Lessons Learned in Designing User-configurable Modular Robotics

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Lessons Learned in Designing User-configurable Modular Robotics

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Abstract. User-configurable robotics allows users to easily configure robotic systems to perform task-fulfilling behaviors as desired by the users. With a user configurable robotic system, the user can easily modify the physical and functional aspect in terms of hardware and software components of a robotic system, and by making such modifications the user becomes an integral part in the creation of an intelligence response to the challenges posed in a given environment. I.e. the overall intelligent response in the environment becomes the integration of the user's construction and creation with the semi-autonomous components of the user-configurable robotic system in interaction with the given environment. Components constituting such a user-configurable robotic system can be characterized as modules in a modular robotic system. Several factors in the definition and implementation of these modules have consequences for the user-configurability of the system. These factors include the modules' granularity, autonomy, connectivity, affordance, transparency, and interaction.

Keywords: Human-robot interaction, reconfigurable robots, educational robots, distributed intelligence, modular robotics.

1 Introduction

Robotics and artificial intelligence (AI) research has strived to create fully autonomous systems, which can exhibit an intelligent response in the environment. The artificial intelligence research aimed at creating systems, which are able to sense and act, to learn and to think, and figure out the right organization of activities at these different levels. Much work in classical artificial intelligence research built upon the understanding that there would be a level where the body could be abstracted away, and one could investigate the thinking in isolation from the body (e.g. in symbol processing systems, expert systems, etc.). Even though robotic research engineered physical robotic systems since the middle of last century, it was not until the end of the 1980's and the 1990's that robotics became a more widespread tool to study thinking as *embodied*.

A well-known tool which facilitates the study of the intelligence as integration between the body and the brain is the LEGO Mindstorms. The LEGO Mindstorms pro-

adfa, p. 1, 2011.

vides a tool, which allows users to easily build a robot with sensors and actuators, to build bodies with LEGO pieces and to build brains with simple software, e.g. a GUI. As observed in [1], with LEGO Mindstorms the interaction is split into distinct processes of building, understanding syntax & semantics, programming, downloading to robot, testing/debugging, playing.

This split is partly due to LEGO Mindstorms being constituted by a central processor to which sensors, actuators, and LEGO bricks can be attached, and partly due to the programming paradigm of performing the programming on a host computer (i.e. not situated in the environment of the robot). Hence, LEGO Mindstorms is based upon a centralized processing approach with the central processor being programmed via a host computer.

If, on the other hand, we turn to a more *distributed processing* approach based on a collection of self-contained modules each with their own processing and physical expression, it is possible to work towards avoiding or diminishing this split and create direct *action in each interaction* by the user. This is done by the creation of physical and functional modules which allow exploration of interactive, distributed parallel processing in a physical form. Here, action is manifested as soon as modules are manipulated, such as when modules in the form of building blocks are being put together.

In such a distributed processing approach, processing is distributed to a number of modules and the overall processing emerges from the processing of the individual modules and their interaction. In a similar way, the physicality is distributed to a number of modules, and the overall physical expression is a function of the individual physical modules and their interaction. Put together, this can be expressed in terms of a *modular robotic system*: In a modular robotic system, each module has a physical and functional expression, and the overall robotic system emerges from the interaction between the modules.

Modular robotic systems can be used to create *self-reconfigurable modular robots* [2], which autonomously change their physical shape. In the self-reconfigurable modular robots, the modules are able to autonomously move around attaching and detaching from each other, moving to locations so that the overall shape of the robot (the ensemble of modules) becomes appropriate for the task at hand.

However, instead of focusing exclusively on the creation of fully autonomous and self-contained systems to provide an intelligent behavior, there is an attractive possibility of focusing on the creation of systems that allow human-robot interaction to create an intelligent response. The concept of user-configurable modular robotic systems aims at facilitating such generation of intelligent response in the environment through the human-robot interaction.

2 User-configurable Modular Robotics

In a *user-configurable modular robotic system*, the user constructs with modules (i.e. technological building blocks) to create a physical system and the functionality of this system. By making changes to the physical shape of the entity, the user can change the functionality of the system. This happens simply by attaching or detaching modules and moving modules to different positions. Hence, in such a case, the user is making the physical configuration in a hands-on manner, and the user does not need to do traditional programming to change the functionality of the system. As soon as the user is manipulating with the modules there is a reaction in the environment, i.e. there is *action in the interaction*, and the interaction is not split into distinct processes as was the case e.g. with LEGO Mindstorms interaction.

Therefore, in some cases, it is believed that user-configurable modular robotics may lead any user to develop solutions in a simple and very flexible manner. Further, the modularity and distributed processing means that the produced solutions are robust to failure of individual modules through graceful degradation. If one module fails then the rest will still be working, contrary to most traditional technological solutions with a central processing that may make everything fail if one component fails. Also, since there is no central processing and large infrastructure, but the system is composed of a set of individual modules, these may potentially be easily transported around and set up anywhere.

Hence, the overall intelligent response in the environment becomes the integration of the user's construction and creation with the components (modules) of the user-configurable modular robotic system in interaction with the given environment. We formulate this concept as the playware ABC: By *building bodies and brains* with the user-configurable modular system, the user can *construct, combine and create* to make solutions for *anybody, anywhere, anytime*. Several factors in the definition and implementation of the modules have consequences for the user-configurability of the system. These factors can be viewed as design issues and include the modules' granularity, automation/autonomy, connectivity, affordance, and interaction. To shed light on these design issues, we have researched user-configurable modular robotic system in a wide range of designs, implementations, and applications, some of which will be reported below.

2.1 Granularity

Granularity of the modules is a crucial issue to consider in the design of modules for a user-configurable modular robotic system, both in terms of physical and functional granularity. With *coarse-grained modules*, the user will be working on a high abstraction level with only a few modules needed to obtain the intelligent response, i.e. to obtain the right physical and functional response. Hence, the cognitive load on the user for creating the intelligent response is considered to be low in a user-configurable modular robotic system with coarse-grained modules. On the other hand, the versatility may be low in a coarse-grained modular system not allowing the user to create subtle physical and functional structures lower than the graining size of the individual modules. I.e. if all modules are $1m^3$ (e.g. like the MusicTiles magic cubes Fig. 1(k)), then it is difficult to make variations in the centimeter-scale of the physical structure – and a similar argument goes for the functional variations.

Fig. 1. Examples of modular systems with user interaction: (a) ATRON self-reconfigurable modular robot, (b) I-Blocks in LEGO Duplo, (c) Light&Sound Cylinders and Rolling Pins for elderly dementia patient therapy in multi-sensory room, (d) modular interactive tiles for rehabilitation of stroke and cardiac patients, (e) modular interactive tiles for rehabilitation of mentally and physically handicapped children in Africa, (f) Fable user-configurable modular robot, (g) Fatherboard modular robotic wearable, (h) modular interactive tiles for soccer and playgrounds, (i) Music I-Blocks, (j) MusicTiles magic matchboxes, (k) MusicTiles magic cubes.

With *fine-grained modules*, the user will be working on a lower abstraction level with more modules needed to obtain the intelligent response, i.e. to obtain the right physical and functional response. The cognitive load on the user for creating the intelligent response can be considered to be higher in a user-configurable modular robotic system with fine-grained modules, since the user will have to combine more modules to obtain the same response as with coarse-grained modules. For instance, the learning curve for being able to create the desired intelligent system with the fine-grained modules may be steeper. Yet, the versatility may be higher in a fine-grained modular system with which the user may be able to create subtle physical and functional structures not possible with coarse-grained modules (e.g. with centimeter-scale modules it is possible to construct centimeter-scale variations).

2.2 Homogenous vs. heterogeneous modules

When designing modules, it is possible to make them as *homogenous modules* (all modules are similar) or *heterogeneous modules* (modules differ from one another). There also exists the possibility of making physical homogenous but functional heterogeneous modules, though some indication of the heterogeneity of function seems necessary for the user, e.g. making the modules in different colors. The Fable modular robotic system (Fig. 1(f)) is an example of a user-configurable modular robotic system based on heterogeneous modules, whereas the ATRON modular robotic system (Fig. 1(a)) is based on homogeneous modules. In the case of Fable, the heterogeneous chain-based modular robotic system consists of various modules, such as different types of joint, branching and termination modules [3]. Joint modules are actuated robotic modules used to enable locomotion and interaction with the environment. Branching modules connect several modules together in tree-like configurations. Termination modules may add structure, a visual expression, additional sensors, or actuators (e.g. grippers or wheels). Similar, the modular robotic wearable exemplified with the Fatherboard (Fig. 1(g)) is also a heterogeneous system with modules of different functions such as a buzz, a recorded sound, a voice, a red light, a blue light, etc. [4].

2.3 Connectivity

Further, it is important to design which *connectivity* is desired and advantageous between modules. The connectivity may vary from loose to tight, from no connection whatsoever to modules all connected, and from chain-based connection to lattice-based connection. Interestingly, the philosophical consideration of intelligence in light of user-configurable modular robotic systems opens up for research into modular systems with no physical connection but only functional connection. The MusicTiles magic cubes (Fig. 1(j)-(k)) present such an example with physical separate modules each representing an instrument, and rotation giving the musical variation of the particular instrument, while together all modules gives the whole music tune. There is no physical attachment between the modules in this user-configurable modular robotic system. On the contrary, in the I-Blocks music cubes (Fig. 1(i)), musical expression of the given module (instrument) is based upon the attachment of the module to another module [5, 6]. As another example, in the case of user-configurable modular devices for a multi-sensory room for therapy of elderly dementia patients (Fig. 1(c)), Sound&Light cubes changed the ambient sound and light based on physical stacking (attaching) the modules together, whereas Rolling Pins changes the responses based upon pattern of interaction with physical separate Rolling Pins (two people rolling the separate pins in synchrony, rolling speed, etc.) [7].

2.4 Ease of construction

In the case of physical connectivity, the connection mechanism may pose a challenge in both homogenous and heterogeneous modular robotic systems. Where the field of reconfigurable modular robotic systems has confronted this challenge in terms of the mechanical and electrical reliability, the mechanical and motion control optimization, etc., the field of user-configurable modular robotic systems needs to take the *ease of construction*, including attachment and detachment, into consideration. For instance, the Fable project (Fig. 1(f)) investigates connectors designed to allow rapid and solid attachment and detachment between modules with scalable connectors to allow modules of different sizes to be combined and designed to permit neighbor-to-neighbor communication [3]. The modular interactive tiles use puzzle-shaped connectors [8], while I-Blocks use the LEGO studs [9], I-Blocks music cubes use magnets [5], and the modular robotic wearable uses simple clothes-buttons [4]. In all cases, the connectors have been carefully researched and developed for the ease of construction to allow anybody to easily build with the system.

2.5 Interaction, affordance, and transparency

As supplement to ease of construction, user-configurable modular robotic systems need to address *interaction* in general. Interaction can be of many forms, apart from attaching and detaching modules, it may be rotation of modules, walking, running and jumping on modules as with the modular interactive tiles (Fig. 1(d)-(e)) for prevention and rehabilitation [10, 11], rolling and stacking as with the modular robotic devices for a multi-sensory room (Fig. 1(c)) [7]. For creating such user interactions, it is important to design for the modules' *affordance* [12, 13], e.g. such as a dice which invites to roll (Fig. 1(k)), a tile which invites to step on it or hit it with a ball (Fig. 1(h)), a LEGO brick which invites to attach (Fig. 1(b)), a wearable module with clothes-buttons which invites to fasten (Fig. 1(g)), rolling pins which invite to roll (Fig. 1(c)), etc. Considering the affordance of modules, it may be possible to communicate the functionality of modules to the user. *Transparency* of functionality of modules and ensembles of modules is indeed a major challenge in user-configurable modular robotic system, and affordance in module design including material design, interaction design, connectivity, etc. must be considered to facilitate the ease of understanding of functionality for the user. Indeed, studying and understanding the affordance of modules and their interplay between each other and with human beings is one of the main defining subjects that distinguish user-configurable modular robotics from other kinds of modular robotics, including self-reconfigurable modular robotics.

2.6 Automatic vs. autonomous modules

The functionality of individual modules and the emergence of the overall intelligent response based on the user's interaction with the modules may be based on *automatic modules* or *autonomous modules*. In most of the known user-configurable modular robotic systems, the system is automatic with pre-programmed content of the modules e.g. as closed-loop control, cellular automata or behavior-based system [1, 9] or as a pre-produced sound piece [5]. Working towards autonomous modules, research with modular interactive tiles (Fig. 1(d)) shows how these may be adaptive in their control, for instance using simple adaptive processing [14] to adapt to the user's physical interactions, or using artificial neural network learning (Fig. 1(k)) [15]. There is an interesting research challenge in understanding how automation and autonomy in modules and their coordination may potentially facilitate and guide user interaction in user-configurable modular robotic systems.

3 Discussion and conclusion

User-configurable modular robotic systems seem a promising concept to allow users to easily configure robotic systems to perform desired, task-fulfilling behaviors. With a well-designed user-configurable modular robotic system, the user can easily modify the physical and functional aspect in terms of hardware and software components of a robotic system, and by making such modifications the user becomes an integral part in the creation of an intelligence response to the challenges posed in a given environment.

As has been outlined, there are several factors in the definition and implementation of modules in a user-configurable modular robotic system, which have consequences for the user-configurability of the system. Some factors are known from modular robotics, but importantly the inclusion of the user poses serious design challenges based upon affordance, interaction, transparency, and ease of use, which are not addressed in traditional modular robotics research. Here, based on lessons learned from a few early examples of user-configurable modular robotic systems, these challenges have been outlined briefly. Future research work should address these challenges in a comprehensive and in-depth manner. Additionally, future research and application work should investigate how user-configurable modular robotic systems may contribute to the development of the *playware ABC*, i.e. investigate how *building bodies and brains* with the user-configurable modular system, the user may *construct, combine and create* to make solutions for *anybody, anywhere, anytime*.

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