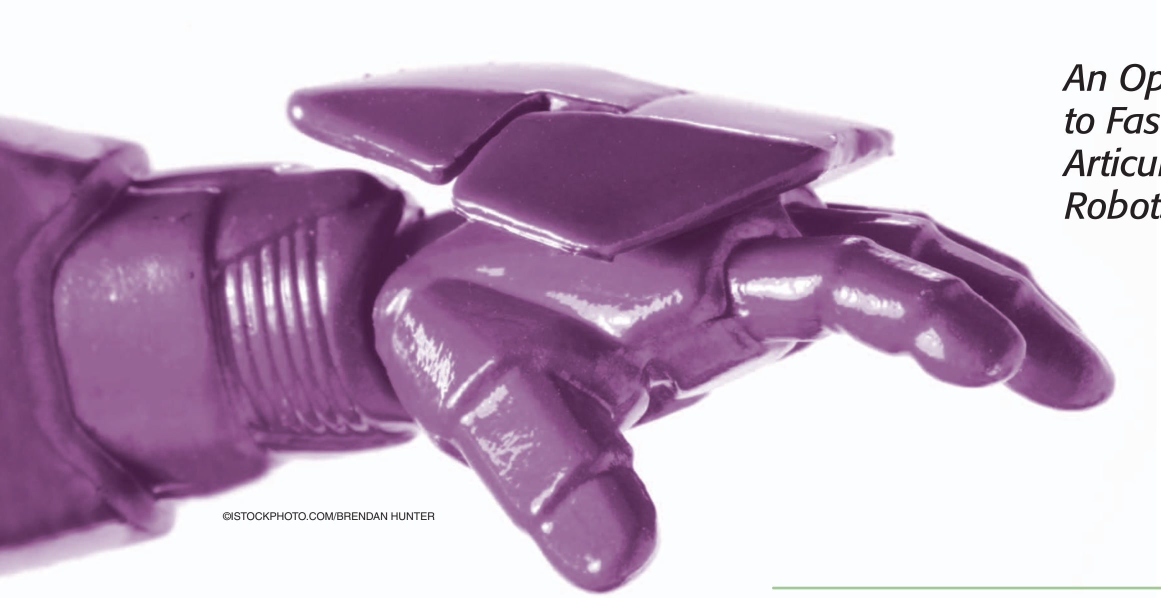
The Quest for Natural Machine Motion



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An Open Platform to Fast-Prototype Articulated Soft Robots

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Soft robots are one of the most significant recent evolutions in robotics. They rely on compliant physical structures purposefully designed to embody desired characteristics. Since their introduction, they have shown remarkable applicability in overcoming their rigid counterparts in such areas as interaction with humans, adaptability, energy efficiency, and maximization of peak performance. Nonetheless, we believe that research on novel soft robot applications is still slowed by the difficulty in obtaining or developing a working soft robot structure to explore novel applications.

In this article, we present the Natural Machine Motion Initiative (NMMI), a modular open platform that aims to provide the scientific community with tools for fast and easy prototyping of articulated soft robots. Such a platform is composed of three main open hardware modules: the Qbmoves variable-stiffness actuators (VSAs) to build the main robotic structure, soft end effectors (EEs) to interact with the world, and a pool of application-specific add-ons. We also discuss many novel uses of the platform to rapidly prototype (RP) and test new robotic structures with original soft capabilities, and we propose NMMI-based experiments.

Many New Robotics Possibilities

Enabling a true integration of robots in human-populated environments is one of the most ambitious long-term goals of robotics research. Robot evolution in terms of safety, intelligence, affordability, and social skills has been impressive in the past decade and has brought several robotic devices to market. However, making robots able to safely interact with the public is hindered by the fact that classical industrial robots, as stiff and heavy machines, can generate dangerous and unstable interactions in uncertain environments.

To overcome this limitation, and inspired by biological actuation, so-called soft robotics was born [1], i.e., robot development that embeds elastic elements with either fixed or variable mechanical compliance. The first goal for soft robots

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has been the achievement of safe interaction with their environment, humans included (see, e.g., [20]).

Two main branches exist in soft robotics research. The first takes its inspiration largely from invertebrates [28] and builds robots with continuously flexible materials. The compliant behavior of these robots is distributed throughout the structure. The other branch, inspired more by the vertebrate musculoskeletal system, aims to build robots in which compliance is concentrated mostly in the robot joints. These robots are also referred to as *articulated soft robots* or *flexible-joint robots*.

Today, soft robotics is extremely popular and is enabling new possibilities in several robotic fields. Among the many examples are humanoid robots [18], manipulators [13], anthropomorphic artificial hands [4], [6], rehabilitation [26], and underwater exploration [19], [21].

Exploration of soft robots' full potential has led to many applications in which the robots overcome conventional-robot performance issues. Some examples are explosive movements [10], energy efficiency in cyclical movements [12], and adaptability in uncertain scenarios [3]. The efforts have produced substantial advances, and it is widely believed that more applications are yet to come. Along with all the new applications, there are new challenges for soft robotics on the planning and control sides. However, we believe that algorithm development and applications discovery are currently slowed by the lack of an available and affordable soft robotics technology. This drastically reduces devices' ready-to-run time for interested users who are not designers.

In recent years, however, overcoming this limitation appears to be possible through open-source and easy-to-manufacture platforms [2], [15], [29]. Through such platforms, designers and other users can share and obtain feedback about the results of their research. Thus, we believe that the development of open platforms can be a strong driver for solving the problem of soft robot availability. In this regard, two interesting examples of open platforms exist in the field of soft robotics [27], [30]. They are both focused on robots built with soft materials and show how knowledge sharing can lead to an increase in user participation.

However, to the best of our knowledge, there is no similar initiative for flexible-joint robots. To try to fill this gap, our group developed hardware modules to build our own robotic structures (see, e.g., [4] and [5]). During this process, we realized that the development of a standardized interface in mechanics, electronics, and software strongly simplifies the assembly of new soft robots. The result of our effort is the NMMI building platform, which significantly simplifies the fast prototyping of soft robots. On the NMMI website [22], users can find 1) open hardware drawings, 2) open software libraries, and 3) projects from contributors.

Some parts of the NMMI platform presented in this work were already introduced in previous publications (e.g., [4], [5]). However, together with a uniform system view and description, this article presents many new technical details, new robotic systems and experiments, and a discussion of the open source–related characteristics of NMMI.

The NMMI Platform

A key aspect of a successful platform is its usage intuitiveness. The platform should be user friendly and ready to run. Our inspiration in designing this aspect of the platform comes mostly from the notorious robotic platform LEGO Mindstorms (www.lego.com/en-us/mindstorms). As in LEGO, we organized our platform in simple building blocks explicitly designed to be easily connected and disconnected. Our goal was to give users all the necessary elements to experiment with novel robotic structures at a level useful for a research group, starting from a pool of basic elements as in Figure 1.

NMMI offers users three groups of hardware building blocks: 1) a family of VSAs, the Qbmoves; 2) a solution for the implementation of soft active EEs; and 3) a database of possible add-ons that can be used as passive EEs, spacers, feet, heads, and so on. Such components are integrated in an infrastructure of mechanical, software, and electronic elements purposefully designed to facilitate fast and intuitive interconnection.

Open Source Versus Do It Yourself

During the NMMI development, the open nature of the platform posed novel design challenges and taught us many new, sometimes unexpected lessons. One important lesson was that open-source hardware and do-it-yourself (DIY) components are not equivalent. In recent years, fast-prototype techniques have become more and more commonly employed. Thanks to the availability of cheap versions of this technology, such as low-cost three-dimensional (3-D) printers, enthusiastic groups of users have been able to take advantage of open-source designs and build their own systems. This trend has brought many positive contributions but has also led to the view that the more open the design, the more involved may be the amateur element. However, especially in the mechanical field, the open-source versus DIY distinction is very important, since the creation of some parts may require facilities not available to many practitioners. Thus, to achieve a maker-oriented device, a suitable design is needed, independent of the open nature of the project.

For this reason, the performance difference between self-made devices and more professional and conventionally built

Figure 1. A set of components (grippers, compliant actuators, and batteries, among others) of the NMMI platform. Through them, flexible-joint robots can be intuitively built and tested.

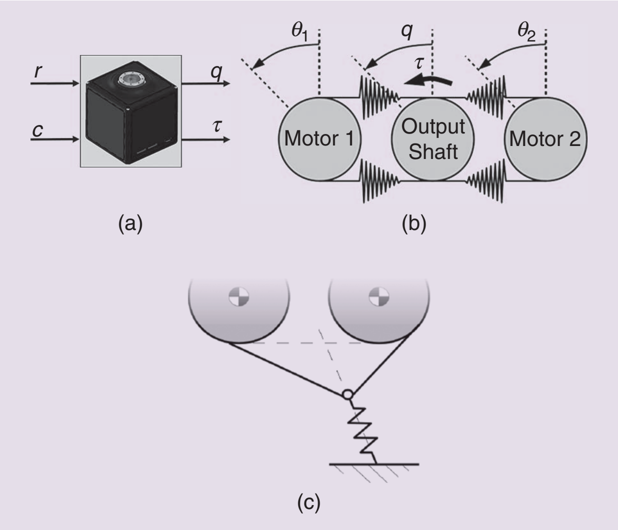


Figure 2. (a) A biologically inspired black box model, where r and c are the inputs, corresponding to the desired equilibrium position and stiffness, respectively, and q and τ are the output, corresponding to the resulting joint angles and interaction torques, respectively. (b) The antagonistic mechanism (with the major quantities shown by arrows), which permits implementing such behavior in a human-like manner. (c) The scheme that implements the nonlinear compliant elements in the Qbmoves. The two circles are one of the motors and the output shaft. One linear spring is employed. Thanks to this interconnection, the resulting characteristic is nonlinear, allowing the implementation of the agonist–antagonist mechanism.

devices may be substantial, up to the loss of functionalities. Hence, the choice of pushing a project toward extreme DIY requirements has to be carefully judged. Even where DIY is discarded to preserve functionality and performance, the openness of the project can be kept. The open release of Tesla Motors patents (www.teslamotors.com/blog/all-our-patent-are-belong-you) is an example of this.

The right tradeoff between maker-oriented and performance is often difficult to find and is not always uniquely identifiable. In NMMI, this led, for example, to the design of three different types of actuators (as described in the section "Compliant Actuators: Qbmoves") that implement three different levels of performance. Furthermore, we introduced a very basic and easy-to-implement grasping system, the pincer presented in the "Add-Ons" section, to complement the more complex SoftHand of the "Soft End Effectors" section.

Compliant Actuators: Qbmoves

The Qbmoves [5] are VSAs designed to be modular and user friendly. Qbmoves constitute the main source of motion for every NMMI robot. They offer the possibility of moving their output shaft while simultaneously adapting the mechanical stiffness of the shaft itself, similar to natural musculoskeletal systems. From the user point of view, Qbmoves implement the servo-like model described in Figure 2(a).

Like a pair of muscles acting on a natural joint, Qbmoves mechanically implement the antagonistic principle [Figure 2(b)] via two motors connected to the output shaft. Each of them is connected to the output shaft through a nonlinear elastic transmission implemented with linear springs, as sketched in Figure 2(c). The two inputs are the semisum and semidifference of the motor position for r and c, respectively. A low-level controller is implemented in the onboard controller to regulate θ_1 and θ_2 according to the reference inputs r and c. When the two pulleys rotate in opposite directions, the nonlinear springs are loaded. This results in a change in their working point and thus in a different stiffness. Since the two transmission systems have the same characteristics, this movement does not change the output-shaft equilibrium position in the absence of an external load. Conversely, pulley rotations in the same direction move the output-shaft equilibrium with no load. The resulting behavior is in accord with the well-known equilibrium point hypothesis [9], one of the main theories behind the generation of human movement [8].

Three versions of Qbmove actuators exist: Maker, Maker Pro, and Advanced, each version implementing a different tradeoff between the possibility of autonomous implementation and performance. Figure 3 shows a section of all three versions. Table 1 presents the corresponding key performance characteristics. The Qbmove Maker is oriented toward makers. All the plastic parts are designed to be printed by low-cost

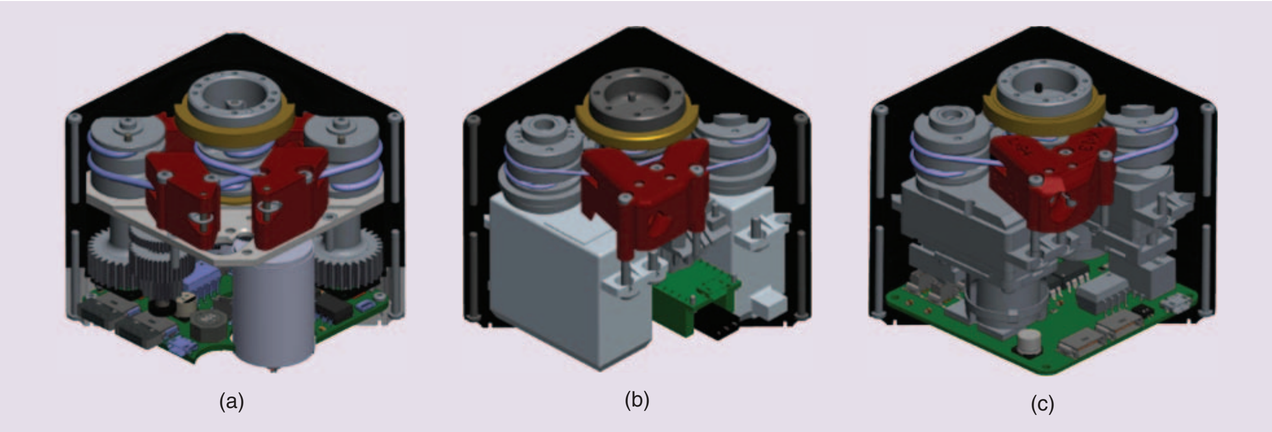


Figure 3. The three versions of Qbmove actuators: (a) Maker, (b) Maker Pro, and (c) Advanced. All the designs are available for free. Each version implements a different tradeoff between the possibility of in-house implementation and performance.

3-D printers (not requiring either elevated accuracy or support material for printing). The other parts can be easily acquired commercially (e.g., common springs and bearings, and radio controlled motor-grade servomotors).

Qbmove Maker Pro is directed toward a Maker public with better equipment, as that of a high school lab, a FabLab, or fast-prototyping computer numeric controlled services. Plastic parts are thought to be realized by 3-D printers, but the accuracy needed for the details requires a more expensive printer. Other parts, designed to support higher loads, have to be manufactured in aluminum.

Finally, Qbmove Advanced reaches the best performance in the Qbmove family, at the cost of a more sophisticated design. Many components are highly customized (e.g., gears, pulleys, and frame), and only a few of them can be created through RP. The current design employs a numerically controlled machine. However, injection molding will be the final target technology. This is less accessible for small groups, since it requires a large scale to be economically feasible, though it offers the best performance with the smallest weight.

Soft EEs

EEs with soft characteristics endow NMMI robotic systems with the ability to perform safe and effective interactions with the environment. That is, hands and grippers [4], [7], [24] can grasp and manipulate objects, and feet [25] enable walking. Each NMMI EE is created with a combination of modular elements designed for soft behavior and to resist disarticulations and impacts. Such modules allow the creation of systems with different numbers of fingers and phalanges, customizing the design for different applications (examples are shown in the "User Experiences" and "Conclusion and Future Works" sections). The phalange design consists of two cylindrical structures in rolling contact with each other. Elastic bands hold each pair of phalanx modules together, giving intrinsic elasticity to the joints.

NMMI soft hands and grippers are designed with the idea of adaptive synergies in mind, inspired by the well-known concept of postural synergies, as introduced in [14]. This framework allows the design of robust and adaptable grippers by a proper combination of compliance and underactuation. The first example of an NMMI soft hand is the Pisa/IIT SoftHand [4] (see Figure 4). It has 19 degrees of freedom (DoF) actuated by just one motor driving one tendon, which goes through the whole hand on an array of pulleys. The tendon routing results in a differential mechanism that lets the hand compliantly adapt to the environment and grasp objects of different geometries and sizes, as shown in Figure 4.

A lesson learned during the development of the platform is strictly related to the technical use of RP techniques, i.e., where and when to use them. In fact, in first approaching the problem, we considered RP as just a way to realize preliminary prototypes, afterward shifting the final design to much more conventional technologies. However, we realized that this is not always the best way.

Table 1. The performance of the three Qbmoves versions.

	Nominal Torque (N·m)	Nominal Speed (rad/s)	Stiffness Range (N·m/rad)	Rotation Range (°)
Maker	0.6	3	0.2 – 2	± 90
Maker Pro	1.3	7	0.5 – 13	± 180
Advanced	6.0	10	0.6 – 30	± 180

For example, the Pisa/IIT SoftHand was first designed to be completely built with RP, which allowed us to have working prototypes in little time. With the increasing use of the hand, however, RP-produced phalanges were not always sufficiently robust to maintain the stress they were subjected to during strong grasps and impacts. So, for this subcomponent, we decided that injection molding techniques were more convenient. Furthermore, injection molding produced multiple hands extremely fast and more cost effectively.

But we realized that RP remains the best candidate for bigger parts, since they can be designed with sufficient thickness. Examples are the palm, motor support, and wrist interface. RP's extreme versatility allowed us to experiment on these components with high flexibility. For example, just by changing them we were able to move from the hand-like structure to the gripper.

Another example of NMMI EE is the SoftFoot [25] (Figure 5), a soft robotic adaptable foot. Its design starts from the same building blocks as the NMMI grippers and hands, combining them to implement a deformable sole and five toes. Furthermore, a tendon is embedded in the foot, implementing a windlass mechanism. In humans, this mechanism

Figure 4. The Pisa/IIT SoftHand, a simple and robust robotic hand with 19 DoF but actuated by only one motor. Its closing movement replicates the synergy of the human hand.

Figure 5. The Pisa/IIT SoftFoot is a passive deformable foot designed to adapt to uncertainties and walk on uneven terrain.

provides the foot the abilities to store energy, absorb impacts, adapt, and stabilize the body [17].

Add-Ons

One of the main advantages of using RP is related to the possibility of building and operating a whole robotic system in a few hours. For this reason, another relevant part of NMMI consists in the group of add-ons specifically designed by users for one or more tasks. The add-ons database includes a series of elements that can be combined with Qbmoves and soft EEs, thanks to the standardized interconnection system. In this database, it is possible to find all the ancillaries that allow for the creation of soft robotic interacting systems of arbitrary complexity. All of them have to be designed to be mechanically interconnected with the other components. Figure 6 shows some examples.

Interconnection Layer

The interconnection layer provides a standard mechanical interfacing system, a highly customizable family of electronic boards, and a software layer that lets users freely combine, customize, and interface with NMMI modules. On the mechanical side, flanges allow the intuitive assembly of NMMI modules to form different kinematic chains. This is possible by properly using the flanges of different shapes, as shown in Figure 7. Each Qbmove is housed in a box of cubic shape. This regular shape allows for the interconnection of the actuator with other modules in any direction, thanks to the grooves provided on each edge. We fixed the cube edge lengths low, i.e., 66 mm, with the idea of further increasing the manageability of the modules. Similar interfaces are also embedded in the soft EEs.

With the idea of making all devices self-contained, NMMI includes custom-made electronic boards. They are presented in Figure 8 and are used in all the modules, with the exception of the Qbmove Maker, which uses an Arduino board. Thanks to such electronics, multiple Qbmove units can be connected in series, using different identifiers with a daisy-chain topology. In Figure 8, the circuit uses a Cypress PSoC 3, communicating with the external personal computer through a micro universal serial bus port. An input/output set of ports is included in the boards and is used to retrieve data from magnetic encoders and to supply power to the dc motors. Current-sensing circuits are included and used to enable the user to estimate the power consumption, which, in turn, can be used to estimate the torque/stiffness behavior of the device.

NMMI also comprehends a set of software libraries. A first layer is developed in C and allows the setting of basic parameters, reading sensors, and writing commands to NMMI modules. The second layer is aimed at parsing first-layer functions to the most commonly used robotics software, such as matrix laboratory (MATLAB)/Simulink (www.mathworks.com) and Robot Operating System (ROS) (www.ros.org). Dynamic simulators for the Qbmove and soft grippers for both MATLAB/Simulink and ROS are also provided.

User Experiences

NMMI is a project in constant evolution. Novel setups and components are continuously thought up and added to the platform through its web portal [22]. We believe that this

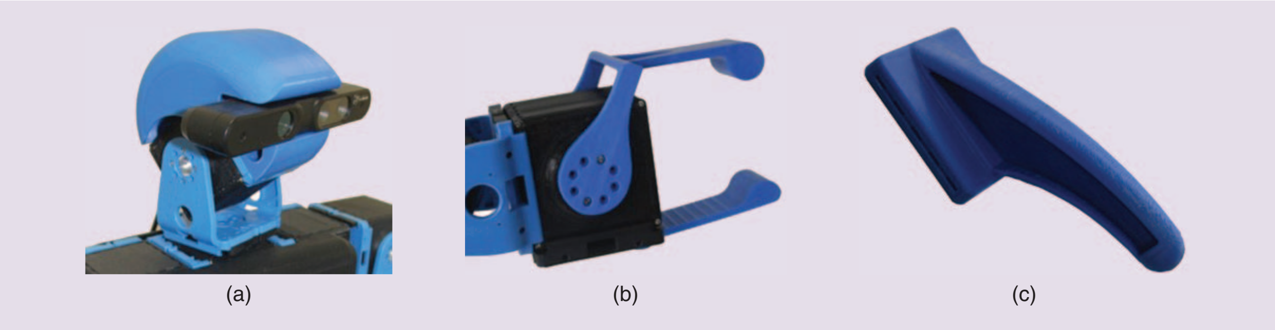

(a) (b) (c)

Figure 6. Some examples of the add-on pool: (a) a one-shell head that holds a 3-D camera actuated by two Qbmoves implementing roll-and-pitch neck DoF, (b) a pincer consisting of two rigid parts actuated by a Qbmove, providing a variable-stiffness pinch grasp, and (c) a paw designed to realize a hexaped and to support it in the lifting and walking phases.

process will continue to generate novel ideas, helping soft robotics to make new steps in unexpected application areas. In the following sections, we illustrate some examples of soft robotic systems built by users thanks to the NMMI platform. They are intended to give the reader an idea of what can be easily built and mounted from the components found on the NMMI platform (Figure 9). Through these robotic structures, the use of soft paradigms in different applications is investigated. As with all the other contributions described in this article, the prototype designs are available on the NMMI website [22]. Multimedia material can be found on the NMMI YouTube channel (https://goo.gl/zcKz8i and https://goo.gl/AEvQV7) and in a video that accompanies this article on IEEE *Xplore*.

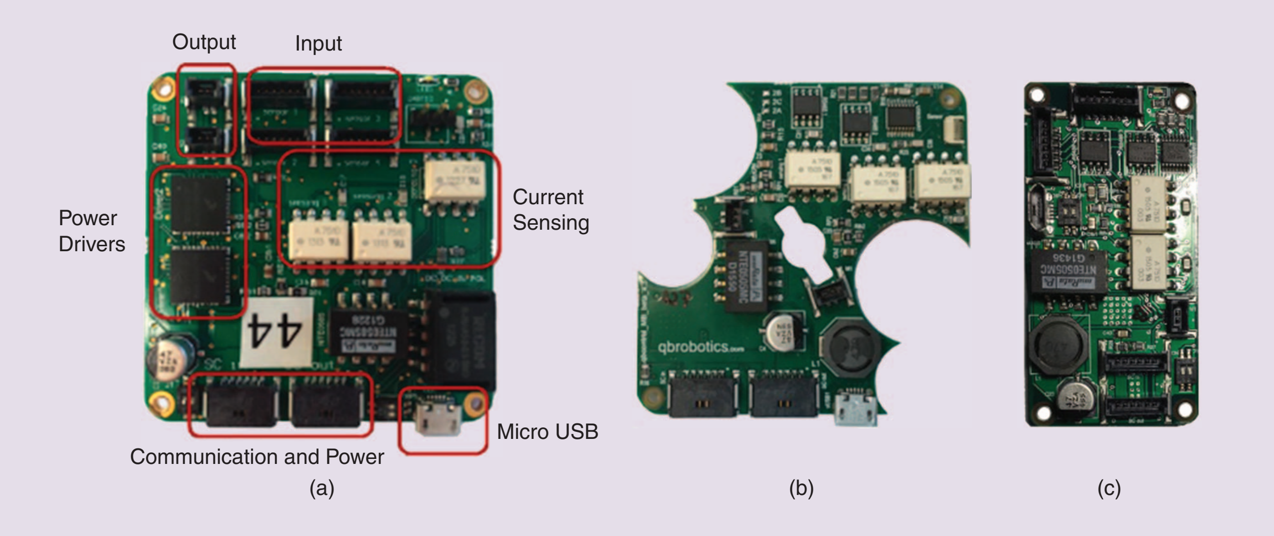
Thanks to its modularity and simplicity, the NMMI platform has found a natural use in education. For example, it has become a useful tool in master's classes at the University of Pisa, allowing students of robotics, mechanics, and control to experiment and propose new ideas. A different successful educational application of the NMMI platform was the Saphari NMMI winter school (goo.gl/oaeJel) on soft robotics, held in Rome, 20–25 February 2015. The school featured classes on the basics of soft robotics design and control and allowed extensive hands-on sessions on physical soft robots. The school's climax was a competition among student teams that were asked to implement a peg-in-hole task using NMMI modules.

The Pisa/IIT SoftHand has been used as a prototype design for the hands of the humanoid robot Walk-Man, which participated in the U.S. Defense Advanced Research Projects Agency Robotics Challenge (http://www.darpa.mil/program/darpa-robotics-challenge). The design solutions provided for the Pisa/IIT SoftHand have been kept for the new hand model in terms of actuation and modularity but were adapted to the new performance requests. On the other hand, the decision to release all the projects with open-source licensing will hopefully promote the spread of the ideas and inspire new designers. Examples of such a result are [23] and other commercial robots (e.g., tiago.pal-robotics.com).

Humanoid Torso

A nice example of the usage of the whole structure is the humanoid torso presented in Figure 9(a). This structure is built with different building blocks from NMMI. Its arms are built using four Qbmoves, three of them providing DoF for the shoulder and one for the elbow. The first actuator of the chain is a Qbmove Advanced, since it has to hold the arm and the weight of a grasped object. The other actuators are Qbmove Maker Pros. A pincer is connected at the end of each arm. Alternatively, Pisa/IIT SoftHands can be used, as in

Figure 7. With the use of interconnection flanges (blue objects), rigid connection or revolute joints can be intuitively formed, obtaining more complex systems.



(a) (b) (c)

Figure 8. The NMMI electronics: (a) for the Qbmove Maker Pro, (b) for the Qbmove Advanced, and (c) for the gripper. The boards consist of a six-line bus, four lines being used for powering and ground motors and logic, and the last two lines for implementing RS485 communication. USB: universal serial bus.

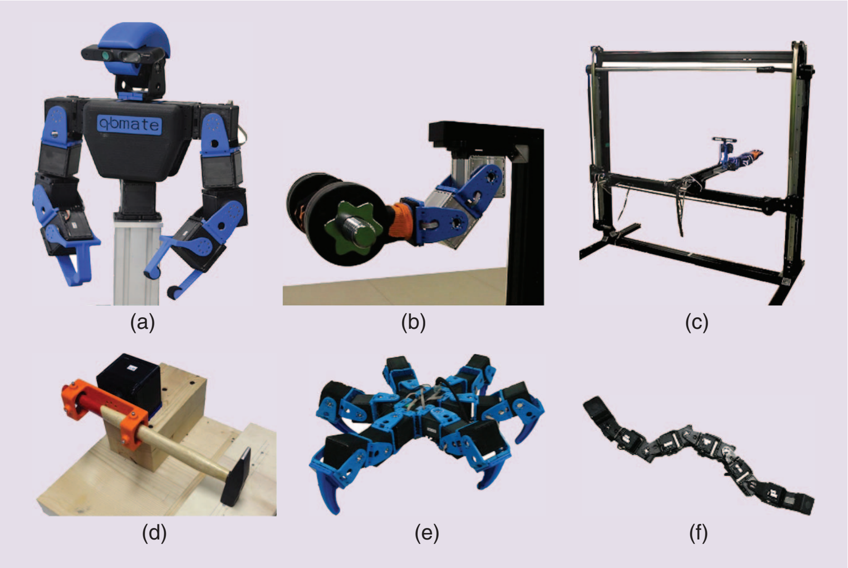


Figure 9. A selection of structures built through the NMMI platform: (a) torso, (b) hand-arm system, (c) industrial robot, (d) hammer, (e) spider, and (f) snake. The applications include manipulation, locomotion, prosthetic, and industrial uses. Additional details for most of the projects are available on the website [22].

Figure 10(a)–(e). The other two Qbmoves Maker Pros are used to provide motion to the neck DoF.

The head and chest are 3-D-printed add-ons. The first incorporates a standard visual system, while the second supports the arms. Thanks to the NMMI software libraries, the humanoid torso can be directly controlled by Simulink. In MATLAB, moreover, we developed a user interface on Raspberry Pi 2 (www.raspberrypi.org/products/raspberry-pi-2-model-b/) that allows the user to intuitively interact with the robot and provide a reference trajectory for it to follow.

This robotic system can be used to experiment in the field of manipulation and human–robot interaction. For example Figure 10(a)–(e) shows the humanoid torso that robustly performs the handover task, thanks to its arms' compliance. The theoretical results behind this execution are presented in [11].

Hammering Robot

Springs can be used to store and release energy during cyclical motions. This allows compliant actuators to outperform rigid actuators in efficiency and peak performance [16]. Figure 9(d) presents a simple robot able to display this behavior in a practical manner. It is made of a Qbmove Maker Pro and an add-on that attaches it to a hammer. In this task, both efficiency of limit cycles and shock absorption were exploited to drive nails into a thick wooden block.

2-DoF Arm

To test soft robot performance, a simple robotics manipulator can also be made, as in the 2-DoF arm in Figure 9(b). It is built with two Qbmove Advanced and a Pisa/IIT SoftHand as an EE. The arm shows the force and speed capabilities of the actuators. A 5-kg dumbbell is grasped by the hand, and suitable commands then produce a swinging movement of the weight, as in bicep exercises. Further tests, focused on the speed, can then be performed. A ball is grasped by the hand and proper references for joints are commanded to throw the ball to a subject with a swift motion (see the video that accompanies this article on IEEE *Xplore*).

Industrial Robot

The application of soft robots in industrial scenarios is considered promising by the robotics community [1]. Figure 9(c) shows a prototype of an industrial soft robot manipulator built with the NMMI platform. It consists of a 3-DoF Cartesian structure. On the last linear track, a 3-DoF arm composed of Qbmoves Maker Pros has been attached to accurately orient the Pisa/IIT SoftHand used as an EE. A 3-D camera is mounted at the end of the Cartesian structure for autonomous object recognition and grasping. This robot was designed by a group of master's students at the University of Pisa who successfully qualified for and then participated in the first Amazon Picking Challenge (amazonpickingchallenge.org) during the 2015 International Conference on Robotics and Automation. It was possible to test this structure's adaptivity and compliance in an industrial pick-and-place task, with uncertainties in the object's shape and in the scenario. In Figure 10, some snapshots show a sequence of the structure's motions during the operation.

Moving Robots

The soft hexaped and the soft snake robot depicted in Figure 9(e) and (f), respectively, are solutions built to investigate the advantages of soft robotics in locomotion tasks. The embedded compliance of these systems endows their structure with proper adaptability. This allows the robots to achieve better performance on uneven terrain than that of rigid robots. In the case of walking robots, the compliant elements also dampen the impact from ground contact. A particular case is the snake soft robot, which, thanks to its compliance, is able to move inside narrow spaces (e.g., water pipes) without any prior knowledge of the environment. Instead, the environment itself drives the robot form, which is controlled to proceed straight ahead. Figure 10(f)–(j) shows a photo sequence of the snake performing this task.

Conclusions and Future Work

In this work, we presented NMMI, a platform for the fast prototyping of soft robots with flexible joints that fully embraces open-source philosophy in hardware and software. Together

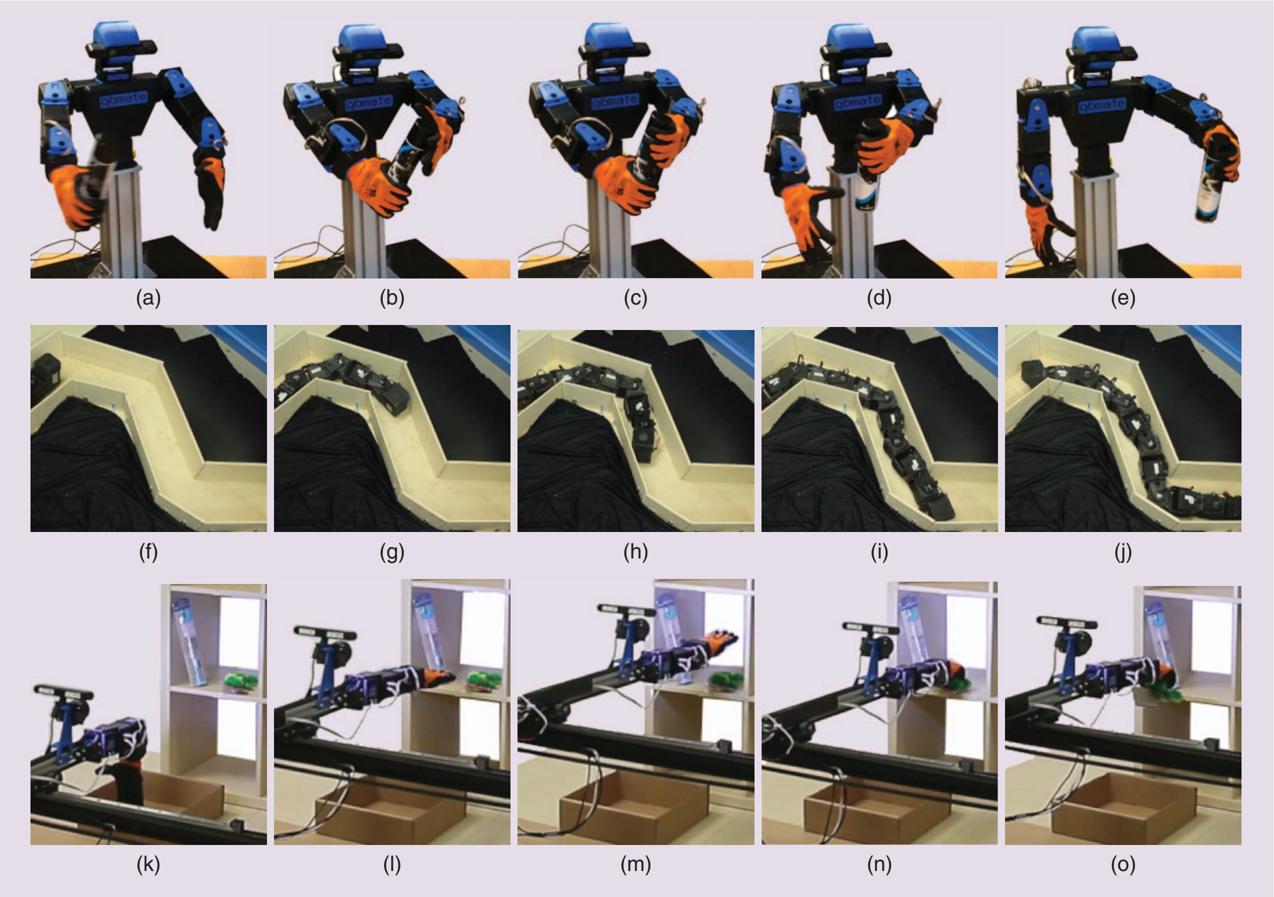


Figure 10. Photo sequences of various tasks performed by robots using NMMI: (a)–(e) the humanoid torso performs a handover; (f)–(j) the snake moves into a narrow space, guided by the environment; and (k)–(o) the Amazon Picking Challenge robot recognizes, reaches for, and grasps a target object.

with a description of the platform components, we discussed the design choices related to the open nature of the platform, and we provided many user experiences showing its effectiveness in building robotic structures.

The platform is in continuous evolution. Many building blocks will be added, such as novel projects and tutorials. To our best knowledge, the NMMI platform is currently used by more than 40 research groups worldwide for soft robotics experimentation. Future work will be devoted to further spreading the platform, e.g., through including mechanisms to make contributors' participation easier.

Acknowledgments

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