Simulation of a Variable Stiffness Actuator in Gazebo

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Abstract—Abstract Variable Stiffness Actuators (VSAs) are becoming ubiquitous in soft-robotics, for they present the novel capability of adapting their mechanical output stiffness. To fully integrate their possibilities in modern Computer Aided Engineering design-simulation loops and ultimately speed up the design process and the application development, a detailed simulation of their behavior is fundamental. Up to the authors knowledge,no current mainstream robotic simulator features VSAs as possibility for joint actuation, hence the motivation of this work. The Gazebo simulation environment is widely used in robotics due to its many qualities, its connection with the Robot Operating System (ROS), its relation to the DARPA Robotics challenge (DRC) and its wide user community. This makes it an ideal candidate to host the proposed simulation module. This paper focuses on the qbmove VSA, whose designs are published open-source on the Natural Machine Motion Initiative (NMMI) platform. After a brief description of the the device design and function, the simulation implementation is presented and a comparison between the simulation and real experimental data is performed. Finally, we present some usage examples in which several instances of the module are assembled in complex structures. The simulation module and the assembled examples are freely available in the form a easy-to-use plug-in, and released open-source under the Apache v2.0 on the NMMI platform.

Index Terms—Variable Stiffness Actuators, Gazebo, robotic simulation, modeling of soft-bodied robots
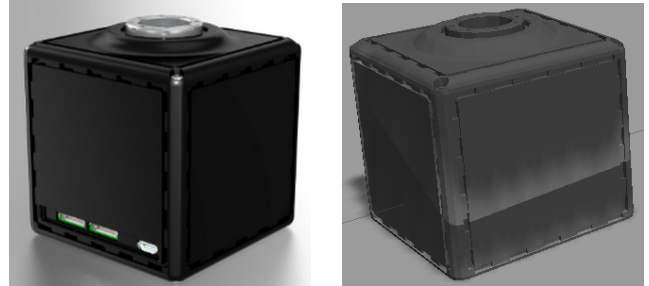
Fig. 1. The goal: narrow the barrier between a real (left) and a simulated (right) *qbmove maker pro* device to enhance the design process of hardware and applications.

I. INTRODUCTION

To operate outside factories and share spaces with humans, robots of the future will possess the same rich repertoire of motor skills which characterizes humans. Physical power, agility, robustness and ultimately the effective skill to physically and safely interact with uncertain environments and delicate humans are among the characteristics we expect a future machine should ultimately exhibit. Years ago Hogan [7] introduced and formalized impedance control as the key instrument to tackle this kind of problems in robotics. Later years witnessed the introduction of novel kind of actuation systems, designed to incorporate in their hardware the lesson learned thanks to impedance control. Abandoning the paradigm of rigid actuation that dominated industrial robotics for decades, in [14] springs were introduced as integrating part of an actuation system to shape its mechanical output characteristic so as to make it more apt to interaction tasks. This technology, called Series Elastic Actuation (SEA) and born 20 years ago, is now becoming part of the core of innovations that, today, are used to try and solve problems such as those posed by the Darpa Robotics Challenge [13], and to innovate the manufacturing market, with robots such as Baxter [16].

About ten years later, Variable Stiffness Actuation, introduced by [2] and [8], walked the next step by designing devices that can adapt their mechanical output characteristic online to adapt to changing external conditions and optimize efficiency and interaction capabilities. After this, the landscape of robotic actuation kept evolving continuously, with multiple variations and innovations. In particular the general trend described here evolved, more recently, in Variable Impedance Actuators - or VIAs - (see [20] for a review), which are devices that can adapt their mechanical impedance characteristic in a broader sense, including system that can adapt their mechanical damping [3], [11] and systems that exploit parallel springs and non-reversible mechanisms [12], [18] to limit energy consumption, among many others.

While most recent actuators, as VIAs, remain the very interesting subject of a lively research, the field of VSAs is rapidly approaching - or perhaps already crossing - the critical line that separates pure research from application. Proposals for common grounds, shared between VSA designers and their potential users, are being presented in literature [5], and specialized courses are being issued on the use of such devices [22]. The authors believe that VSAs are on the edge of moving the same step that SEA did a few years ago, and becoming accepted as a technology, rather than an idea.

To complete this passage and make VSAs available as components, VSAs should to be integrated in the modern design loop, which involves the early design and simulation of hardware within specialized software to avoid costly prototypes while still being able to experiment and evaluate designs and algorithms. This needs for a detailed simulation of their physical behavior. Focusing in the field of robotics, toward which VSA technology is oriented, simulation tools are more and more important to tackle issues such as planning,

navigation, decision-making, and in general to experiment complex scenarios that are not always easy to reproduce. In this landscape, Gazebo [9] is, *de facto*, the most widespread and user accepted tool to offer such capabilities. With a large basin of users and a ripe library of devices (sensors, actuators and robots), it is used by researchers as well as students in the field of robotics all around the world. Unfortunately, up to the authors knowledge, Gazebo does not feature VSAs as a possibility for joint actuation, as no other current mainstream robotic simulator framework does; hence the motivation of this work.

In this paper we present an easy-to-use software plug-in for Gazebo which is able to simulate a VSA joint module. The authors chose to simulate the *qbmove maker pro* device, manufactured by qbrobotics s.r.l. (see [15]) because it is the first VSA available on the market and because its design are published as open hardware on the online soft robotics community called Natural Machine Motion Initiative (NMMI) [21]. Moreover, given the modular nature of the chosen actuator, which can be assembled forming a variety of robots, it will be possible in the future to test interesting hardware solutions found in simulation with almost the same ease in the physical world.

The paper is organized as follows: section II shortly presents the actuator and describe its design and function. Section III, presents some details of the plug-in implementation, including a glimpse of the software architecture and reporting the value of the physical parameters used for the simulation. Section IV compares some simulation results to data acquired from the real hardware for validation and section V presents some demonstrations examples of the plug-in use. Finally, section VI draws the conclusions.

II. DESCRIPTION OF THE QBMOVE

In [4], during ICRA 2011, the VSA-Cube was presented as the first VSA modular servomotor, designed to be realized in small series to let researchers easily create prototypes of VSA powered multiple degrees of freedom robots. After roughly two years, in 2013 the design of two models of VSA actuator derived from the VSA-Cube, the *qbmove maker* and *qbmove maker-pro*, were published on the website of the NMMI community [21]. Both systems share the an open approach but, as the design of the *qbmove maker* makes it a device optimized for being realized with the least amount of heavy manufacturing (requiring mostly 3D printing of some parts and assembly), the *maker-pro* is an optimized version of the *qbmove* in terms of output performance. This come at the cost of incorporating metal parts that require machining to be built and custom electronics board. The popular nature of the *qbmove maker* scatters its electro-mechanical characteristic in function of the quality of its components and assembly, which can not be uniform. This led our choice of concentrating toward the *qbmove maker-pro*, which usually presents less variance in terms of performance.

A formal characterization of the *qbmove maker-pro* system can be extracted from its data-sheet [15], following the guide-lines reported in [5]. In the following we summarize its design and function for the reader's convenience[1].

A black-box description of the *qbmove* would define it as a VSA servo-actuator integrating an elastic variable stiffness transmission, two electrical motors and their gearboxes, sensors, driver circuits and communication & control electronics. The following describes each of these subsystems.

1) Elastic variable stiffness transmission: The *qbmove* is an agonist-antagonist VSA, where two driving pulleys move the output shaft through a non-linear elastic connection (see [20] and [23] for deeper understanding). The transmission is composed of four inextensible tendons which are kept in tension by four sleeves kept in tension by springs (one each, as in Fig. 2). The springs give the system elasticity, while the changing angle between the spring and the line of action of the tendon change the perceived stiffness from the output. The more the tendon becomes parallel to the line connecting the two pulleys, the stiffer the transmission between the driving pulley and the output becomes. While a precise description of the dynamics of the system requires the introduction of many variables, it is out of the scope of this paper. It will suffice to know that a very good approximation of the mechanical output characteristic of the transmission can be expressed as

$$\tau = k_1 \sinh(a_1(x - q_1)) + k_2 \sinh(a_2(x - q_2)) . \quad (1)$$

2) Motors and Gearboxes: The two driving pulleys are mounted on the output stage of two parallel gearboxes, each one powered by a DC motor. The dynamics of each motor can be described by the equations

$$J_i \ddot{\theta}_i + d_i \dot{\theta}_i = K_\tau I_i - \tau_i \quad (2)$$

$$L \dot{I}_i + R I_i = V_{ini} - K_{CEMi} \dot{\theta} , \quad (3)$$

where θ is the motor rotation angle, τ is the torque transmitted from the motor to the gearbox, I is the current on the motor windings, V_{in} the input voltage, J_i accounts for the combined inertia of the motor and the gears of the gearbox, reported to the rotation of the motor, d_i accounts for viscous friction on the motor shaft, K_τ is the torque-current constant of the motor, L is the electrical inductance of the motor windings and R

Fig. 2. Elastic variable stiffness transmission of the *qbmove*. The output shaft is dark gray pulley, in the middle, which is moved from the two driving light gray pulleys, on the sides, thanks to the force transmitted by the 4 black tendons. The tendons are kept in tension by the four white sleeves attached to the four gray springs. Panel (a) shows the system without any torque applied, in a soft configuration. When an external load (white arrow) is applied, the system ends in the configuration of panel (b), where the torque is balanced symmetrically by the two pulleys (black arrows) and a displacement is generated due to the deformation of the springs. If the two driving pulleys apply a differential torque (i.e.: in opposite directions), as in panel (c), the spring deform and the tendon becomes more straight. This implies that in case of an external load, as in panel (d), the allowed deformation is much smaller, i.e. the system is stiffer. In this case the two driving pulleys balance the torque asymmetrically.

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[1]For the sake of brevity, in the rest of the paper we will reefer to the *qbmove maker-pro* actuator simply as *qbmove*.

the resistance, and finally K_{CEM} is the counter-electromotive force constant. The subscripts $i = \{1, 2\}$ refer to each of the two motors. while each gearbox is described by

$$\theta_i = nq_i \tag{4}$$

$$\tau_i = \frac{1}{n}T_i - \tau_{\text{loss}}, \tag{5}$$

where n is the gear ratio, q_i s the rotation of either of the driving pulleys, T_i the torque transmitted from the gearbox to the pulley and τ_{loss} accounts for the losses in the gearbox due to friction.

A. Sensors and Electronics

Each of the two driving pulleys and the output shaft are sensed by one AMS5045 magnetic rotary digital sensor [1] which return their absolute rotation with 12 bit of resolution. The motor is driven with an H-BRIDGE driver controlled with PWM by a PSOC cy8c3246pvi-147 micro-controller [19], which also senses the current flowing in each driver with a resolution of $5/1638 mA$ and the input voltage with a resolution of $15.4 mV$. The micro-controller also closes a PD loop with a frequency of $500 Hz$ and communicates on an RS485 bus with which the actuator can be connected to the other modules and/or to a master unit. Each actuator also possesses a USB port and electronics that acts as a bridge to and from the RS485 bus.

III. IMPLEMENTATION

Gazebo is a robotics simulator which includes a powerful 3D viewer and open-source physic engines. Models in Gazebo consists of a Simulation Description File (SDF) and may include a custom dynamic behavior in a plug-in written mostly in C++ language.

Our module is implemented following the Gazebo plug-in structure and guidelines. On the invocation of the plug-in *load* method, all variables are initialized, parameters are set, and the communication configuration is established.

The core of the simulation is contained in the *update* method, which implements the simulation of each actuator separately from the simulation of the robot Lagrangian mechanics (which is entrusted to the Gazebo core), thanks to the notorious decoupling hypothesis of [17]. The following describes the implementation of the *update* method.

To achieve an accurate behavior, we implemented the motor dynamics which is not negligible in the overall dynamic of the variable stiffness actuator. Each servomotor is modeled using a state-space representation of a standard DC motor. The electrical dynamic is too fast to be simulated within the Gazebo sampling time. Hence, we use a simplified 2-state model which considers the position, θ, and speed, $\dot{\theta}$, of each DC motor. The current flowing in the motor I_i, can be readily computed using the equation

$$I_i = \frac{V}{R} - \frac{K_b}{R}\dot{\theta}, \tag{6}$$

if required.

Note that as the motor dynamic implementation is rather standard, the simulation of the two of them connected with the elastic transmission is, up to the authors knowledge, novel to the community. Moreover, the model validation presented in the next section is one of the missing point in current repositories [10].

Another element that affects the overall dynamics is friction. Friction is considered in both the motors and the output shafts. In both cases, we use the Hayward-Dahl model from [6]. The amount of static friction is rather different between motors and output shaft, because of the friction coming from the gearboxes.

Concerning the communication, the plug-in listens to two topics for the two references of equilibrium position and stiffness preset (the difference $q_1 - q_2$ between the angles of the two motors, which is linked to the stiffness of the system - see also Fig. 2). It is worth noting that, real *qbmove* units are connected in series, and have a serial RS485 communication. Thus, the delay in sending commands to complex assemblies has been also implemented according to how the units are connected. Thus, the plug-in structure replicates the real communication protocol using COM ports.

A PD controller is implemented (as in the real system) to generate the input voltage to the motors. This voltage goes to the motor driver, where the combined effects of PWM modulation H-bridge dynamics have been simulated using a dead zone and a saturation limit.

TABLE I
PARAMETERS OF THE *qbmove* PLUG-IN

symbol	description	value	unit
J	Motor inertia	0.001	[Kg·m^2]
b	Torsional friction	0.01	[Nm]
K_τ	Motor torque constant	0.8	[Nm/A]
K_b	Back-emf constant	0.3	[Vs/rad]
R	Resistance of wiring	2.3	[Ω]
L	Inductance of wiring	4	[H]
k_i	Stiffness model parameter	0.022	[Nm]
a_i	Stiffness model parameter	6.85	[1/rad]
$\tau_{\text{loss out}}$	Output shaft static friction	0.01	[Nm]
$\tau_{\text{loss}i}$	Motors static friction	0.8	[Nm]
	dead band	[-0.3,0.3]	[#]
	Saturation	[-1, 1]	[#]
K_p	Controller proportional gain	0.1	[1000/ticks]
K_d	Controller derivative gain	0.8	[1000/ticks]

All the relevant dynamic parameters of the actuator used in the plug-in for simulation are reported in Table I. Finally, the actual torque that moves the joint in simulation is computed using a straightforward implementation of (1-5).

The plug-in provide a gazebo interface using topics&messages, and no other external dependencies are required. Future work will extend the interface to the ROS community. The plug-in is available at: https://github.com/valeria-parnenzini/qbmove_plug-in.

IV. VALIDATION

In this section, a methodology for the characterization of a VSA is discussed. In particular, a method for the measurement

of salient physical quantities for the characterization of a VSA is presented. Most important characteristics concern mechanics and are related to torque and speed. Another quantity which is fundamental for a VSA is stiffness. Hence three different experiments have been conducted in order to compute typical values of three main physical quantities for a VSA: stiffness, maximum speed and stiffness variation time.

A. Stiffness experiments

The stiffness of a mechanism, σ, is the partial derivative of the applied torque, τ, with respect to its deflection, δ, expressed as

$$\sigma = \frac{\partial \tau}{\partial \delta}. \tag{7}$$

To measure the deflection, and therefore the stiffness, a known torque is applied to the actuator, and the position of the output shaft and motors are measured. This procedure is repeated for different torque values within a feasible range. A simple method to apply a desired torque is to use load a mass, M, hanging at a known distance, r, from the rotation axis. This can be realized with a flange of negligible weight rigidly connected to the output shaft of the actuator. The variation of the torque is obtained rotating the actuator. The attached mass and distance from the actuation axis affect maximum applicable torque. The torque exerted by the actuator as a function of the angular position of the output shaft θ is

$$\tau = Mgr\sin(\theta). \tag{8}$$

The exploration of the range of feasible torques, i.e. from zero to the maximum (Mgr), is done by commanding the actuator such that the link sweeps from the horizontal position ($\theta = 0°$) to the vertical position ($\theta = 90°$). To this end, a sinusoidal waveform has been chosen to provide a smoothed ramp. In fact, this function reaches the extremes of its range with zero velocity. The frequency of the sinusoid is set low enough to make the inertia interference negligible too. The load has a mass of 1 Kg placed at a proper distance to correspond to the maximum torque of 1.5 Nm. This experiment has been executed for several presets, as shown in Fig. 3.

B. Maximum speed experiments

A step input is used for the characterization of maximum speed, since the time required for the output shaft to reach the desired position is the objective of this experiment. Moreover, since several repetitions are needed to have a robust estimation, a square wave is fed as input to the actuator with a period that is long enough to allow the system to reach a steady state between transitions. In this case, no load is required and the actuator can lay on a plane with the rotation axis in vertical direction to avoid gravity effects. The maximum speed of 3.75 rad/s has been calculated feeding the equilibrium position input of a VSA with a square wave. The step response on the output has provided the rise time Δt and the variation of angle $\Delta \theta$. The angular speed is approximated by

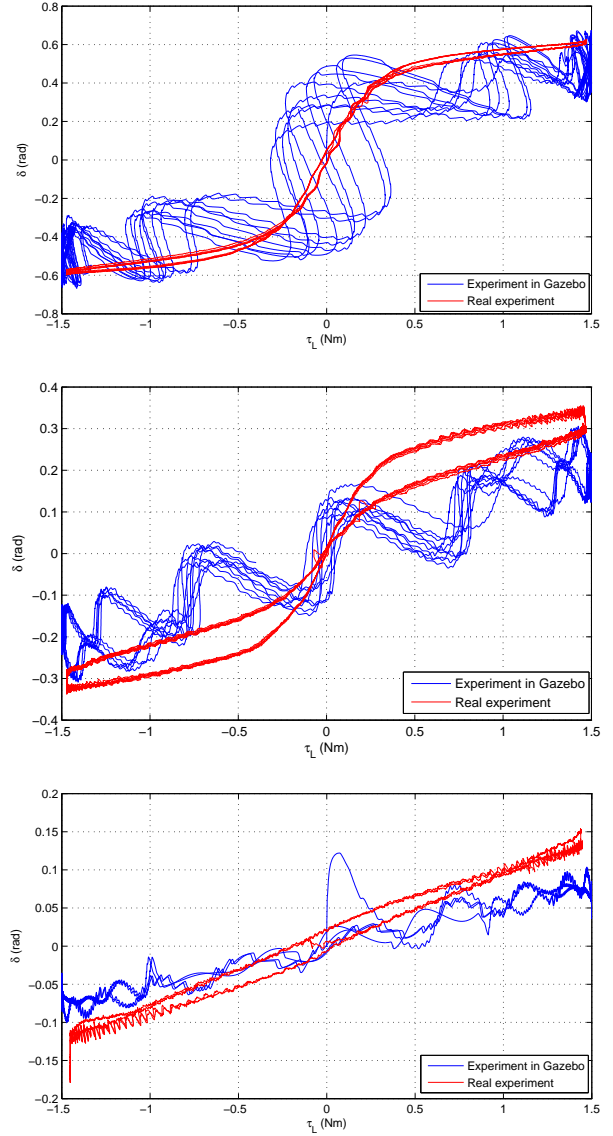$$\omega = \frac{\Delta \theta}{\Delta t}. \tag{9}$$

Fig. 3. Stiffness experiment with presets at: 0 rad (top), 0.4602 rad (middle), and 0.6903 rad (bottom).

This experiment has been executed for several presets, as shown in Fig. 4.

C. Stiffness variation time experiments

The stiffness variation time is obtained similarly to the maximum speed. It is evaluated feeding the inputs with a signal that generates a step for the stiffness regulation variable, and then reading the response of the measured variables to estimate the response time. In this experiment, two different cases have been considered: 1) using no load, and 2) using the nominal torque, both refering to the output shaft. In case one, the experiment has been conducted as for the estimation of the maximum speed, i.e. with the rotation axis parallel to the vertical direction. In case two, we use the characterization
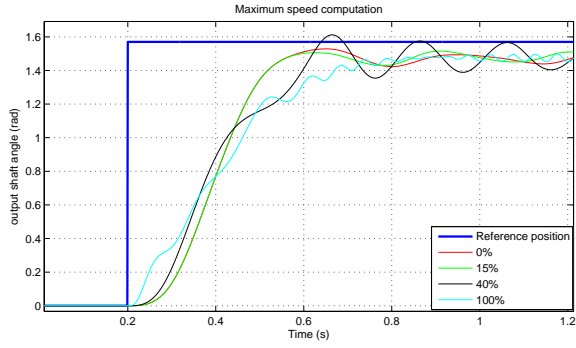
Fig. 4. Maximum speed experiment for different stiffness preset values.
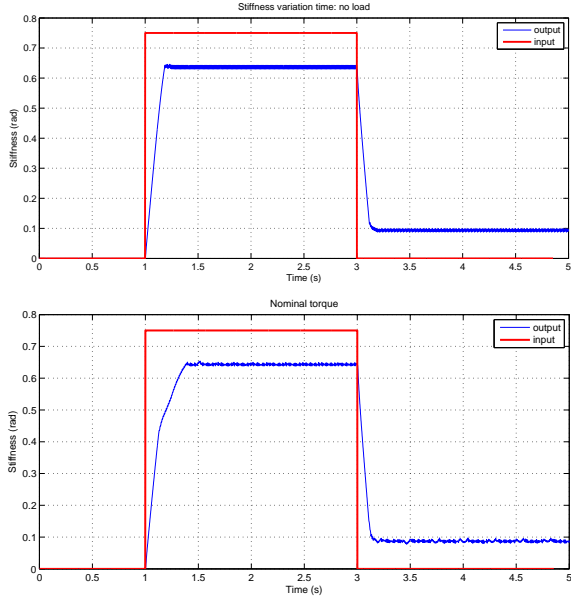

Fig. 5. Stiffness variation time experiment with no load (top) and nominal torque (bottom) on the output shaft.

structure by producing a torque of 1.5 Nm in the actuator shaft. The plots for the two cases are shown in Fig. 5.

V. EXAMPLES

A. Snake

The snake is a robot composed of 12 *qbmove* modules connected in series. All actuators can be coordinated using wave signals to emulate the motion of a real snake. For this purpose, VSAs are divided into two groups: the "even" and the "odd" ones, assuming that the first VSA in the chain is even. Moreover, rotation axis of the odd VSAs are vertical, while in even actuators, they are horizontal. Hence two different sinusoids are given as input to each group of actuators, whose general form is

$$y(t) = D + Asin(\omega t + \phi), \qquad (10)$$

where D is the offset, A is the amplitude, ω is the oscillaition frequency, and ϕ is the displacement. The advantage of using
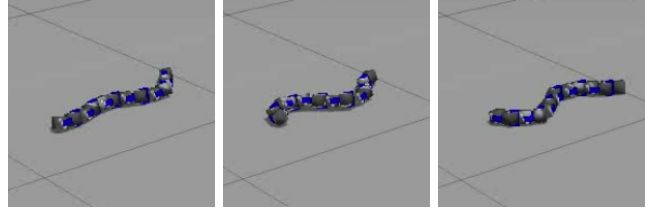

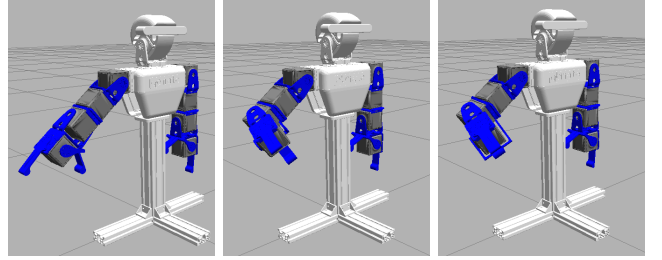Fig. 6. A snake model composed of 12 qbmove modules connected in series.

Fig. 7. Frank, the qb mate robot, composed of 8 qbmove modules connected in series.

a modular VSA such as the qb move relies on the adaptation to hostile terrains via stiffness variations. Having a reliable simulation tool to test different motion primitives is crucial for tunning the robot behavior in several scenarios before building and using it. The screenshots in Fig. 6 show how the snake is able to pass over a terrain by using the parameter configuration shown in Table II.

In particular, the values λ_v, λ_o and δ are given as inputs, and the vertical and horizontal displacements are computed as $\phi_v = \frac{\pi}{\lambda_v}$ and $\phi_o = \frac{\pi}{\lambda_o} + \delta$.

B. Frank, the qb mate

Frank is a robot composed of 8 *qbmove* modules connected in a human-like upper body fashion, that is, two arms, two grippers at the end of each arm, and the head. In Fig. 7, we show Frank performing moving its amr exploiting the variable stiffness actuator simulation.

The examples using the *qbmove* plugin are best appreciated in actual motion, which can be seen in the videos available at .

TABLE II
PARAMETERS OF THE SNAKE EXAMPLE

parameter	value
Vertical parameter λ_v	5
Horizontal parameter λ_o	5
Frequency ω	4.71 rad/s
Vertical amplitude A_v	60 °
Horizontal amplitude A_o	20 °
Vertical offset D_v	0 °
Horizontal offset D_o	0 °
Vertical stiffness s_v	35 °
Horizontal stiffness s_o	35 °
Horizontal parameter δ	90 °

VI. CONCLUSIONS

The contribution of this paper is two-fold. First, we successfully implemented the behavior of a Variable Stiffness Actuator (VSA) with current available tools provided by Gazebo. The plug-in is released as open-source with several examples via the Natural Machine Motion Initiative [21]. At the present, up to the authors knowledge, there are no out-of-the-box ways to simulate VSA in any simulator. This is in part because VSAs are a very recent technology, that was not commercially available until two years ago. The second is a methodology to validate this kind of simulation models. According to several simulation experts, the lack of validated models in simulators is, unfortunately, a diffused issue. The presented plug-in has been tested on the same test configurations that are used to characterize the real hardware. Moreover, we assembled two example applications: a snake robot and a humanoid upper-body composed of simulated *qbmove* units. These contributions aim to complement the design loop of hardware and applications.

In the future, we have plans to generalize the plug-in for the family of actuators of this kind and for soft actuators in general, by including their mechanical characteristics and their validation procedure. Moreover we plan to extend the software interfaces to other ecosystems such as ROS. We also hope this work be an impulse to encourage the community to use and improve free simulation tools for soft robotics.

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