Extending Mechanical Construction Kits to Incorporate Passive and Compliant Elements for Educational Robotics

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Abstract—Robots are a popular educational tool to introduce science, technology, and engineering to students. The field of educational robotics is growing and consequently a number of educational robot kits have been developed within the last decade. Our laboratories have a tradition of teaching embodied artificial intelligence and biomechanics to students with different backgrounds. The robots we use both for research and education are usually built incorporating compliant materials as well as passive dynamics. These kind of properties are often not available in classical robot kits or mechanical construction kits. In this paper we describe some of the robots we use for education. So far we built the robots using 3D printing technology which is convenient but too expensive for class use. Our aim is to find cheaper, commercially available solutions. After a short review on educational robot kits and mechanical construction kits we describe interface solutions between several kits. Further we show some solutions to incorporate compliant materials and passive dynamics to traditional mechanical construction kits by using cheap and widely available materials.

I. INTRODUCTION

The notion of embodiment, which has formed the major research target of the Artificial Intelligence Laboratory (AILAB) over the last 15 years, has dramatic implications for our understanding of intelligence [1]. For example, behavior is not the result of brain processes only, but of a subtle interplay between brain, body (morphology and materials) and environment; an insight that contradicts the classical Cartesian position. According to the embodied artificial intelligence perspective, morphological and material characteristics of an organism can take over a large part of its functionality [2]. We use the term morphological computation to designate the fact that some of the control or computation can be taken over by the dynamic interaction derived from morphological properties (e.g. the passive forward swing of the leg in walking, the spring-like properties of the muscles, and the weight distribution) [3]. By taking morphological computation into account, an agent will be able to achieve not only faster, more robust, and more energy-efficient behavior, but also more situated exploration by the agent for the comprehensive understanding of the environment.

Our laboratories (AILAB, Modular Robotics Research Lab) have a tradition in teaching the principles of embodied intelligence to students with different backgrounds. For instance in the context of an informatics degree program for high school teachers, we (AILAB) conducted a LEGO NXT robot competition where solely the morphology was allowed to be changed in order to achieve faster locomotion [14]. The initial LEGO robot morphology has been inspired by a robot built by Rinderknecht et al. [5]. In a variety of other teaching activities we used robots that locomote using passive dynamics (Fig. 1), inspired by the quadruped robot of Iida et al. [4] as well as unusual robots inspired from both research and arts. We used for instance a smaller version of the RHex robot [6] (Fig. 2) and an actuated one of Theo Jansen’s Strandbeest1 (Fig. 3) for several robot workshops.

With the exception of the LEGO NXT robot competition example mentioned above we usually use our open toolkit “EmbedIT” for the robot control (electronics and software)[7].

1http://www.strandbeest.com/
For the mechanical construction we custom built the robots in the past, using 3D printing technology (all the white plastic parts in Fig. 1, 2, 3). The possibility to 3D print the desired parts is convenient and fast. They are lightweight, high in precision such that generally no additional machining is necessary. The parts are further surprisingly stable, considering the strong impact forces that act especially on RHex’s wheels and Puppy’s legs. Even after several classes not a single 3D printed part had to be replaced (opposed to the motors which frequently broke due to jammed gears). However, 3D printing is still expensive, not particularly environmental friendly and not necessary if reasonable alternatives are available. Additionally, many institutions don’t have 3D printing infrastructure, the required software licenses and knowledge to design parts using CAD. In trying to solve this, a trend is emerging towards low-cost personal fabrication solutions with projects such as RepRap, fab@home or MakerBot. However, if the robot parts are not too specific and complicated, a cheap off-the-shelf solution of mechanical construction components is still preferable, especially if they are made out of reusable, stable and lightweight material such as aluminum.

Building objects (cars, trucks, planes etc.) using mechanical construction kits had been very popular at the beginning of the last century. Brands such as “Meccano” are widely known in the generation born in the 1940’s. These kind of playing activities are no longer popular with young people and thus traditional manufacturers such as Meccano, Märklin and Stokys suffered.

This paper describes our search for a low-cost solution to build robots with unusual shapes using compliant, passive dynamic elements for educational purposes. We give a short review on off-the-shelf robot kits and mechanical construction kits in order to identify their advantages and disadvantages. Since most of the classical mechanical construction kits do not support any interfaces to standard actuators we show some easy solutions how to overcome this constraint. We describe how to use common and cheap materials everyone can find at home or in a conventional do-it-yourself store to build unusual robots and without the need of 3D printing technology. We show some examples how to interface proprietary robot kits with other construction kits to achieve a greater construction flexibility. Further we introduce our robotic construction kit “LocoKit”, which is currently under development [15]. This system is targeted towards legged robots, and promises to make it possible to build dynamically walking robots in a fast and easy way. The LocoKit is described more deeply in section V.

II. A REVIEW ON ROBOT KITS AND MECHANICAL CONSTRUCTION KITS FOR EDUCATION

In the following section we list a number of robot platforms that are usually used for educational robotics and robot competitions. The list is far from complete, however, the robots mentioned are a good representation of what is usually used. This is followed by a short review on mechanical construction kits. Also here we give a broad overview of different kits using different materials and concepts how to connect the elements together.

From this short survey we select one or two example platforms and describe how to interface them with each other and how to extend them using other materials, which do not originally belong to the toolkit in order to build the robots we would like to use in class.

A. Robot Kits

Robots have been used in the last decade to introduce kids to science and technology [8],[9]. Class activities with robots range from kindergarten over secondary school to universities. A large number of robot competitions emerged such as the FIRST Lego League, Eurobot, RoboCupJunior, Botball or Robolympics, all with the aim to engage young people in these disciplines [10]. Consequently, many robot kits have been developed in research projects as well as in commercial
companies. A widely used robotic platform for educational robotics is the LEGO NXT\(^5\) (Fig. 4i) [11,12]. It provides actuators, a variety of sensors, building blocks as well as an easy-to-use graphical programming language. Additionally, the LEGO NXT platform can be programmed using high-level programming languages, such as JAVA. A low cost educational robotic platform is the Asuro\(^6\) (Fig. 4b). By soldering all electronic components to the PCB the user has to assemble the robot from scratch. Asuro is designed to be a wheeled robot, thus the user has not much flexibility to modify the default shape. Many other educational robotic platforms use the popular Arduino\(^7\) boards [13]. We also used a small custom made wheeled robot based on the Arduino board to teach robotics to secondary school teachers [14]. Other commercial robot platforms designed for educational purposes are E-puck\(^8\) (Fig. 4c), ThymioII\(^9\) (Fig. 4d), NAO\(^10\) (Fig. 4e).

The above list of robots used in educational robotics and robot competitions shows that the platforms are often fixed, wheeled and equipped with common sensors such as light, distance, touch etc. (Fig. 4a,b,c,d,f,g,h). The sensors and motors are usually connected to a central control unit. The user programs the controller of the robot on a PC using C/C++, Java or derived simplified programming languages and uploads the code to the robot. Besides Botball (Fig. 4f) which is a robot kit composed out of several different platforms, LEGO NXT (Fig. 4i) is the most open and flexible one regarding the shape of the robots that can be built.

B. Mechanical Construction Kits

We use the term “mechanical construction kit” synonymously with “model construction kit”. With these terms we refer to construction systems usually comprising re-usable elements such as strips, plates, angle girders, axles and gears with nuts and bolts to connect the pieces. The elements can be made out of plastic or metal, the connections can be screwed or stucked. We distinguish between “construction sets” and “construction kits”. A construction set has a determined and fixed set of elements which can be assembled into one specific object (e.g. a truck) by following an assembly guide. On the contrary, a construction kit has a variety of different elements to enable the construction of any object possible within the constraints of the elements at hand and the imagination of the user.

The history of classical mechanical construction kits goes back to the beginning of the last century with Frank Hornby who invented and patented 1901 a new toy called “Mechanics Made Easy”, also known as “Meccano”. Since then a variety of similar products emerged such as Eitech, Märklin or Stokys, some compatible with the 0.5 inch (1.273 cm) spacing of Meccano. Basically all of the traditional manufacturers suffered lately from decreasing interest in these kind of toys and the takeover of other construction kits such as LEGO. From the traditional manufacturers that survived until today, many still do not support interfaces to standard actuators and sensors (some provide a limited selection of proprietary motors).

Table I lists a collection of mechanical construction kits from manufacturers from all over the world. A short descrip-
This on the other hand constrains the possible shapes that can be realized. It can be said that generally an object is built around an initial base plate of different sizes (or around a controller unit). The components are stuck or screwed on that base plate. Basically all construction kits (except Makeblock) force the user to connect the attached components according to their fixed hole spacing grid, additionally they often provide very few varieties of angles (often 90° or 45°). None of the listed mechanical construction kits provide passive dynamic elements (except the spring in Lynxmotion) and unconventional, soft materials.

Based on the advantages and disadvantages shown in Table I, we decided to pick Stokys and LEGO as the two base construction kits for the extensions described in the following section. We took LEGO because it is widely used in educational robotics and Stokys because each part can be purchased individually and it uses metric hole sizes (this is more convenient when located in Europe and it’s compatible with the LocoKit rod size). Nevertheless, the examples we show in the following sections can also be transferred to some of the other listed construction kits.

III. INTERFACE SOLUTIONS BETWEEN MECHANICAL CONSTRUCTION KITS

There is no universal robot kit or mechanical construction kit that meets each user’s particular need. Therefore, it makes more sense to combine different products to achieve more flexibility. Sometimes the LEGO NXT robotic components such as the controller and the motors are fine but the mechanical construction has to be more stable than plastic parts stuck together. Interfacing mechanical construction kits such as Meccano or Stokys could be a solution. On the other hand these traditional construction kits do not provide any interfaces to standard actuators in case the user would like to use DC motors or servo motors. The following sections show some simple solutions to these problems.

A. Solutions to Interface LEGO with Stokys

Everyone is familiar with LEGO blocks. The LEGO NXT kit provides a variety of bricks, connectors, wheels, rubber parts etc. Assemblies can be built and changed quickly and easily. However, since these parts are not screwed and the material is plastic they might not be precise enough or wear out too quickly for some applications. Fig. 5a presents an example where a metric M4 screw is screwed in a LEGO motor in order to get a more stable motor shaft. Despite the screw thread that is created within the motor due to this procedure, the original LEGO shaft can still be used (the star-shape hole remains). We had to produce a small customized part (little block mounted on a base part on the right side of Fig. 5a) in order to interface the LEGO motor with a mechanical construction kit (Stokys). By means of this custom metal part and the screw shaft a variety of Stokys components can now be attached to the LEGO motors, sensors and other LEGO components (Fig. 5b). Stokys uses standardized, metric hole sizes which increase flexibility to add other off-the-shelf components.
<table>
<thead>
<tr>
<th>Product</th>
<th>Picture</th>
<th>URL</th>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Lego (DK)</td>
<td></td>
<td>mindsstorms.lego.com</td>
<td>Comprehensive mechanical construction kit made out of plastic. Includes actuators, sensors, a control unit. Provides graphical and classical programming. Stick connectors.</td>
<td>Great flexibility, robustness of hardware and software, large variety of sensors, availability of individual parts, big community, variety of educational materials, general familiarity with LEGO blocks, 3rd-party add-ons, graphical programming and classical programming.</td>
<td>Plastic parts wear out, sticked connections aren’t stable enough for high impact applications (e.g. legged locomotion), proprietary mechanical interfaces (e.g. plugs, hole size), only 3 motor outputs and 4 sensor inputs per controller, big size and heavy weight (esp. controller).</td>
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<tr>
<td>Mindstorms NXT</td>
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<tr>
<td>Pitsco Education (USA)</td>
<td><a href="http://www">www</a>. tetrixrobotics.com</td>
<td>Aluminum mechanical construction kit that includes structural material, actuators, gears, motor controllers and wheels. It provides interface solutions with LEGO Mindstorms NXT controller as well as LEGO blocks. Screwed connectors.</td>
<td>Great flexibility, availability of individual parts, robustness due to screwed connectors and aluminum material.</td>
<td>Imperial system (not metric), rather expensive, no soft or passive components.</td>
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<td>Tetrix</td>
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<tr>
<td>Fischertechnik (GER)</td>
<td><a href="http://www">www</a>. fischertechnik.de</td>
<td>Plastic construction kit with actuators, sensors, and a controller. Graphical and classical programming. Sticked connectors.</td>
<td>Flexibility, easy assembly, a variety of sensors and unusual actuators, such as pneumatic motors.</td>
<td>Plastic parts wear out and might not be stable enough for high impact applications, limited variety of construction parts, construction parts aren’t usually sold individually, proprietary mechanical interfaces.</td>
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<tr>
<td>ROBO</td>
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<td>Lynxmotion (USA)</td>
<td><a href="http://www">www</a>. lynxmotion.com</td>
<td>Mechanical construction kit made out of aluminum. Provides additionally actuators, sensors, grippers, springs, controllers, and a GUI. Screwed connectors.</td>
<td>Good quality material, stability, availability of individual parts, use of standard motors.</td>
<td>Imperial (not metric) system, rather expensive, very limited variety of components, no soft components.</td>
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<tr>
<td>Lynxmotion</td>
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<tr>
<td>Makeblock (CHN)</td>
<td>makeblock.cc</td>
<td>New mechanical construction kit made out of aluminum. Compatible with industrial standards. Screwed connectors.</td>
<td>Stability, originality due to flexible screw positioning and adjustable components, provides interfaces to standard actuators, interfaces with Arduino, relatively cheap price.</td>
<td>No passive or soft components, product is still new and under development.</td>
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<tr>
<td>Makeblock</td>
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<td>Eitech (GER)</td>
<td><a href="http://www.eitech.de">www.eitech.de</a></td>
<td>Mechanical construction kit made out of steel. Provides additionally DC motors, gears, wheels, solar panels. Screwed connectors. Metric hole spacing (1 cm).</td>
<td>Stability, variety of elements, unconventional power supply (solar panel), cheap price, compatible hole size with Meccano and Stokys.</td>
<td>Relatively heavy weight (steel), no passive or soft components, no standard actuator interfaces (only to proprietary motors), hole spacing incompatible with Meccano or Stokys.</td>
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<td>Eitech construction</td>
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<tr>
<td>Meccano (UK)</td>
<td><a href="http://www">www</a>. meccano.com</td>
<td>Traditional construction kit made out of steel. Provides DC motors, gears and wheels. Imperial system hole spacing (1.273 cm) and hole size (4.2 mm). Screwed connectors.</td>
<td>Stability, variety of elements, cheap price, generally known in Europe.</td>
<td>Relatively heavy weight (steel), no passive or soft components, no interfaces to standard actuators, components usually not sold individually.</td>
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<tr>
<td>Meccano</td>
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<tr>
<td>Stokys (CH)</td>
<td><a href="http://www.stokys.ch">www.stokys.ch</a></td>
<td>Mechanical construction kit made out of aluminum. Provides additionally gears, wheels, DC motors. Imperial system hole spacing (1.273 cm) but metric hole size (4 mm). Screwed connectors.</td>
<td>Stability, availability of individual parts, compatibility with Meccano hole spacing and hole size (only 0.2 mm difference), variety of elements, light weight (aluminum).</td>
<td>No passive or soft components, no interface to standard actuators, relatively expensive (aluminum has its price).</td>
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<td>Stokys</td>
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B. Solutions to Interface Stokys with Actuators

The casing of servo motors are not standardized and vary with each motor type. This is problematic since servo motors break easily when frequently used in a class environment. If the very same servo type is not available, often the replacement servo does not fit into the current setup. Fig. 6b shows a custom aluminum part designed for a servo motor to be screwed onto a Stokys or Meccano plate. Fig. 6a shows a proprietary DC motor casing screwed onto a Stokys element by means of a custom made wooden connector part. Fig. 6d shows proprietary servo wheels screwed onto Stokys elements to achieve a greater variety of possible servo wheel extensions.

The CAD files of all custom parts described in this paper are available on our website.

IV. SOLUTIONS TO EXTEND STOKYS WITH PASSIVE DYNAMIC MATERIALS

To build robots as in Fig. 1, 2 we need to incorporate passive dynamic materials. Structural elements that posses these kind of characteristics are usually not supported by robot kits or mechanical construction kits. Our goal was to achieve this with easy available materials, so we tried plastic tubes, spring steel, steel ropes, and strings from speedometers usually used in motorcycles. Fig. 6c demonstrates how a simple piece of spring steel wired around a joint can achieve passive dynamic properties. The stiffness can be varied easily.

The advantage of steel rope is that it is stable, flexible but

\[11\text{http://www.embed-it.ch} \]
Fig. 9. A selection of the most important mechanical LocoKit parts.

not fully elastic. It suits perfectly to construct a flexible spine for walking robots, see Fig. 7a. Figure 7b shows a selection of unconventional wheels made out of strings from speedometers, plastic tubes and steel ropes. LEGO actuators are interfaced with Stokys or Meccano according to the interface description in Fig. 5.

Fig. 8 shows a Theo Jansen Strandbeest robot built with the Stokys construction kit. Even though it is a lot bigger and heavier than the 3D printed version in Fig. 3, it is nice to see that it is possible at all to build a robot like that using solely one mechanical construction kit.

V. NEW TRENDS WITH THE LocoKit ROBOTIC CONSTRUCTION KIT

The philosophy behind this system is embodiment and that the interplay between individual components of the system have to work together to form dynamic locomotion. Being a construction kit, it enables the user to make adjustments to the robot after it has been built. Opposed to other systems, LocoKit does not constrain the user to place components at fixed positions or to use determined sizes of structural elements. In the review section of this paper we saw that mechanical construction kits usually have a fixed grid size of 1 cm or more. LocoKit enables the user to adjust the position of a component within a range of a few millimeters. Hereby, the user can explore how changes of the morphology effects the performance of the system on a very fine scale. Examples of such changes could be body width, leg length, center of mass, angle of attack etc.

LocoKit distinguishes itself from the other construction kits mentioned earlier in this paper, by being the only one directly targeted to walking, running or jumping robots (Fig. 10). Also, by being designed with a focus on non-rigid elements, it gives the user the opportunity to build robots, where the body is not rigid but bendable. This feature is controversial because rigid systems are often preferred since they are easier to model and control. However, the aim of LocoKit is to be a system that supports the creating of model-free, bottom up robots with limited need for a mathematical model to describe the system beforehand.

Everything in the LocoKit system is designed such that it fits to a 4 mm rod (Fig. 9). For now, these rods are mainly composed of fiberglass or carbon fiber but could in theory be made of any material as long as it forms a 4 mm round rod. The reason for this design choice is that the user is more free to choose other materials, e.g. more soft, rigid, lighter or heavier ones. It also opens up the opportunity of making some parts of the structure stiff and other ones soft, depending on the kind of desired structure.

Fig. 10. A quadruped robot built in the LocoKit construction kit of Fig. 9. The used structural materials are all bendable, enabling the body to bend under its own weight. A more slip-like walking pattern is achieved due to the springs located in the upper part of the legs.

This system is still under development and therefore not yet commercially available. For more in dept information, see Larsen et al. [15].

VI. CONCLUSION

In this paper we described our need for unconventional robot morphologies for teaching embodied artificial intelligence and biologically inspired robotics. We described the
robots we usually use in class which are custom built by means of expensive procedures such as 3D printing. Our aim is to replace the 3D printed parts using cheap, commercially available materials. After a short review on educational robot kits and mechanical construction kits we selected Stokys and LEGO as example kits. We described how common actuators can be interfaced with those proprietary toolkits by using easy custom made components. Further, we described examples on how to incorporate passive dynamic properties and compliant materials to those systems. In addition, we introduced the LocoKit, a new toolkit which is currently under development and which aims at providing those required properties for walking robots. Generally, we are pleased about the number of the toolkits available. However, we hope that in the future the manufacturers will go more towards open, standardized interfaces rather than proprietary hardware and software.

VII. ACKNOWLEDGEMENTS

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REFERENCES