Open Source VSA-CubeBots for Rapid Soft Robot Prototyping

Kamilo Melo, Manolo Garabini, Giorgio Grioli, Manuel Catalano, Lorenzo Malagia, Antonio Bicchi

Abstract— **Nowadays, rapid robot prototyping is a desired capability of any robotics laboratory. Combining the speed of 3D plastic printing and the use of custom Open Source electronic hardware/software solutions, our laboratory successfully developed and used tools related to variable impedance robot technology. This paper describes how we capitalized the design and use of one kind of variable stiffness actuators as a modular tool to prototype and test in a quick fashion several robot capabilities. The extension of such a modular tool for rapid prototyping allowed us to use it in several applications and scenarios, including the educational setting, aiming to speed up the gap between theory and practice in robotics. The complete palette of developments of our laboratory in hardware/software as well as some robotic systems applications shown here, are open source and contribute to the Natural Motion Initiative.**

I. INTRODUCTION

The Natural Motion Initiative (NMI) is an open-source community aiming at the diffusion of technologies that will propel the next generation of robots. NMI fosters the use of new actuation technologies for robotics research and educative purposes, enabling students and researchers alike to perform tests and experiments using new robot muscles as laboratory platforms. One of the main foci of NMI is on a new generation of actuators called Variable Stiffness Actuators (VSA), capable of making robots move more naturally than they do at present, and to approach human-like motor behaviors. The VSA technology also affords higher performance in terms of energy efficiency, speed, robustness and task adaptability. In our hopes, Natural Motion robots will outshine conventional robots with unparalleled human-like grace and dexterity.

As a contribution to NMI, our lab, has recently released several hardware and software open-source projects to build actuators, along with simulation and control tools and soft robotic demos. Our contributions to NMI include complete open source documentation for the construction of the VSA-CubeBot, a modular, compact "servo like" variable stiffness actuators (VSA) [1], as response to a lack of affordable variable stiffness technology for scientific research and fast and simple applications development. VSA-CubeBots can independently and simultaneously adjust the equilibrium position of the output shaft as well as its stiffness using just two reference signals. Because of the modularity in their concept, electronics and mechanics, these actuators can be interconnected to form, in short time, several robotic prototypes for different applications. A low-cost, readily available implementation of the VSA-CubeBot design, dubbed as qbmove, is produced by the spin-off company qbrobotics[1], who supports NMI by publishing the project as open-source.

Fig. 1: VSA-CubeBots set.

In this paper, we want to present several contributions to Natural Motion Initiative from the Open Source VSA-CubeBot perspective. Describing how these actuators work, their components and how this technology overpass the prototyping stages as actuator to become a whole robotic platform to test more complex systems (i.e. multi DOF robots) in a fast and reliable manner. Consequently, after describe some basic aspects of the VSA-CubeBot in section II, their integration schemes and modularity in III, some application cases will be presented in section IV. Then, an application of this technology related to education is discussed in section IV-F, finalizing with conclusions.

II. THE OPEN SOURCE VSA

A. VSA Technology in a Small Package

The novel prototype of servo VSA, the VSA-CubeBot, a picture showing a set of them is shown in Fig. 1. The main design considerations for this actuator correspond to high modularity, small size, and low cost. This actuation unit is intended to be part of an advanced robotics kit (as it will be shown). The basic idea of this actuator similar to a servo motor, so that assembly of any robotic system could only take into account performance and capabilities of the actuator as a whole: energy storage, torque range, stiffness range and stiffness settling time.

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Authors are with Centro di Ricerca E. Piaggio, Universita di Pisa, Italy. kamilo.melo@km-robota.com, bicchi@centropiaggio.unipi.it

[1] www.qbrobotics.com

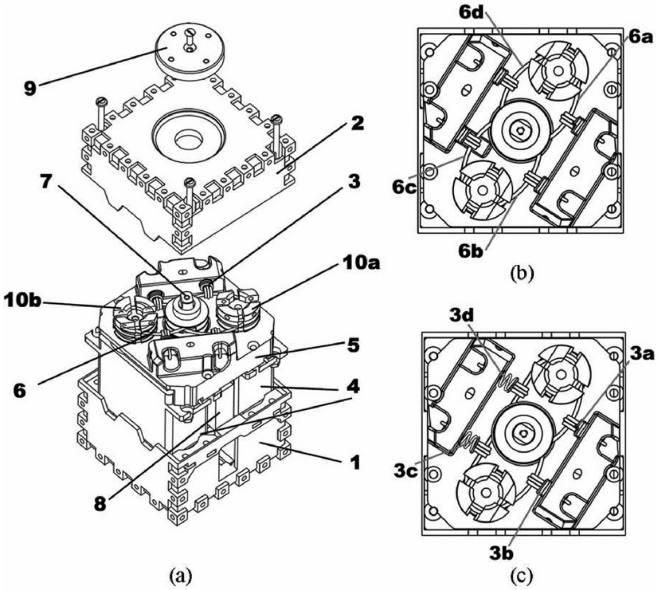

Fig. 2: VSA-CubeBot detail.

The VSA-CubeBot embeds the features of a servo motor and, moreover, the possibility of adjusting the output shaft stiffness. Stiffness control and output position are commanded by explicit references. Similarly to a normal servo motor the user can employ the VSA-CubeBot relying only on the knowledge of its output performance.

B. Mechanics

As we mentioned in [1], the actuator external shape is a cube with a 55 mm edge (for current versions 65 mm, see [2]). Small grooves are machined along the edges to allow interconnection with other components to form multi-DOF systems. All actuator frames are made with ABS plastic using, rapid prototyping techniques. Pulleys and shafts are realized with aluminum and steel alloys. Motors are Hitec Inc. TH-7950 servo actuators, which use DC motors and linear steel gearboxes. Finally, tendons are made with Dynema fibres. Structural details (1-10) of the construction can be seen in Fig. 2(a). The elastic transmission is realized via four tendons (6a, 6b, 6c, 6d) and four extension springs (3a, 3b, 3c, 3d) in Fig. 2. One end of each tendon is wrapped and locked on to the output shaft, while the other end is wrapped and locked on to a pulley (see Fig. 2(b)).

The VSA-CubeBot uses a Bidirectional Antagonistic design, as shown in Figs. 2(b) and 2(c). This layout, is used in some actuators (e.g. [3]). Fig. 2(b) shows the system in a low stiffness configuration, where springs (3) and tendons (6) are not loaded. When the two pulleys (10a) and (10b) rotate in opposite directions, two of the four tendons get loaded, stretching their springs and realizing a high stiffness configuration (Fig. 2(c)). Movement of the output shaft (7), is simply obtained by rotating the pulleys in the same direction.

For more details and Open Source resources related to the mechanics of the VSA-CubeBot, please refer to the NMI website [2] in categories:

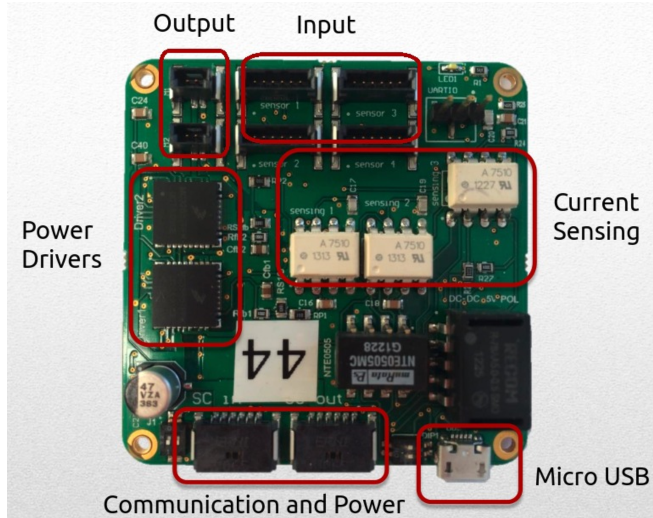

Fig. 3: VSA-CubeBot custom circuit board.

- Parts list.
- Documentation.
- Construction details and CAD diagrams
- Construction assembly instruction videos

C. Electronics

The electrical interface of every VSA-Cube is comprised by a five-line bus. The lines correspond to: one line for ground, two lines for powering motors and logic and the last two lines are used for implementing an I2C bus. Multiple VSA-CubeBot units can be serially connected using a daisy-chain topology. Each VSA-CubeBot unit has its own address on the bus. A writing operation on the unit has the effect of sending it a command, while a reading one is used to retrieve its internal configuration.

The circuit board inside the VSA-CubeBot is depicted in Fig. 3. It uses a Cypress PSoC®3:CY8C32 Family microcontroller, running at 50 MHz with 64kB of memory. The board consist of several parts. These includes the communication and power ports (two) which allow the interconnection with other modules in daisy-chain configuration sharing the power with other actuators. The micro USB port (connected to a single module in a multi-DOF system), allow data to be loaded and retrieved from an external control PC through a high level application (i.e. Matlab/Simulink). As the actuator mechanical setup comprises two servomotors as prime movers, two driver circuits supply the required power to obtain motion. The board has an input/output set of ports, which made part of the internal servomotors position control closed loops. The input ports receive data from specially located angular position sensors (magnetic encoders) for the two prime movers and the output shaft. An extra port is available for a general purpose sensor (i.e. temperature sensor). The output port drives the power directly to the DC motor terminals that correspond to the prime movers. Finally, there are current sensing circuits, that along with the position encoders, provide feedback to the user to reconstruct

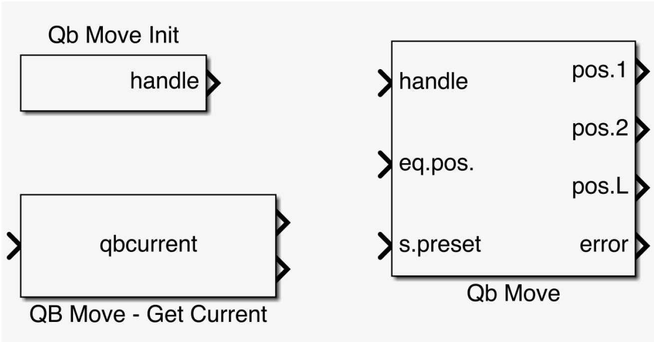

Fig. 4: VSA-CubeBot Matlab/Simulink block.

the torque/stiffness behavior of the actuator.

Different control modalities are possible. The main one is servo-unit like: the rest position and the stiffness of the output shaft can be set. Other modalities include, but do not limit to, setting output shaft position (in closed loop as a non-VSA servo), and independent control of the two motors. This last option is made available to give the user the possibility to implement other low-level control strategies derived from the higher control layers.

For more details and Open Source resources related to the electronics of the VSA-CubeBot, please refer to the NMI website [2] in categories:

- Schematics
- Documentation

D. Software

Three different open source software components have been developed as part of the NMI releases. First, there is a standard C communication library. This library allow users to control from console any VSA-CubeBot unit. The library features many commands to test, reset, control the actuators, and make modifications in the board firmware. It is intended for advanced users and we foresee this library as a basis for a future SDK. The second software component released is a Matlab/Simulink library to interface the real actuator. The blocks shown in Fig. 4, are the components of such library. It comprises a handle block to initialize communication link from Matlab host PC to the external VSA-CubeBots chain. Two extra blocks are available. One that represents a real VSA-CubeBot featuring the same input commands (i.e. equilibrium position and stiffness preset), which output (besides the actual motion of the real actuator) corresponds to the encoder readings of position of prime movers, the actuator's output shaft and the position error of the internal position tracking system. The last block, provides the user in the Matlab/Simulink environment with the current readings intended for torque control.

The third and last software component released in the NMI, corresponds to the Matlab/Simulink model (Fig. 5). The purpose of this Simulink block is to simulate the behavior of one VSA-CubeBot in order to simplify the controllers design and implementation prior its use in real soft robotic systems using the actuators.

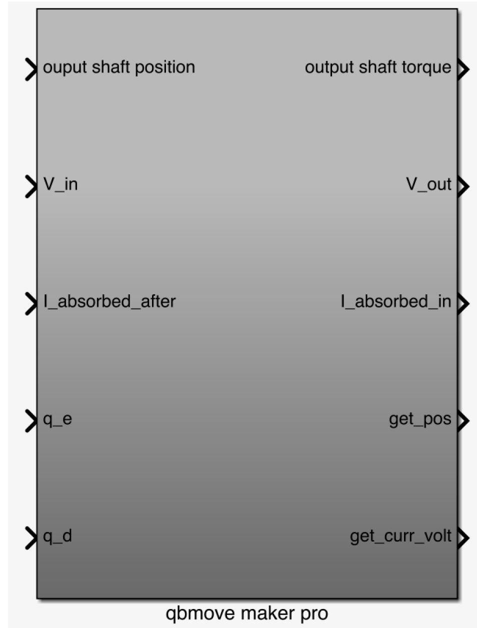

Fig. 5: VSA-CubeBot Matlab/Simulink simulated actuator.

One important feature of these last mentioned Matlab/Simulink blocks is that they can be used as a single actuator or an array of actuators in the case of a multi DOF system. In that case, bus signals are used carrying multiple data as input/output from the blocks.

For more details and Open Source resources related to the software of the VSA-CubeBot, please refer to the NMI website [2], in categories:

- General Software Documentation
- Simulink Library

III. MODULARITY KEY FOR RAPID ROBOT PROTOTYPING

Three basic connection possibilities make the VSA-CubeBot modules capable of forming different assemblies. Each connection is obtained by attaching a VSA-CubeBot with an interconnection flanges, as shown in Fig. 6. Using these flanges, there are two kinds of revolute joints assemblies, with perpendicular and parallel axis respectively, and also rigid connection. Fastening of the actuator unit on the flange is achieved by inserting the key of one actuator inside the flange's complementary groove. Particularly, the C shape (6, bottom) is used to extend the output shaft range extending the link. Open source resources of these interconnecting parts can be found in [2].

For us, the key of the rapid robot prototyping is related to the capability to build and operate a whole functional robotic system in few hours. The use of a combination of the VSA-CubeBots, special interconnecting flanges and the Matlab/Simulink library, allow users, to construct different configuration of robots. In the next section, we will present several robotic applications made so far included as contribution of our lab to the NMI.

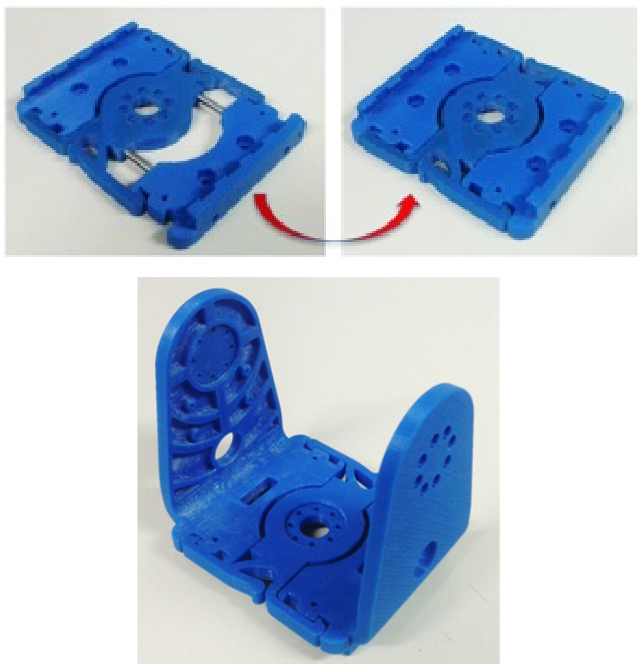

Fig. 6: Flat interconnecting flange (top), “C” shape flange (bottom).

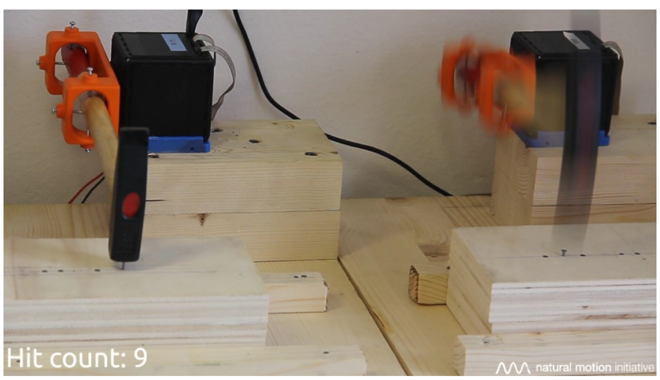

Fig. 7: Screenshoot of the Hammering process with VSA CubeBots, using Stiff and soft configurations.

IV. CASES OF STUDY

In this section, we would like to illustrate some of the possible applications as a whole robotic system that can be settled up in little time, using the VSA-CubeBots and their controlling software. Some of these cases of study, are reported as contributions of the NMI. Accompanying videos of these applications, showing the use of the systems and parts mentioned here can seen in [2].

A. Hammering

We have been exploring different dimensions of the hammer process using VSA technology [4]. Different comparisons (Fig. 7) using stiff and soft hammer actuators allow us to understand and model the underlying dynamics of this problem. The set up of the experiments is very fast and the use of the Matlab/Simulink blocks allow the simplified controller design.

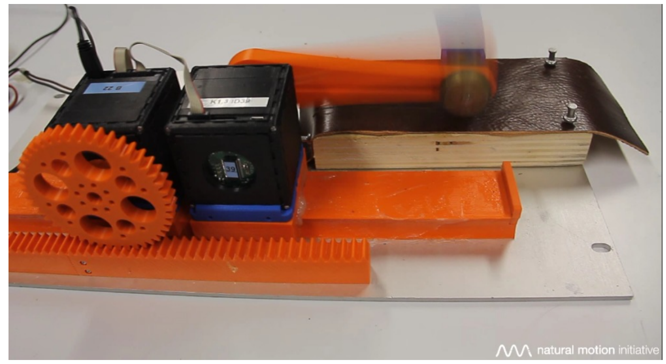

Fig. 8: Leather cutter prototype.

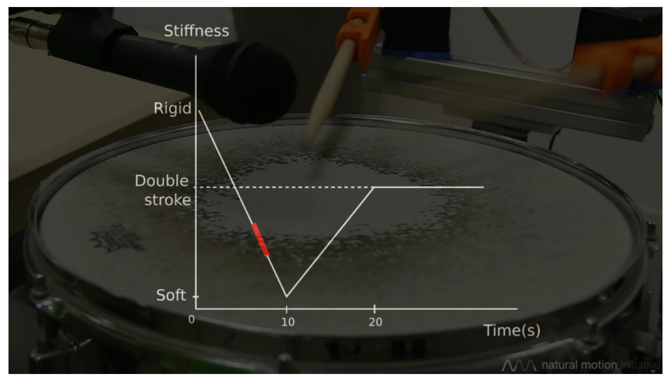

Fig. 9: Snare rolling with VSA set up.

B. Cutting leather

A very simple, yet fast to set up application is a cutter by resonance (Fig. 8). Using one VSA-CubeBot with an scalpel as end effector, oscillating in its resonance frequency, we maximize the effectiveness of the perforation in the material. A second actuator is used to displace the whole system laterally to perform the cut.

C. Drumming

An interesting application of the VSA-CubeBot is related to achieve higher frequency of percussion. In this example, a snare drum is used (Fig. 9), while the stiffness of the actuator is changed in time, looking for the correct value of the actuator’s stiffness preset, in order to achieve “rolling” sounds. This is when the compliance is such that the drumstick impacts the drum several times per stroke.

D. Robotic Snake

In the current trend for search and rescue robots, the snake robots had shown some potential capabilities to cope with some specific tasks [5]. Up to the date, several snake robots have been proposed. However, the study of the compliance in their mechanical construction and actuation have been addressed few times. With this example, as seen on Fig. 10, a robotic snake built with VSA-CubeBots, offers the intrinsic capability to change the body stiffness “on the fly”, in order to, tackle specific situations, for instance adapt the

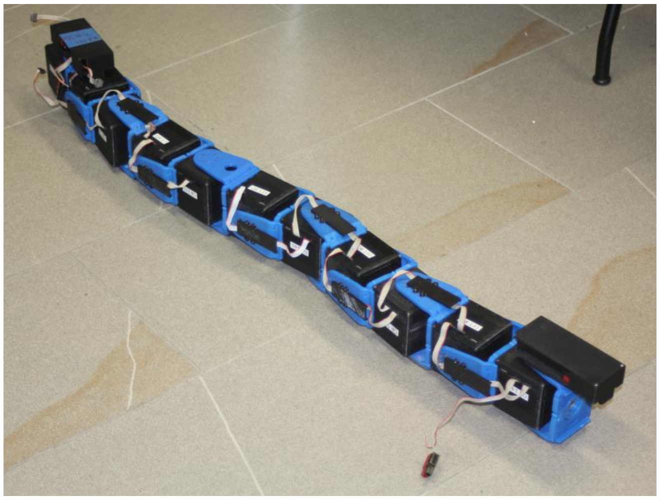

Fig. 10: Snake robot conformed by VSA.

Fig. 11: Torso and legs of humanoid robot using VSA.

body shape to a specific terrain while maintain a well defined cyclic locomotion gait, without put special care in the design of controllers for such adaptability.

E. Humanoid

Finally, and as major contribution to NMI, our lab had developed a humanoid robot. The set of actuators and interconnecting parts, as shown in Fig. 11, allow users of these system to rapidly create a humanoid robot prototype with some specific features. Likewise, the addition of external components, like a 3D depth sensor (in the head) or the Pisa/IIT hands, are demonstration of the quick set up capabilities and high degree of integration of this system.

F. Soft robotic systems rapid prototyping in education

Recently, we have been using this rapid robot prototyping system, and tested several of tools reported in this paper, in the Master on robotics engineering and automation at the University of Pisa in the course Robot Control (rapid robot prototyping session)[2]. Students were trained to understand the VSA technology with this practical component as validation tool.

V. CONCLUSIONS

With the rapid robot prototyping capabilities embedded in the modular VSA-CubeBot system, we are constantly inviting future roboticists to seize the advantages of the soft robotics in a direct way. Conventional actuators are widespread in different sizes and capabilities, but there is a lack of affordable variable stiffness technology for scientific research and fast and simple applications development. Our laboratory, through NMI wants to bring this technology to the community in a reachable, affordable and reliable way. This community may range from individual persons, to small, up to big laboratories, which can contribute to this open source project as well, improving the hardware/software and the controllers already developed. We foresee new applications using these tools and expect to inspire the community to improve the current technology and formally apply these tools in the educational setting.

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