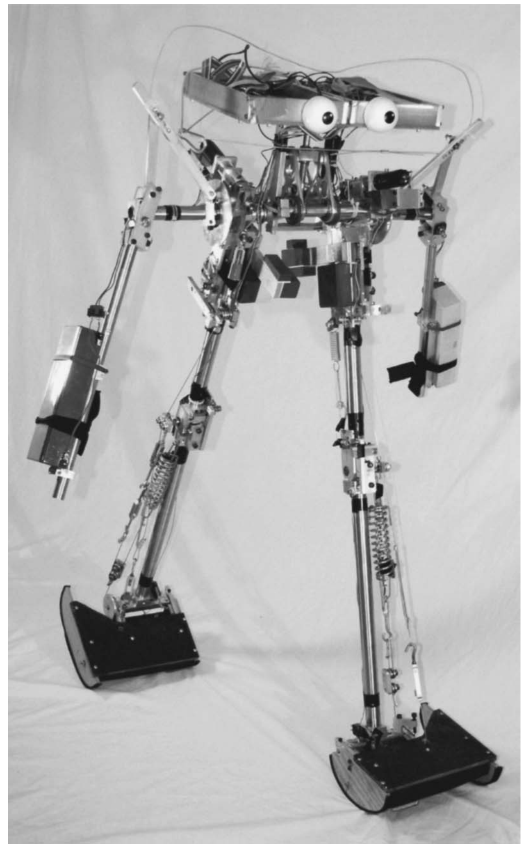

Fig. 7 The Cornell biped (courtesy of S. Collins and A. Ruina)

rotations and only counterweights are required for complete balancing. The balancing conditions given in [35] impose strict constraints on the dimensional parameters of the linkage. These dimensional constraints make all three types of linkages "foldable," i.e., all the bars can be aligned on the base. Therefore, these mechanisms are generally not suitable for machinery, where the input link must be driven through full rotations. However, for multi-degree-of-freedom applications (e.g., robotic applications), the above linkages can be considered as one-dof components providing sufficient range of motion for most practical purposes.

In Refs. [36,37], the above results on the reactionless planar four-bar linkages were used to synthesize 3-dof and 6-dof reactionless parallel mechanisms that do not involve any counter-rotations. In Ref. [38], a prototype (shown in Fig. 6) of a reactionless 3-dof planar parallel mechanism was built and demonstrated.

The parallel mechanisms mentioned above are dynamically balanced and therefore reactionless for any trajectory within their workspace. They can be viewed as mechanical devices that are capable of adapting to any trajectory (any set of positions, velocities and accelerations) without inducing reaction forces or moments at their base, regardless of the quality of the trajectory planning and control. As opposed to mechanisms in which the reactionless property is obtained through trajectory planning, dynamically balanced mechanisms will remain reactionless even in the presence of errors in the trajectory since the reactionless property is embedded in the mechanics.

**4.4 Mechanically Adaptive Robotic Walkers.** Walking robots have been the subject of many research initiatives over the past decades. Although most of the investigators addressed this problem from a computer control point of view, some researchers considered the mechanical adaptiveness of walking machines, in a framework similar to the approach proposed in this paper. In Ref. [39], it was shown that a passive planar mechanism with two legs could be designed to walk stably down a slight slope with no other energy input or control. Later, this exercice was extended to three-dimensional passive walking robots with knees [40].

Referring to the methodology proposed in this paper, one could address the problem of the design of a mechanically adaptive robotic walker as follows:

1. Definition of the variables (see Sec. 3.1): The vector of configuration variables, $\boldsymbol{\theta}$, contains the joint variables associated with the leg joints, while the vector of design parameters, $\mathbf{k}$, contains the dimensional parameters, mass, positions of the center of mass, inertial tensors of the moving links as well as the stiffness and undeformed length of the springs included in the system.
2. Fundamental mechanical properties (see Sec. 3.2): In this application, the important property is the ability of the mechanical system to robustly generate stable trajectories in state space of the system.
3. Conditions for adaptiveness (see Sec. 3.3): By studying the above trajectories and the trajectories required for walking, conditions on the dimensional and inertial parameters may be obtained.
4. Design rules (see Sec. 3.4): Finally, the above conditions can be used as design rules for the robotic walkers.

Although the above description is oversimplified, it clearly illustrates the connection between the design of robotic walkers and the concept of adaptive mechanical systems.

It is clear that the adaptiveness (or intelligence) of the robotic walkers developed using this principle is embedded in their mechanics. Obviously, in practical applications, walking machines cannot be passive and actuation is required. However, the principles used in the design of the passive walkers (mechanical adaptiveness) can be used to a great advantage in the development of actuated systems. Indeed, it can be shown [41] that robotic walkers based on mechanically adaptive systems are much more energy-efficient than other walking robots. As an example, the Cornell biped [41] (shown in Fig. 7), built using the principle of mechanical adaptiveness, is more than 15 times more energy-efficient than the well-known Asimo robot. This is clearly evidenced by the mere observation and visual comparison of the two robots performing a walking sequence.

## 5 Conclusion

In this paper, the concept of *adaptive mechanical system*, alternatively referred to as *mechanically intelligent system* was investigated. The concept was first formalized and a general methodology was proposed for its application in the design of advanced robotic systems. Examples of applications were then given. In the first application, mechanically adaptive robotic hands that can conform to the shape of the objects being grasped by the mere mechanical action of the contact forces were presented. Then, gravity-compensated parallel mechanisms that can support their own weight in any configuration within their workspace with zero actuator torques were discussed. Such mechanisms can also be considered to be mechanically adaptive since they are capable of reacting to any change of configuration and always provide the zero actuator torque condition. Dynamically balanced mechanisms were also presented. These mechanically adaptive systems provide the reactionless condition for any position, velocity, and acceleration of the inputs, which makes them very robust to perturbations. Finally, the application of the paradigm to walking robots was mentioned. Mechanically adaptive walking robots are capable of producing energy-efficient and stable walking without resorting to complex control strategies and powerful actuators.

It should be emphasized that the robotic applications discussed in this paper are only examples and that the concept of adaptive mechanical system is a general paradigm that can be used in many other instances. Because of the very nature of robotic tasks, mechanically adaptive systems should be at the core of the development of intelligent robotic systems. By proposing a general and inclusive formulation of this principle and by providing a number of illustrative examples, it is hoped that this paper will contribute to raising awareness amongst researchers and engineers who are currently shaping tomorrow's advanced robots.

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