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Analysis of a Variable Stiffness Differential Drive (VSDD)

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Abstract— **In robotics, differential mechanisms are widely used when lightweightness and compactness are a requisite for the robot design. Moreover, the last decades have seen the rise of (variable) compliant acuators as important elements to perform safe interaction and dynamic tasks. This paper introduces a Variable Stiffness Differential Drive (VSDD), i.e., a differential transmissions with variable stiffness actuators (VSAs), and presents a dynamic analysis. The analysis shows that, when variable stiffness actuators are used in coupled differential transmissions, the allowable stiffness range at the output of the system depends on the position of the springs inside the device. In particular, independent output joint stiffness can be obtained by dislocating the actuation from the elastic elements.**

I. INTRODUCTION

The mechanics of robotic manipulators is constantly changing due to the advancements in the field of physical human robot interaction and robot safety. In the last decades, the design of robotic manipulators entered the era of compliant mechanisms [1], [2] and lightweight structures [3].

Springs and compliant elements are widely accepted in the robotic community for their advantages of increasing safety and robustness of the robotic system. Elastic mechanisms in the robotic structure have been studied for their intrinsic characteristics of storing and releasing the energy during the execution of a task. These studies led to the development of innovative mechanisms and actuators [4]–[8] that are characterized by being energy efficient, safe but also capable to perform fast dynamic motions. Actuators that embed elastic elements are in fact capable to absorb/store mechanical energy in the form of potential energy, and to release it to perform highly dynamic tasks [9], [10]. The main categories of such kind of actuators are series elastic actuators (SEAs) and variable stiffness actuators (VSAs). The former feature constant stiffness at the output of the joint and are typically used to increase the safety of the robotic system by decoupling the reflected inertia of the motor and the output inertia [11]. The latter instead are also suitable when highly dynamic tasks are required for their characteristics to efficiently store the kinetic energy and release it in form of potential energy of the variable stiffness springs [9].

Firstly studied in the form of actuators, compliant joints are now becoming the new frontier of robotic manipulators, in both research and industry. These types of actuators have in fact lately been implemented in robotic manipulators. The CompActTM [12] is one of the few robotic arms using SEAs, to which a variable damping mechanism has been added. Another robotic arm, which can be considered a pioneer in this field, is the DLR arm and hand system [13], a complete robotic arm with variable stiffness actuators. In [14], a modular design is proposed to allow the development of cheap robots completely powered by VSAs.

A lightweight design represents an important issue in the mechanical development of robotic manipulators aimed at being inherently safe. One of the major examples in this field is represented by the KUKA Light Weight Arm, developed by DLR [15] and now sold by KUKA [16], which employes a series of modular joints to obtain a very light and powerful system. In this case, safety issues rely on the control of the system itself. An important example of lightweight design is the Whole Arm Manipulator (WAM) [3], [17], [18], where differential drives are exploited in a cable driven transmission to place the motors at the base of the manipulator, therefore reducing the moving inertia of the robotic structure. A similar design has been used in the mechanical design of the iCub humanoid robot [19], in order to obtain a very compact and lightweight, yet powerful 53 DoF robot. Differential transmissions represent in fact a powerful and compact way of designing mechanisms that require high torque capabilities and compact design.

Motivated by the importance of the development of a new generation of robots, this paper proposes and analyses a novel Variable Stiffness Differential Drive (VSDD), a differential drive joint with variable stiffness actuators, which combines mechanical properties such as lightweightness, compactness and safety. In particular, the analysis of the dynamics of the system reveales that, when VSAs are used as inputs of the differential drive, the overall output stiffness is coupled to the stiffness of each VSA. Therefore, an innovative design that dislocates the motors from the variable stiffness mechanism is proposed. A first prototype has been developed. The prototype is driven by the parallel of two electric actuators that are decoupled at the level of the output of the differenial mechanism by means of variable elastic elements.

The remainder of the paper is organized as follows. Section II presents the dynamics of a generic differential drive joint. Section II-B shows the dynamics of a differential drive joint when Variable Stiffness Atuators are used to power the transmission and when the compliant elements are dislocated from the motors. Two case studies are reported in Section III and a first prototype realization is presented in Section IV. Finally, conclusions are drawn in Section V

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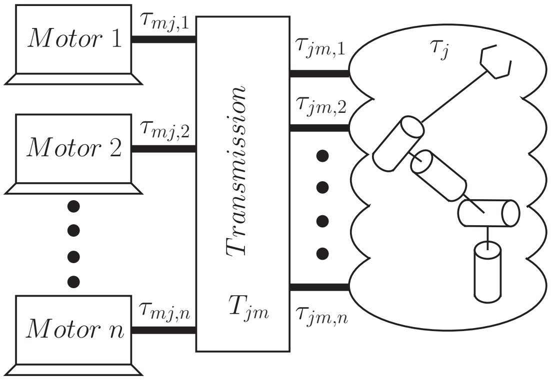

Fig. 1. Generic scheme of a coupled transmission: the motor power is coupled together by means of a kinematic relation T_{jm} that allows that distributes the power of each motor to the joints of the robotic manipulator.

II. Dynamics of Differential Drive Systems

Differential drive mechanisms employ motors that couple their power to perform a desired joint motion. When elastic elements are present within the actuator units employed in the differential mechanism, the dynamic properties of the joint are influenced by the design choices.

To better understand the dynamics of differential transmissions with compliant elements, the dynamics of coupled mechanisms is derived in Section II-A. Moreover, Section II-B shows the dynamics of the VSDD when the elasticity is located at the motor side of the transmission, while Section II-C shows the dynamics of the VSDD when the elasticity is present at the load side of the transmission.

Note that in the derivation of the following formulation we consider the case of differential drive mechanisms characterized by constant and linear kinematic couplings between motors and joints.

A. Dynamics of Rigid Coupled Transmissions

Let us consider a series of n links whose joints are actuated by a total on n motors that are coupled to give power to a $n-$DoF manipulator, as sketched in Fig. 1. In case of rigid and constant transmissions, we can consider that the motor velocities and the joint velocities are coupled by a constant linear relation T_{jm}, i.e.:

$$\dot{\theta}_j = T_{jm}\dot{\theta}_m \tag{1}$$

where $\dot{\theta}_j$, $\dot{\theta}_m \in \mathbb{R}^n$ represent the links and the actuators velocities respectively, and $T_{jm} \in \mathbb{R}^{n\times n}$ is a full-rank matrix that transforms motor velocities into joint velocities. The dual reltaion for the torques is:

$$\tau_{mj} = T_{jm}^{\top}\tau_{jm} \tag{2}$$

where $\tau_{jm} \in \mathbb{R}^n$ represents the torque that the joints exert on the motor side and $\tau_{mj} \in \mathbb{R}^n$ the torque that the motor exert on the joint side.

The dynamic equations of a coupled system can in general be derived by means of a balance of dynamic contributions of the joints and the motors, and take the form:

$$\begin{cases} M\left(\theta_j\right)\ddot{\theta}_j + C(\dot{\theta}_j,\theta_j) + g(\theta_j) = \tau_{jm} - \tau_j \\ \\ B\ddot{\theta}_m = \tau_m - \tau_{mj} \end{cases} \tag{3}$$

where θ_j, $\dot{\theta}_j$ and $\ddot{\theta}_j \in \mathbb{R}^n$ represent the joint position, velocities and accelerations respectively; θ_m, $\dot{\theta}_m$ and $\ddot{\theta}_m \in \mathbb{R}^n$ the motor position, velocities and accelerations respectively; $\tau_j \in \mathbb{R}^n$ is the vector of externally applied joint torque and $\tau_m \in \mathbb{R}^n$ the vector of motor torques; $M\left(\theta_j\right) \in \mathbb{R}^{n\times n}$ represents the inertia matrix of the robot, $C(\dot{\theta}_j,\theta_j) \in \mathbb{R}^n$ the centrifugal and Corioli's vector, $g(\theta_j) \in \mathbb{R}^n$ the gravitational components of the load side of the transmission; $B \in \mathbb{R}^{n\times n}$ is the diagonal matrix representing the inertia of the motors on their axis.

Note that Equation 3 describes a system composed of n ideal motors connected to a $n-$DoF manipulator by means of a transmission whose coupling is represented by the mutual torque exchanged between the motors and the links, as in Equation 2.

Let define:

$$\tilde{\tau}_j = C(\dot{\theta}_j,\theta_j) + g(\theta_j) + \tau_j \tag{4}$$

such that Equation 3 can be simplified as:

$$\begin{cases} M\left(\theta_j\right)\ddot{\theta}_j = \tau_{jm} - \tilde{\tau}_j \\ \\ B\ddot{\theta}_m = \tau_m - \tau_{mj} \end{cases} \tag{5}$$

In case of rigid transmissions, the system is composed of a single set of equations governed by the n degrees of freedom actuated by the motors. By using the relations presented in Equation 1 and 2, Equation 5 can therefore be rewritten as a single set of equations in the form:

$$\left(B + T_{jm}^{\top}M\left(\theta_j\right)T_{jm}\right)\ddot{\theta}_m = \tau_m - T_{jm}^{\top}\tilde{\tau}_j \tag{6}$$

where it can be noted that the inertia at the motor side is reflected by a composition of the mass matrix of the robot. This composition depends on the coupling matrix T_{jm}. Similarly, a torque acting on the joint side is projected to the motor side as a function of the transposed of the coupling matrix T_{jm}^{T}.

B. The effect of the elasticity at the motor side of the transmission

Let consider a system composed of n VSAs that are used to give power at the input of the differential drive. With reference to Figure 2, the system results in the series of motors, elastic elements, transmission and links. When elasticity is introduced in the transmission system (e.g. at the input of the differential drive), Equation 1 is not anymore generally satisfied. Nevertheless, if we consider the elastic elements to be concentrated at the motor level (i.e. between the motor output and the input of the kinematic coupling), and by appropriately chosing a zero configuration position for the motors and joints at rest, it is still possible to consider

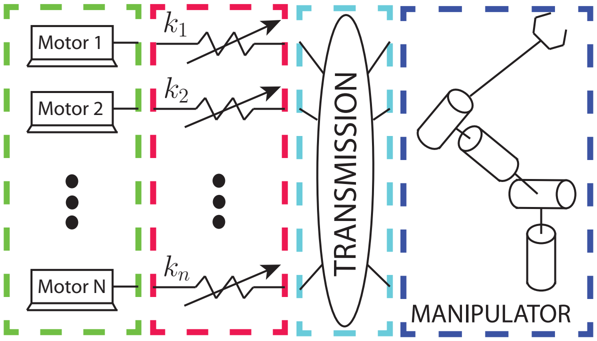

Fig. 2. Sketck of the transmission when the elastic elements are located at the output of the motors and before the kinematic couplings represented by the transmission element. The figure refers to the case reported in Section II-B

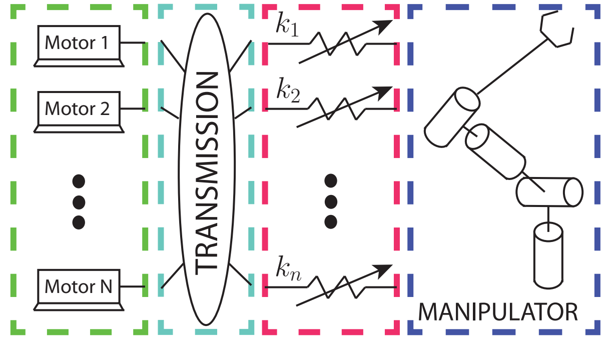

Fig. 3. Sketck of the transmission when the elasticity is concentrated at the load side of the kinematic couplings. The figure refers to the case reported in Section II-C

the coupling due to the transmission as rigid and write the elastic torque at the motor side as:

$$\tau_{mj} = K\left(\theta_m - T_{jm}^{-1}\theta_j\right) \tag{7}$$

where $K = K(t)$ represents the $\mathbb{R}^{n\times n}$ stiffness matrix of the elasticities imposed by each VSA. Note that, with reference to Figure 2 the stiffness matrix at the motor side of the transmission is a diagonal matrix, where each element of the diagonal represents the output stiffness of each VSA. Torque τ_{mj} can be reflected on the joint side, by using Equation 2, into the equivalent elastic torque at the joint side:

$$\tau_{jm} = T_{jm}^{-\top}\tau_{mj} = T_{jm}^{-\top}K\left(\theta_m - T_{jm}^{-1}\theta_j\right) = T_{jm}^{-\top}K\Delta\theta_m \tag{8}$$

where $\Delta\theta_m := \theta_m - T_{jm}^{-1}\theta_j$ represents the elastic displacement at the motor side of the coupled elastic transmission. Under the assumption that the coefficients characterizing the transmission T_{jm} are constant, this is equivalent at having an elastic displacement on the joint side given by:

$$\Delta\theta_j = T_{jm}\theta_m - \theta_j \tag{9}$$

Therefore, the equation of the coupled transmission with localized elasticity at the motor side due to elastic actuators, can be written as:

$$\begin{cases} M\left(\theta_j\right)\ddot{\theta}_j = T_{jm}^{-\top}KT_{jm}^{-1}\Delta\theta_j - \tilde{\tau}_j \\ B\ddot{\theta}_m = \tau_m - K\Delta\theta_m \end{cases} \tag{10}$$

which shows the behavior of a manipulator with indipendent motor stiffness. Note that the system is here presented in terms of stiffnesses in order to be consistent with the remaining part of the formulation and for an intuitive comparison with the system that will be presented in Section II-C.

Equation 10 shows that the motors are coupled by means of a kinematic relation T_{jm}, generally not diagonal, which gives origin to a stiffness matrix at the joint side $K_j = T_{jm}^{-\top}KT_{jm}^{-1}$ that is also non diagonal, even if K is diagonal and its elements can be arbitrarily changed.

This means that by changing the stiffness of one of the VSAs (i.e. of one of the elements of matrix K) at the motor side of the transmission, it is not guaranteed that only the stiffness of one DoF in the manipulator is modified. This introduces a strong limitation in the range of stiffnesses that the robotic system can assume at the load side. In other words, although independent motor stiffness can be chosen, the stiffness at the load side cannot be changed arbitrarily. A case study is reported in Section III-A, where the analysis of the stiffness matrix of a $2-$DoF transmission with localized variable stiffness at the motor side is reported.

C. The effect of the elasticity on the load side of the transmission

Let consider another system in which, on the contrary, the elastic elements are shifted to the output of the differential drive (see Figure 3). With reference to the figure, the system results in the series of motors, transmission, elastic elements and links. When the output stiffness is separated from the motors and is placed at the output of the differential kinematic coupling, it is possible to write Equation 5 as follows:

$$\tau_{jm} = K\left(T_{jm}\theta_m - \theta_j\right) = K\Delta\theta_j. \tag{11}$$

It is also possible to derive the corresponding disturbance torque at the motor side τ_{mj}, by using Equation 2, as:

$$\tau_{mj} = T_{jm}^T KT_{jm}\left(\theta_m - T_{jm}^{-1}\theta_j\right) = T_{jm}^T KT_{jm}\Delta\theta_m \tag{12}$$

Therefore, the overall dynamics of the coupled system with localized elasticity at the load side of the transmission can be derived by combining Equation 3 and 11, i.e.:

$$\begin{cases} M\left(\theta_j\right)\ddot{\theta}_j = K\Delta\theta_j - \tilde{\tau}_j \\ B\ddot{\theta}_m = \tau_m - T_{jm}^T KT_{jm}\Delta\theta_m \end{cases} \tag{13}$$

Equation 13 shows the behavior of a manipulator with indipendent stiffness at the load side of the transmission (see Figure 3). Compared to the system presented in Section II-B, also in this case motors are coupled by means of a kinematic relation T_{jm}, which is generally not diagonal. Nevertheless, the stiffness matrix K at the joint side can be chosen arbitrarily (see Equation 10 for a comparison with Equation 13).

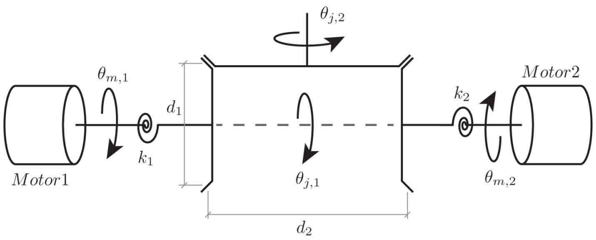

Fig. 4. Sketch of a two DOF differential drive joint: motors with elastic elements are the input to the differential transmission. The joint stiffness at the output of the transmission results from the kinetostatic coupling of the elasticities present at the input of the transmission.

Therefore, if the mechanics is designed in such a way that every elastic element can be placed at the output of each DoF of the transmission, the stiffness matrix K can take the form of a diagonal matrix, where every element on the diagonal can be changed arbitrarily and independenly. This means that by changing the stiffness of one of the variable stiffness units placed at the load side of the transmission, it can be guaranteed that only the stiffness of one DoF of the robot is modified.

Section III-B reports an example on a $2-$DoF transmission with localized variable stifness elements at the load side of the transmission, and draws some conclusions on that specific mechanism.

Finally note that, although the stiffness at the joint side of the transmission is independent for each DoF, the elastic torque on the joint side is reflected on the motor side of the transmission. Nevertheless, the coupling effect of the transmission is perceived by the motors as an external torque that influences the motor dynamics and can be rejected by means of control of the motor position.

III. CASE STUDIES

To better understand a kinematic coupling with VSAs, two examples are presented hereafter.

A. Case 1: Differential drive with independent motor stiffness

A first example refers to the case where the VSAs are placed at the motor side of the transmission (as in Figure 3). Figure 4 shows one possible implementation constituted by two motors actuating two joints in a differential configuration. The coupling matrix T_{jm} for the specific mechanism is full, meaning that the motion of both the joint DoFs are influenced by the motion of both motors. At the motor side, between the motors and the differential transmission, springs with stiffness $k_1 = k_1(t)$ and $k_2 = k_2(t)$ are placed, decoupling the motion of the motors from the motion of their output axis, i.e. the input of the differential mechanism.

The differential transmission is characterized by the dimensions d_1 and d_2, representing the diameters of the gears constituting the transmission. These quantities define the kinematic coupling of the system.

Let define the configuration variables $\theta_m = [\theta_{m,1}, \theta_{m,2}]^\top$ and $\theta_j = [\theta_{j,1}, \theta_{j,2}]^\top$, representing the vectors of the degrees of freedom of the motors and joints, respectively. Let also define:

$$K = \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix} \tag{14}$$

the matrix of the independent motor's stiffness and:

$$T_{jm} = \begin{bmatrix} \frac{1}{2} & -\frac{1}{2} \\ \frac{d_1}{2d_2} & \frac{d_1}{2d_2} \end{bmatrix} \tag{15}$$

the coupling matrix relative to the full differential mechanism, as sketched in Figure 4.

It follows that, the stiffness matrix at the joint side K_j, which is due to the localized stiffness at the motor level takes the form:

$$K_j = T_{jm}^{-\top} K T_{jm}^{-1} = \begin{bmatrix} 1 & -1 \\ \frac{d_2}{d_1} & \frac{d_2}{d_1} \end{bmatrix} \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix} \begin{bmatrix} 1 & \frac{d_2}{d_1} \\ -1 & \frac{d_2}{d_1} \end{bmatrix} = \\ = \begin{bmatrix} k_1 + k_2 & \frac{d_2}{d_1}(k_1 - k_2) \\ \frac{d_2}{d_1}(k_1 - k_2) & \frac{d_2^2}{d_1^2}(k_1 + k_2) \end{bmatrix} \tag{16}$$

which shows that the stiffness at the joint side is fully coupled to the stiffness that is placed at the motor side. In case the motors are constituted by VSAs, the motor stiffness can generally be changed ($k_1 = k_1(t)$, $k_2 = k_2(t)$). This feature characterizing this particular type of mechanism directly influences the stiffness of the joint side of the coupled transmission. It is noticeable that the elements of the stiffeness matrix at the joint side are coupled in such a way that it is possible to obtain independent joint stiffnesses if and only if $k_1 = k_2$. In this case, in fact, the matrix of joint stiffness becomes diagonal.

It must finally be noted that when one of the two stiffnesses is set to zero (i.e. $k_1 = 0$) the matrix loses rank.

From a mathematical point of view it means that the stiffness matrix has a kernel and, therefore, there is a set of configurations $\theta_j = [\theta_{j,1}\ \theta_{j,2}]^T \in Ker\,(K_j)$. It can be shown that all the combination $\theta_j = \theta_{j,2}\left[-\frac{d2}{d1}\ 1\right]^T \in Ker\,(K_j)$, $\forall \theta_{j,2} \in \mathbb{R}$.

From a physical point of view, setting one of the motor stiffness to zero consists in having a prefered direction in the joint space along which it is possible to move the joints without modifying the joint torque and, therefore, also the energy stored in the springs. This direction depends on the kinematic coupling between motors and joint and, for the proposed differential mechanism, it is not possible to obtain zero stiffness on one joint independently from the stiffness of the other joints.

B. Case 2: Differential drive with independent joint stiffness

The second example refers to the case where the variable stiffness units are placed at the load side of the transmission (see Figure 3). Figure 5 shows one possible implementation constituted by two motors actuating two joints in a differential configuration. The coupling matrix T_{jm} for the specific mechanism is the same as the previous example, meaning that the motion of both joints are influenced by the motion of both motors.

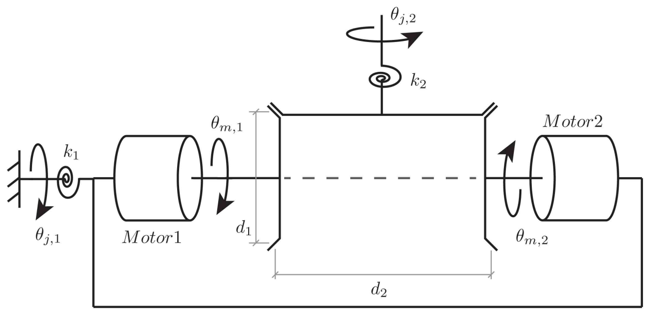

Fig. 5. Sketch of a two DOF differential drive joint: motors are the input to the differential transmission while the elastic elements are dislocated at the output of the kinematic coupling. The joint stiffness at the output of the transmission can now be set independently on the stifness on the other joints.

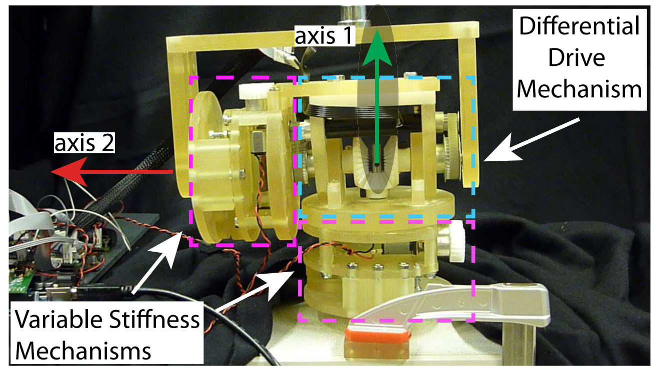

Fig. 6. Snapshot of the developed prototype. The picture highlights the presence of Variable Stiffness Mechanisms (VSMs) located at the joint side, dislocated from the motors that are directly used to drive the differential transmission.

This example shows that if we choose a stiffness matrix $K = K(t)$ that is diagonal, it is possible to change the stiffness of each joint independently from the choice of the stiffness of the other joints. In other words, given a mechanism as the one sketched in Figure 5, the motor torques at the load side τ_{jm} take the form of Eq. 11, where:

$$K = \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix} \tag{17}$$

while the equivalent stiffness at the motor side takes the same form as in 12, thus resulting:

$$T_{jm}^T K T_{jm} = \frac{1}{4} \begin{bmatrix} k_1 + \left(\frac{d1}{d2}\right)^2 k_2 & \left(\frac{d1}{d2}\right)^2 k_2 - k_1 \\ \left(\frac{d1}{d2}\right)^2 k_2 - k_1 & k_1 + \left(\frac{d1}{d2}\right)^2 k_2 \end{bmatrix} \tag{18}$$

It must be noted that the reflected effect of the elasticity at the joint side of the transmission is perceived at the motor level as a disturbance torque, which can be rejected by means of a high gain control of the motor position.

IV. Development of a VSDD Prototype

The proposed study has demonstrated that it is possible to obtain a joint constituted by a differential drive and independent output joint stiffness, by dislocating the actuation units by the variable stiffness units as proposed in Section II-C. A VSDD prototype has been design according to the case study presented in Section III-B using 3D printing technology (see Figure 6). A differential drive provides the power necessary to actuate the mechanism along two orthogonal directions. Variable stiffness units are attached to the outputs of the differential drive and allow changing the output stiffness of the differential axis independently. More precisely, the system is composed of a central unit where the motors and the differential gears are placed, and two variable stiffness units placed along the two orthogonal axis of the differential drive. The differential drive system provides the power to move the degrees of freedom. The variable stiffness units allow setting the compliance along each output axis of the differential drive system.

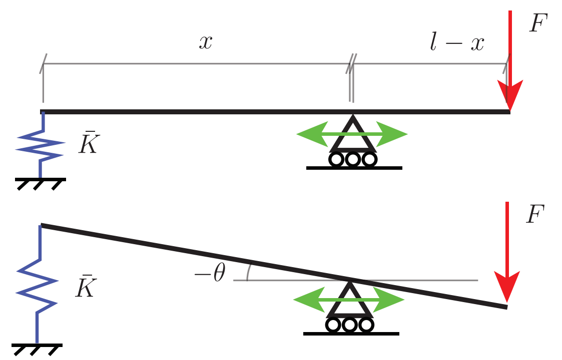

Fig. 7. Schematic representation of the working principle of the proposed Variable Stiffness Mechanism (VSM) used to change the stiffness of the joints.

A. Differential Drive

The differential drive unit is constituted of two motors with parallel axis that supply power to the two orthogonal joints. The kinematic coupling T_{jm} between the velocities of the motors and those of the joint is given by:

$$T_{jm} = \begin{bmatrix} 1 & -1 \\ a & a \end{bmatrix} \tag{19}$$

being a the ratio between the diameters of the bigger and smaller gears of the differential gear.

B. Variable Stiffness Unit

The variable stiffness unit is based on the principle of the lever arm introduced in [10] and its construction reminds the devices developed in [8] and [20]. One actuator modifies the position $x = x(t)$ of a pivot sliding along a lever arm. One one extremity of the lever arm the external force is applied. On the other extremity, constant springs contribute to store the energy that is transmitted to the lever arm by the externally applied forces. The apparent output stiffness at the output of the vaiable stiffness unit is given by:

$$K(x(t)) = \frac{\delta\tau}{\delta\theta} \approx \frac{F}{(l-x)\theta} = \bar{K}\frac{x^2}{(l-x)^2} \tag{20}$$

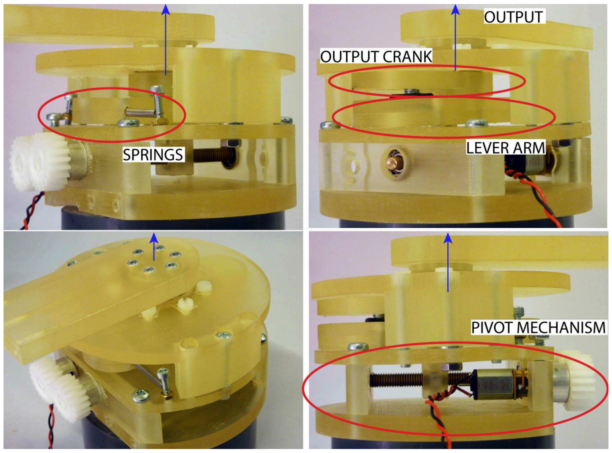

Fig. 8. Different views of the variable stiffness unit used in the prototype of the variable stifness differential drive joint. The picture highlights the different elements constituting the variable stiffness unit, which allow to change the apparent mechanical stiffness of the device.

Figure 7 represents the well known working principle for such class of VSA, while in Figure 8 is presented a snapshot of the variable stiffness unit that is attached at the outputs of the differential drive, as shown in Figure 6. It is visible in Figure 8 the lever arm, connected to one extremity to the output crank. Inside the leve arm, a pivot slides into a groove. Its position determines the apparent output stiffness. A motor provides the power necessary to move the pivot, in this case by means of a threaded shaft.
The video attachment shows the working prototype perturbed by an unknown environment.

V. Conclusion

The paper presented a VSDD, constituted of a differential drive with elastic elements. The work originates from considerations on the new developments in robotic design. Lightweight and compliant robots now represent the new fronteer of robotic manipulators, thanks to the advantages in terms of safety and performance. Lightweight robots often make use of differential drive systems to couple the power of the motors and, at the same time, to increase the compactness of the motor units. SEAs and VSAs introduce compliant element in the transmission, which allow decoupling the motors from the joint.
The mechanics of differential kinematic coupling with compliant mechanisms have been analysed. The mere use of these compliant actuators at the input of the coupled transmission introduces limitations in the allowable range of stiffness for each joint that can be overcome by separating the motor from the (variable) compliant mechanism. Variable stiffness units, dislocated from the actuators ouput overcome the problematics, allowing independent joint stiffness in coupled transmissions. Applications of the proposed technology is foreseen to brakethrough in the of wearable devices and rehabilitation, where lightweight designs and independent joint stiffness regulation is desired.

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