Roombots—Mechanical Design of Self-Reconfiguring Modular Robots for Adaptive Furniture

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Abstract— **We aim at merging technologies from information technology, roomware, and robotics in order to design adaptive and intelligent furniture. This paper presents design principles for our modular robots, called Roombots, as future building blocks for furniture that moves and self-reconfigures. The reconfiguration is done using dynamic connection and disconnection of modules and rotations of the degrees of freedom. We are furthermore interested in applying Roombots towards adaptive behaviour, such as online learning of locomotion patterns. To create coordinated and efficient gait patterns, we use a Central Pattern Generator (CPG) approach, which can easily be optimized by any gradient-free optimization algorithm. To provide a hardware framework we present the mechanical design of the Roombots modules and an active connection mechanism based on physical latches. Further we discuss the application of our Roombots modules as pieces of a homogenic or heterogenic mix of building blocks for static structures.**

I. INTRODUCTION

Future working and living environments will be composed of places where people and new technologies cohabit seamlessly. Thanks to the recent progress in tangible interaction with computers [1], ubiquitous computing [2], and augmented reality [3], a movement is observed towards integrating technologies in everyday artifacts, ranging from tables to walls and even carpets or kitchen furniture. This new field is referred to as *roomware* [4] or interactive furniture. It addresses the design and the evaluation of computer-augmented room elements like doors, walls, furniture with integrated information and communication technology.

Although roomware projects deal with user interaction, users have few possibilities to contribute to the design. This project intends to design and control modular robots, called Roombots, to be used as building blocks for furniture that moves, self-assembles, self-reconfigures, and self-repairs—depending on the users preferences.

Modular robots are robots made of multiple simple robotic modules that can attach and detach [5]. Connectors between units allow the creation of arbitrary and changing structures depending on the task to be solved. Compared to "monolithic" robots, modular robots offer higher versatility and robustness against failure, as well as the possibility of self-reconfiguration.

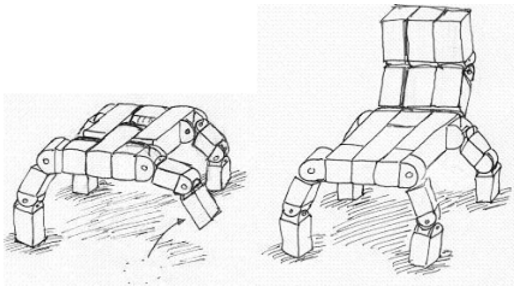

Fig. 1: Initial design sketches for a stool and a chair.

We envision a group of Roombots that autonomously connect to each other to form different types of furniture, e.g. stools, chairs, sofas and tables, depending on user requirements. This furniture will change shape over time, e.g. a stool becoming a chair, a set of chairs becoming a sofa, as well as move using actuated joints to different locations. When not needed, the group of modules can create a static structure such as a wall or a box. Fig. 1 shows some examples of the possible furniture.

In addition, the Roombots should be capable of locomotion by using the actuated joints of the modular robots. For instance, a chair slowly moving, with or without a person sitting on it, like a quadruped robot from a point A to a point B, possibly climbing or descending stairs. When not needed, the group of Roombots can leave the floor, and create static structures such as walls or boxes.

Roombots modules, the basic building blocks for our adaptive furniture, are classified as self-reconfiguring modular robots (SRMR). Modular robots can be described according to their main characteristics, e.g. according to their general usage and their connection type as chain-like or lattice-like [5]. Roombots fall into the second category regarding the configuration possibilities and their lattice. However they will be used mainly as chain-type modular robots, by assembling into adaptive furniture, made from Roombots modules and passive beams and panels. Hardware for chain-like self-reconfiguring modular robots consists mostly of self-sufficient[1] robot modules with a low degree of freedom (dof). An active connection mechanism (such as [6], [5]) provides the modules with the ability to connect to other neighboring modules, or the environment.

Mechanical design constraints for self-reconfiguring modular robots are largely determined by their application: (a) self-reconfiguration (b) locomotion and (c) their usage as

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[1] Self-sufficient in terms of power supply, computation, sensors, communication and actuation.

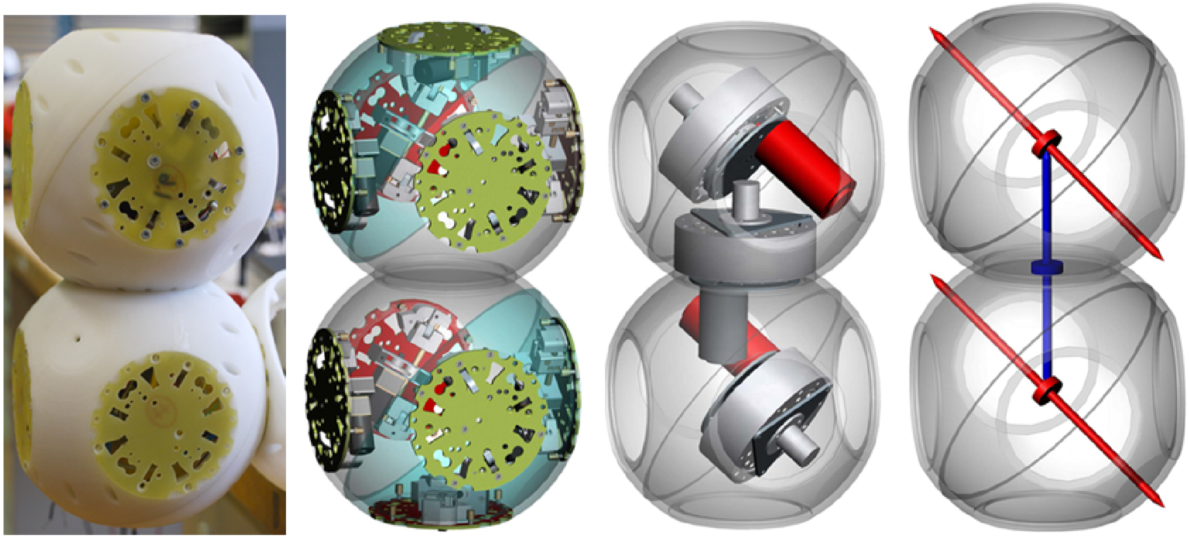

(a) One Roombots module. (b) Up to 10 ACMs. (c) 3 main Motors/gearboxes. (d) 3 axes of rotation.

Fig. 2: (a) One Roombots module, attached on the lower right side. Each RB module consists of four half-spheres made of 3D-printed ABS plastics, three DC-motor-gearbox combinations, and up to 10 active connection mechanisms (ACM). Size of a RB module is 220 mm by 110 mm by 110 mm. One RB module weights about 1.4 kg, including battery pack and electronics. (b) 10 active connection mechanisms can be mounted into one RB module. Alternatively just one *active* connection mechanism per half-sphere can be mounted, filling up the remaining slots with passive connection plates. (c) Our custom designed motor-gearbox combination provides a torque of minimal $M_t = 5$ Nm, and up to 7 Nm. (d) All three axes can rotate continuously, e.g. there is no joint angle limitation. The two outer axes, displayed red, have three main orientations *relative to each other*, aligning the RB module inside the cubic grid. *Parallel*, as displayed, *skew*, when turned by 90°, and *orthogonal* when rotated another 90°.

furniture, or within static structures. We consider furniture as a special case of static structures but with an additional external load and the need for reconfiguration. In addition a user-oriented design is necessary, with key issues such as human-robot interface (HRI), safety, comfort and robustness.

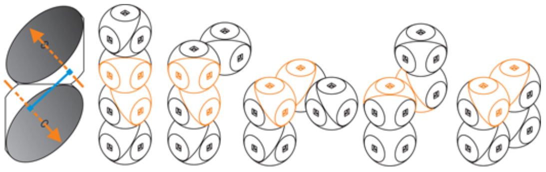
This article presents our progress in the design of the Roombots modules and a characterization of the applying torques, in applications where RB modules will be used as building blocks of adaptive furniture. This paper is structured as follows: In Section II we briefly describe hardware design issues for the three degrees of freedom and the active connection mechanism, and present our first design proposal for the Roombots modules. In Section III we consider our three main applications: using RB modules for testing distributed control algorithms (CPG), RB as building blocks for adaptive furniture, and solving the reconfiguration task of modular robots. We finish with with a conclusion and a description of future work.

II. DESIGN OF THE ROOMBOTS MODULES

The objective of the Roombots project is to develop a new modular robot platform, suitable for creating adaptive furniture by making use of the self-reconfiguration abilities of its modules. Each Roombots module will consist of several actuated joints, controllers, and energy supply. Mechanical connectors allow rapid and solid attachment and detachment between modules. The modules and the connectors need to be designed robust enough to support high loads (e.g. a person sitting on a chair or a stool made from Roombots modules). We do not restrict ourself to a homogeneous Modular Robot approach, RB modules should be able to connect to larger, passive and also lightweight elements to shape furniture. When designing the new Roombots modules, we took inspiration from several other Self-reconfiguring Modular Robot projects, such as the Molecubes [7], Atron [8], M–TRAN [9], Molecule [10] and Superbot [11].

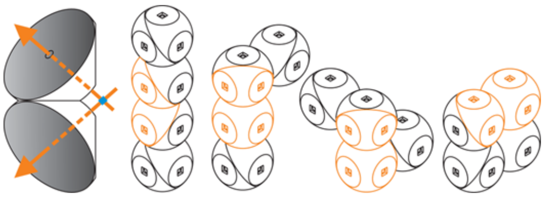
A. *Roombot degree of freedom*

Each Roombots module features three degrees of freedom (dof), Fig. 2d. Both outer dof, red axes, use the *diametral* axis of a cubic grid with a 110 mm grid size. This choice of dof was used firstly in modular robots by [12], [13]. For our Roombots modules we have introduced an additional dof, blue axis. It allows the rotation of the two neighboring red axes. Two in-series connected Roombots modules fix the in-between dof (Fig. 3), because the ACMs are fixed within the frame of a Roombots (RB) module, and lock all dof with the neighboring module. All three RB dof are designed for continuous rotation, there are no joint limits. Of-the-shelve slip rings in each joint (part (10) in Fig. 4) allow to transfer of electric power, and communication.



(a) Axes orientation skew.

(b) Axes orientation parallel.



(c) Axes orientation orthogonal.

Fig. 3: Possible grid-reconfigurations with two Roombots modules connected in-series. The resulting shapes depend on the axis-orientation of the two center blocks, colored in orange: (a) Skew: 5 options, I-, L-, 3DS-, S- and U-shape. (b) Parallel, 4 options. (c) Orthogonal, 4 options.

B. *Motor-gearbox design*

Our goal is to design the RB modules to have enough torque to move at least two combined modules, what is itself and another module. This configuration leads to a necessary torque of 4 Nm, in the worst-case of lifting the above configuration from a stretched horizontal position. To have an acceptable security margin of available torque, the RB modules should have a torque between $M_t = 5$ Nm and $M_t = 7$ Nm. Deciding for a larger security margin, what is even more required torque, would increase weight and size of the RB modules, and would require a re-calculation of the above limitations. Speed is of lesser importance in our applications, therefore a gearbox with a relatively high gear ratio is required. We chose the FH2232 ([14], 10 mNm) DC-motor for the actuation of the center dof, and the FH2342 (16 mNm) for the outer dof. With the above available motor torques of either and a slight over-tuning of the motors, it needs a gearbox ratio between 320 : 1 to 400 : 1. At the same time the gearbox needs to support the resulting output torque. For gearboxes, planetary gearboxes or harmonic drives are commercially available. Harmonic drives are by far too expensive for our budget, as we need three gearboxes per RB module and we are aiming at building 10-20 modules. Available planetary gear-heads are, in comparison, acceptable in price. Though they ”only“ deliver torques around $M_{output} = 1$ Nm, with max-values up to 2.5 Nm.

A second limiting design criteria is our demand for a continuously rotating dof. To transmit electric power between the half-spheres we want to use a commercially available slip-ring, e.g. a pancake style slip ring as used in [8], or a drum-style, used in [13].) Pancake-style slip rings offer more flexibility in terms of implementation. However commercially available versions are more expensive than their drum-style counterparts. To use drum-style slip-rings, a center hole must be left open in the design of the modules. This demand eliminates solutions with center-placed motor-gearbox combinations, unless motor and gearbox are equipped with a center hole already.

We finally decided to design and build our own gearbox, by using mostly commercially available, cheap, plastic pinions (Fig. 4). A three-stage spur pre-gearbox (module m 05) produces a reduction of 27.2 : 1 with three stages. An in-series double-stage planetary gearbox produces then an *overall* reduction of 366 : 1, each planetary stage provides 3.67 : 1. Four plastic pinions $n = 10$ with a bigger module $m = 1$ are chosen for all planets of the planetary gear-head. A bigger number of planets distributes the applied torque more evenly and enables us to use the RB modules also in high-load configurations, currently tested up to 5 Nm dynamic torque. By placing the DC-motor away from the center, and using a hollow axes for the planetary stage, we can include a six-wire slip-ring for energy transmission and communication between half-spheres of each RB module.

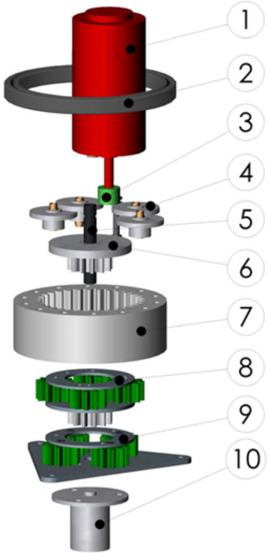


Fig. 4: Explosion view of the DC-motor-gearbox, pinions are made from plastic with metric modules (1) FH2342 DC-motor, to be used in the outer half-spheres (2) thin-section ball bearing (3) first pinion, module $m = 0.5$ (4) spur gear set $m = 0.5$ (5) hollow axis to include 6 wires from the slip ring (6) altering pinion module from $m = 0.5$ to $m = 1.0$ (7) internal gear $n = 32$ teeth, 3D-printed ABS plastic (8) first stage planetary gear: $m = 1.0$, $n_{sun} = 12$, $n_{planets} = 10$, $n_{internal} = 32$ (9) second stage planetary gear (10) drum-style slip ring.

C. Active Connection Mechanism

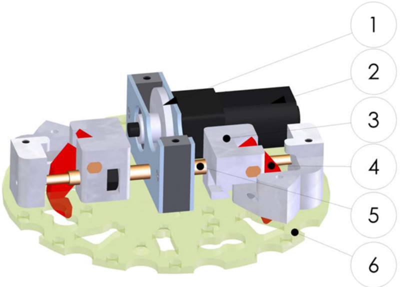


Fig. 5: The ACM in a CAD-view: (1) First piston ($m = 0.5$) (2) Mini-motor-gearbox 150:1 HQ (3) Slider moving the latches (4) Latch, made from fiber-reinforced plastic (5) Worm gear (6) Connector plate, hermaphrodite. The ACM has a height of 16 mm at a diameter of 65 mm.

In previous Modular Robot projects we had developed the DOF-box [15] and YaMoR [16], however both designs lack an active connection mechanism (ACM). ACM design possibilities for Self-reconfiguring Modular Robots are large [17]. We altered our previous [17] ACM design slightly. It now (Fig. 5) features only two mechanical latches, instead of four. This simplifies production, assembly and increases robustness, but also decreased maximum load capacity. If two connecting ACMs are coupled with only two latches, it can also lead to larger buckling of the connecting plates. Hence we currently are evaluating the best design choice. To lock perpendicular forces/torques away from the two remaining latches, spring loaded pins will be placed. The current ACMs main properties are: 1) It uses two mechanical latches to grab into a neighboring module, a single ACM with two latches can hold at least than 16 kg. Holding does not require any energy input, applying forces are entirely routed through the mechanical latches only. 2) An ACM has hermaphrodite features, e.g. any connection plate can grab into another connection plate. 3) Latches and corresponding holes are positioned within a four-way-symmetry. 4) One can replace the active connection mechanism, and use a connector plate as a passive connector plate. By using six passive connector plates, and only four ACM's per module, the RB modules have less weight, are less costly and need lesser time to assembly. 5) An ACM has a height of about 20 mm and a diameter of 65 mm. Each ACM is powered by a DC mini-motor, 150:1 Micro Metal gear motor HP [18]. Sensors to feed back the position of the latches will be implemented soon. 6) Locking and unlocking in a strain-free state works fine, especially unlocking strongly stayed ACMs remains still a problem. One solution could be to use the dof of the modules, and perform freeing movements.

III. APPLICATION EXAMPLES

We currently consider and evaluate at least three applications: (a) Reconfiguration strategies. (b) Testing distributed controller approaches, e.g. on a quadruped robot (Fig. 6a) homogeneously made of RB modules, or a table constructed from RB modules and passive elements (Fig. 6b). (c) Roombots modules for static structures (Fig. 7). We have developed strategies for (a) [19] and (b) [20] before (for our former modular robot system YaMoR), hence we will mainly focus on (c).

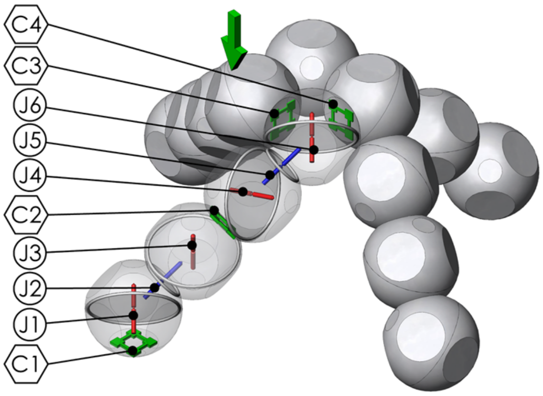


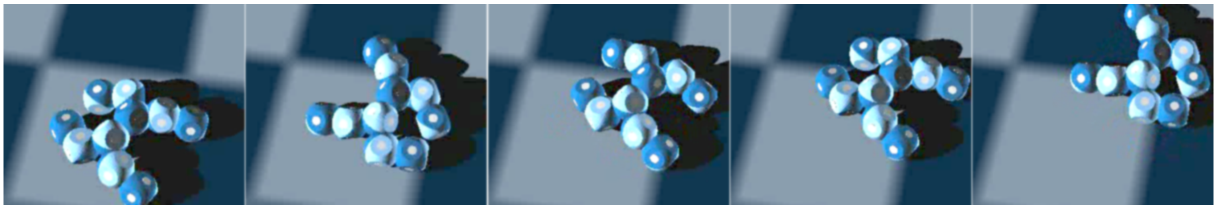
Fig. 7: A stool made of 8 RB-modules. It has a size of 33 cm by 33 cm by 33 cm, what is overall height, width and depth. This example is used to illustrate effecting torques in the RB joints for a static structure, results are explained in detail in Section III-C and Fig. 9. A 50 kg weight is placed on top of the chair, its center of pressure (cop) is shifted horizontally away from the center, marked here with a green arrow, to present a non-symmetric load. Half-transparent leg 1 consists of: RB-module 1, at the ground with green connector C1, joints J1–J3, red and blue, and connector C2, green. Laster fixes RB 1 to RB 2. Perfect alignment of the joints is unlikely due to elasticity and backlash in the RB modules. Therefore relatively large joint in-accuracies were introduced in the simulation; all joints with motors, e.g. for leg 1: J1–J6, *not* the connectors Cx, are arbitrarily mis-positioned about 5°-13° from original joint angles forming a straight leg. All half-spheres on the ground use their ACMs, e.g. C1, to lock into it. Hence the ground needs to be structured accordingly.

A. Self-reconfiguration strategies

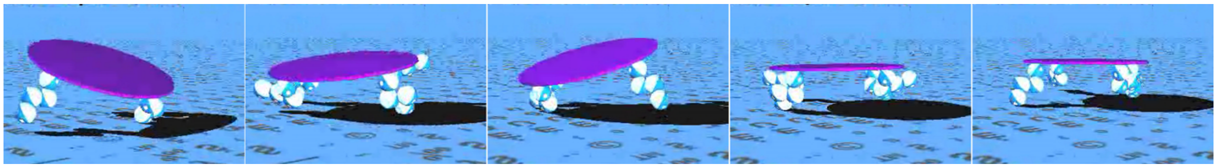
We have recently developed a self-reconfiguration strategy for the YaMoR modular robot [19], and we are currently working on mapping it to the new Roombots modules and its changed topology. Our approach introduces reconfiguration planning for modular robots based on the graph signature and the graph edit-distance. The method has been tested in simulation on two type of modules: YaMoR and M-TRAN. The simulation results show a rapid finding of a near-optimal solution. Our approach is centralized, other projects, e.g. [24], have found decentralized approaches.

B. Distributed Locomotion Control

Our approach to tackle locomotion control is inspired by a control mechanism that nature has found to deal with the redundancies in animal bodies and the requirement to easily modulate locomotion: central pattern generators. Central pattern generators (CPGs) are neural networks capable of



(a) Quadruped robot from RB modules, by Simon Lépine.



(b) Table robot from RB modules, by Sandra Wieser.

Fig. 6: (a) Screen-shot-series of one quadruped robot made of five RB modules. Video and simulation by Simon Lépine [21]. Center dof of the central RB module is also actuated, what leads to a better forward velocity. (b) Table robot, video and simulation by Sandra Wieser [22]. This robot is made from passive elements, the table top, and active elements, the legs. Each leg is made of two RB modules. The table goes forward with a trot gait. Joint torques had to be increased artificially to 10 Nm to gain satisfying results. Videos are available at the BIRG homepage [23].

producing coordinated patterns of rhythmic activity without any rhythmic inputs from sensory feedback or from higher control centers [25]. We developed a method for online learning of locomotion by running an gradient-free optimization algorithm (Powell‘s method) in parallel to the CPG model, with the velocity of locomotion being the criterion to be optimized. The modular robotic system is provided with an estimation of its velocity and explores the parameter space of the CPG model to identify fast gaits. Results from [20] show interesting properties *especially suitable* for modular robotic system. In particular, our CPG model can readily be implemented in a distributed modular robotic system, it is cheap computationally, it exhibits limit cycle behavior; temporary perturbations are rapidly forgotten, it produces smooth trajectories even when control parameters are abruptly changed, and it is robust against imperfect communication among modules. We were also able to present results of learning to move with three different robot structures. Interesting locomotion modes were obtained after running the optimization for less than 60 min. Preliminary results show that the same method can successfully be used to design locomotion controllers online for simulated Roombots modules (Fig. 6), the difference to our previous MR is the higher amount of dof per module, and a higher complexity of the orientation of its dof.

C. Passive structures

We are trying to tackle the application of RB modules in static structures, e.g. furniture. Besides robust connection mechanism, the involved joints need to deliver enough torque to hold a specific structure in shape, unless the robot's dof is blocked otherwise. A solution with no required energy-input at all is shown in Fig. 8, here the stool design uses the shape and orientation of dof of the RB modules to keep its joints torque-free. If that is not the case, as shown in Fig. 7, load forces are translated into joint torques. We have extracted them for the above example from a simulation, results are shown in Fig. 9. The torque applying depends on the orientation of each dof; joint 3 of each leg for example has generally a very low applying torque to compensate. The difference between joints derives from (a) the non-symmetric applied load and (b) from the voluntarily introduced arbitrary, but low joint angle in-accuracies. Torques up to 7 Nm should be possible for the RB modules, what is about the maximum dynamic load for the second joint in this particular example.

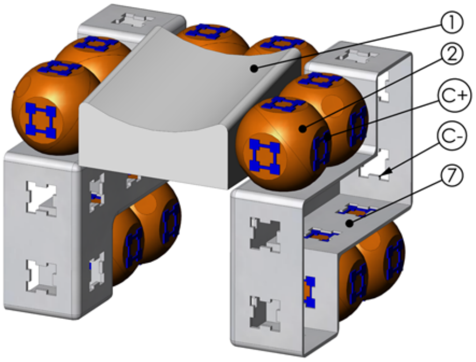


Fig. 8: A first design for a stool made from passive building blocks; (1) and (7), and five RB modules. Building blocks require an ACM couterpart feature (C-), such that the RB modules can grab into it. The shown structure would provide no require energy input for the holding state, e.g. the RB modules can be switched off, and the dof do not need to be blocked.

IV. CONCLUSION AND FUTURE WORK

The mechanical design of the new Roombots modules presented in the article will potentially lead to a new class

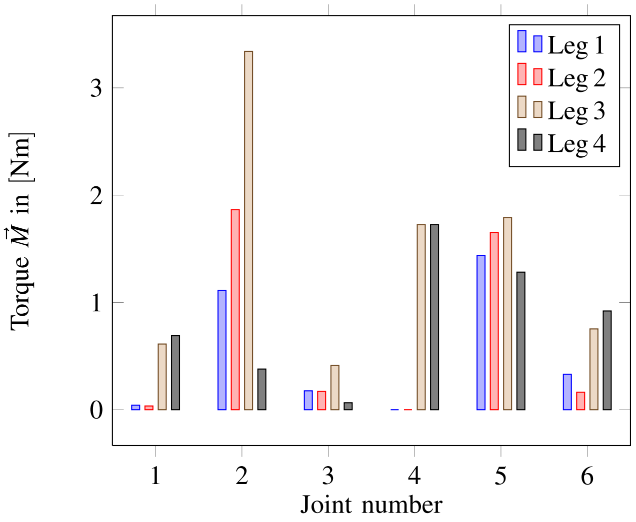


Fig. 9: Joint torque values refer to Fig. 7. We conducted a motion model *simulation*, by placing a 50 kg load non-centered on the stool. Motor-joint angles were displaced by 5°-13° to include backlash, position errors and elasticity in the simulation. Motors in the joints were replaced by spring-damper combinations. Above bar plot sorts the joints by legs, e.g. joint 1 (J1 in Fig. 7) is leg 1, first joint, blue bar. Joint 8 is the second joint of leg 2, red bar plot and so on. Torque values represent applying torque after the stool is in equilibrium state. Dynamic torque values are about twice as high as the ones shown.

of versatile and robust Self-reconfiguring Modular Robots. In addition to interactive furniture, the Roombots could be used to generate different types of static and dynamic structures, e.g. a robot arm oscillating a fan, an interactive artistic sculpture, mechanical support for handicapped persons, and transport of objects.

Current objective is to equip the Roombots modules with reliable electronics and communication hardware (reusing what we developed for our previous modular robotic system [16]). Another future task is to design a user-robot interface to allow users to guide, control and teach the group of modules. We aim at interactions that are high-level and easily learnable by lay people (i.e. general guidance rather than programming), using state-of-the-art PDA-based interfaces and tactile interactions with the modules.

V. ACKNOWLEDGMENT

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