An implementation of muscle-like passive noise rejection (pnR) in variable stiffness actuators (VSA): the pnR-VSA solution

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Abstract—In the last years Variable Stiffness Actuators gathered the interest of the robotic community for their heightening role in new robot design. In particular, many solutions have been proposed to accomplish mechanical robustness, safe interaction and energy storage. In this paper we propose a novel mechanical solution that improves the passive capabilities of VSA. The new property we introduce is called “passive noise rejection” and it refers to the ability of the system to cancel out the effects of noise in a pure passive way. The idea behind this choice is that digital controllers are always band limited and this limitation reflects in the disturbance rejection property of the actuator. Starting from this observation through the use of non-linear springs in agonist and antagonist configuration we mechanically implemented an important characteristic of human muscles, which resides in the ability of open loop reject disturbances by means of muscle co-activation.

1. INTRODUCTION

In the last decade new actuator designs have been presented trying to introduce at mechanical level the advantages of compliance. Ranging from series elastic actuators [1] to different designs of variable stiffness actuators [2] [3] [4], various prototypes have been proposed and implemented on robots, thus allowing performance of novel and challenging tasks. Nevertheless some drawbacks are starting to emerge because relying on feedback in artificial agents (such as humanoid robots) might not be a practical strategy specifically considering the growing amount of sensors (e.g., distributed force/torque sensors, whole-body distributed tactile sensors, gyros and accelerometers) which are currently available and have to be acquired and centrally processed to perform complex actions. We recently proposed a different point of view, suggesting that compliance regulation might also represent a way to deal with unpredictable disturbances in absence of explicit feedback loops [5]. Our main motivation comes from the observation that humans and animals, although slow in closing position feedback loops (typical delays are in the order of one hundred milliseconds), are able to interact easily and reliably with highly unstable force fields [6]. In order to replicate a similar capability in robots we recently designed a novel actuator, shown in Fig. 1, based on an agonist-antagonist configuration [7].

In this work we present the current state of the actuator design and the mechanical improvements that we adopted to improve the performance of the first prototype.

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Fig. 1. The picture shows the first prototype of the pnR-VSA actuator.

II. BACKGROUND

In a recent work we considered a broad class of pVSA (passive VSA) and we computed the associated passive disturbance rejection [8].

In Figure 2 we depict from a mechanical standpoint some of the interaction that can occur between a motor $\vartheta$, a joint $q$ and the environment. For example the key component of a typical pVSA is an elastic element of variable stiffness in between the motor and the joint, this elastic element can be represented through the spring $c$. We study the effect of disturbances entering the system focusing in the passive disturbance rejection, i.e. no feedback has been considered to increase disturbance rejection. Disturbance is represented by stochastic variables acting as forces on the motor and on the joint (white noise). Computations, not reported here given the complexity of the analytical expression [8], show that the passive disturbance rejection monotonically increases with the stiffness of the elastic element in between the motor and the actuator (represented by the parameter $c$). However, the values of $a$, $b$, $d$ and $e$ are also essential to guarantee a certain level of passive disturbance rejection. The spring elements connecting the motor and the joint to the environment, $a$ and $b$ respectively, are typically not present in pVSA designs with rotary motors. Nevertheless, they play a crucial role in determining the overall system passive disturbance rejection. In practice when $a=b=0$ the system is free-floating with respect to the environment and
noise can drive the system arbitrarily far from the initial configuration. In a sense passive noise rejection is increased by augmenting the stiffness of the path which connects the joint to the ground. Therefore, we concentrate on actuators like the ones in Fig. 2 not having $a$ and $b$ simultaneously zero. We name these actuators “passive noise rejecting VSA” (pnrVSA).

III. MECHANICAL DESIGN

During the actuator design we concentrate on the possibility of finding a closed path that connects the frame to the joint. Our goal has been to design a mechanism composed by the elastic element $c$ in series with a structure composed by the motor $\vartheta$ and the second elastic element $a$. As shown in Fig. 3, the implementation of the passive noise rejection property has been achieved thanks to an agonist-antagonist arrangement: $K_{SE}$ is the series elastic element, $K_{PE}$ is the parallel elastic element which in series with $K_{SE}$ account for the passive tension properties of the system and $\vartheta$ is a contractile element (spring elongation equals reel displacement). Intuitively, a clockwise rotation of the motor $\vartheta$ coupled with a counterclockwise rotation of $\vartheta^a$ stretches all springs, changing their local stiffness, and therefore modifying the passive disturbance rejection at the joint without affecting its equilibrium position. If springs are designed in such a way that stiffness increases with stretch, the overall path connecting the joint to the ground is stiffened up, resulting in increased noise rejection. A complete analysis and characterization of these intuitive control laws can be found in [9].

IV. STICION COMPENSATION

We give a qualitative description of the system behavior when subject to static friction (a.k.a. stiction) acting on the motor gearboxes. In particular, all antagonistic actuators are based on the idea of co-contracting both agonist and antagonist motor sides of the system to increase joint stiffness. As a consequence, internal forces increase thus augmenting frictions, and in particular stiction components.

Due to the particular structure of the system, the actuator output joint should posses a unique equilibrium position [9], but the presence of stiction gives rise to a set of indifferent equilibrium configuration. This range of equilibrium position, named “dead-band”, rapidly increases together with actuator co-contraction. In [10], starting from the observation that both friction and spring restoring forces can be represented as a function of the actuator internal tension, we explore the possibility of mechanically compensate the stiction adverse effects by exploiting the actuator elastic elements. Through the analytical representation of the correlations of the system internal states, we derive analytical conditions to ensure that during co-contraction the increase of the restoring forces is “faster” than the increase of the friction forces. We exploit this representation to formulate differential conditions on the spring potential energy to guarantee that co-contraction reduces the effect of friction on the joint equilibrium position. The design of an optimized set of springs, respecting these conditions, led to the construction of a new version of our actuator. This new model shows that for increasing levels of co-contraction the effect of stiction, and thus the dead-band effect, decreases.

V. CONCLUSION

We presented the mechanical design of a novel agonist-antagonist actuator (pnrVSA) capable of actively changing its passive noise rejection characteristic. Crucial elements in the proposed system are four non-linear springs whose force-displacement characteristic has been customized on the specific needs of the foreseen applications. Through an analytical approach we have been able to generate a close form condition over the spring potential energies to decrease the stiction adverse effects for increasing levels of co-contraction. We aim in future at designing a new actuator to fully exploit the stiction-compensation methodology, increase the actuator power and reduce the overall size.

REFERENCES